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Faculty of Engineering and Information Technology

GREP: A Blockchain-based System for Managing Real Estate Provenance and Ownership Certification

by

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A Thesis Submitted
in Fulfillment of the
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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Abdullah Jameel Abualhamayl*, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the *Faculty of Engineering and Information Technology*, *School of Computer Science* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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List of Publications

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Conference Papers

1. Abualhamayl, A. J., Almalki, M. A., Al-Doghman, F., Alyoubi, A. A., & Hussain, F. K. (2023, November). Towards fractional NFTs for joint ownership and provenance in real estate. In *2023 IEEE International Conference on E-Business Engineering (ICEBE)* (pp. 143-148). IEEE. (Covered objective 3, published).
2. Almalki, M. A., Abualhamayl, A. J., Alyoubi, A. A., Al-Doghman, F., & Hussain, F. K. (2024, October). Blockchain-Based Joint Ownership Group Formation. In *2024 IEEE International Conference on e-Business Engineering (ICEBE)* (pp. 206–211). IEEE. (Related to objective 3, published).

Abstract

GREP: A Blockchain-based System for Managing Real Estate Provenance and Ownership Certification

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Real estate management is hindered by numerous challenges, as existing systems are inefficient and complex, leading to issues such as fraud, tampering, and unclear ownership histories. Blockchain technology has the potential to revolutionize real estate management by ensuring traceable, secure, transparent, and immutable records of property ownership and provenance. Despite its potential, there is no global platform for managing and tracing real estate provenance, nor reliable methods for proving ownership and shared ownership.

This thesis proposes the Global Real Estate Platform (GREP), a hybrid blockchain-based system designed to manage real estate provenance and ownership certification. Using blockchain technology, including non-fungible tokens (NFTs) and fractional non-fungible tokens (fractional NFTs), GREP addresses these critical gaps. A nine-step systematic literature review was conducted to explore the integration of blockchain technologies in managing real estate transactions and ownership certification. This process provided valuable observations, implications, and recommendations based on the analysis. Additionally, it identified gaps in the literature, which led to the formulation of research questions and objectives.

Building on this foundation, we present the development of GREP. This hybrid blockchain solution is designed to achieve the research objectives as follows:

- Developing a reliable and global real estate platform for managing real estate provenance, which manages provenance data and access rights, enhances data authenticity, and maintains a balance between transparency, privacy, and accountability.

- Developing a reliable method to prove ownership of real estate property, which incorporates NFTs to address inefficiencies, security vulnerabilities, and the variability of real estate transaction costs and time.
- Developing a reliable method to prove shared ownership of real estate property, which involves utilizing fractional NFTs to effectively manage the creation, division, and transfer of a property's ownership record to multiple parties.
- Validating and evaluating the system to ensure its robustness and reliability, and developing a prototype to demonstrate its feasibility and effectiveness.

Each research objective is addressed in both conceptual and practical terms, with thorough implementation, validation, and use case demonstrations, followed by system evaluation using relevant metrics. In addition to these scientific advancements, this research contributes to addressing challenges such as preventing fraud, including forged documentation and double selling, as well as undocumented land, particularly in rural and underdeveloped regions. Furthermore, it reduces costs, shortens transaction times, improves efficiency, and boosts consumer confidence and public trust. The research also opens new possibilities for future directions, such as serving as a secondary identifier and aiding international investors without prior data.

Dissertation directed by Associate Professor Farookh Hussain
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CHAPTER 1
Introduction

1.1 Introduction

Nowadays, modern technology offers an unprecedented opportunity to simplify the complexities and transform the landscape of traditional real estate transactions. These tools introduce a level of speed, accuracy, and transparency that was previously considered beyond reach. However, despite the promising potential of these technological advancements, the real estate sector still faces numerous challenges as existing systems are inefficient and complex (Wouda and Opdenakker, 2019; Seger and Pfnür, 2021).

One of these challenges is the lack of a secure and unified platform for managing real estate certification and verification, leading to increased risks of fraud and inefficiencies. Traditional paper-based methods remain slow and incredibly vulnerable to document mismanagement and tampering (Yadav and Kushwaha, 2022), while current digital methods are susceptible to cyber threats and data corruption (Mani et al., 2014). Additionally, the absence of effective provenance tracking further complicates these issues, especially in regions with undocumented land or outdated bureaucratic processes, leading to ownership disputes, legal uncertainties, and difficulties in establishing trust in property records. These pervasive problems underscore the critical demand for innovative solutions that can effectively overcome the current limitations and flaws in real estate management systems.

In addressing these pervasive challenges, blockchain technology presents a potential solution by offering a decentralized and secure ledger (Shuaib et al., 2021; Yli-Huumo et al., 2016). It streamlines the verification process and reduces the complexity and duration of ownership verification. This technology integrates NFTs, which provide a unique and immutable proof of ownership (Hasan et al., 2022; Saeidnia and Lund, 2023; Bamakan et al., 2021), consequently enhancing the security and trustworthiness of asset ownership. Furthermore, blockchain promotes transparency, ensuring all parties access comprehensive and accurate property provenance information (Abualhamayl et al., 2024), effectively resolving issues related to transparency in ownership history and mitigating risks associated with document mismanagement and fraud.

Therefore, this thesis develops a blockchain-based system for managing real estate provenance, recording and tracking property ownership, and providing tamper-proof verification for ownership certification. Additionally, this study introduces significant scientific and social contributions to real estate management and blockchain technology, as detailed in this chapter.

The following sections of this chapter are organised as follows: Section 1.2 presents the problem statement which outlines the specific challenges that this thesis addresses within the real estate sector. Section 1.3 provides an overview of the main technologies used in this research, including blockchain technology, NFTs, and fractional NFTs. Section 1.4 explores blockchain solutions to real estate challenges, demonstrating how blockchain technology can overcome common issues in the sector. Section 1.5 highlights the research significance by detailing the scientific and social contributions. Section 1.6 outlines the thesis plan, providing a roadmap for the research conducted. Finally, Section 1.7 concludes the chapter by summarizing the key points discussed and setting the stage for Chapter 2.

1.2 Problem Statement

The real estate sector is currently grappling with several challenges that hinder its efficiency and reliability. A key issue is the absence of an integrated, secure, and reliable platform for managing and tracing real estate transactions. This lack of a unified system results in inefficiencies and increased risks of fraud and tampering. Moreover, current methods for proving property ownership and managing shared ownership are highly susceptible to fraud. Traditional methods rely on paper-based systems that are slow and labour-intensive, leading to significant delays and increased transaction costs, thereby heightening the risk of document mismanagement and fraud. Digital solutions, while reducing reliance on paper, introduce vulnerabilities to cyber threats such as hacking and unauthorized access.

Moreover, the absence of reliable provenance tracking further exacerbates the problem. Provenance typically denotes any digital or physical data that offers details about the origin and production of a final product (Herschel et al., 2017). In the domain of real estate, real estate provenance refers to a complete record of a property's ownership history. However, it can extend beyond ownership to include all information related to the property since its creation. The importance of real estate provenance is vast. Several key aspects of its importance are as follows:

- Provenance tracking in real estate provides a complete history of property ownership and makes it easier for buyers, sellers, and regulators to access accurate records. This eliminates ambiguity and fosters trust in real estate transactions.
- It reduces opportunities for fraudulent transactions such as forged documents, double-selling, or unauthorized transfers by ensuring that all ownership transfers are recorded and verified.
- A well-maintained provenance system assures buyers and investors of the legitimacy of a property's ownership history and enhances confidence in the transaction by recording the property's full transactional history.
- Provenance data ensures that property transactions comply with legal and tax requirements and assists in anti-money laundering (AML) efforts by providing a clear record of ownership and transaction flow.
- Reliable provenance tracking makes it easier for international or remote investors to trust the legitimacy of properties and reduces concerns about unclear ownership or fraud.
- In markets with new buyers or where there is no prior transaction history, provenance systems offer a reliable way to verify properties, which is especially valuable in emerging or international markets where local records may be incomplete or unavailable.

The lack of reliable provenance tracking and a unified system for managing real estate records also contributes to significant delays and inefficiencies. In many countries, these inefficiencies are exacerbated by bureaucratic complexities and outdated processes. For instance, in Bangladesh, securing land registration can take up to 245 days, involving eight complex procedures and costing over 10% of the property's value (Islam and Lee, 2016). The situation is even more daunting in the Philippines, where land title registration requires navigating a staggering 168 steps across 58 different agencies (Reuters, 2016). Similar delays and procedural complexities are observed in India, where it can take up to 44 days. In contrast, Nepal requires just 5 days, while Pakistan extends to 70 days. Comparable delays are also noted in Kenya (Keilitz and Wiipongwii, 2017; Reuters, 2016).

These inefficiencies and delays are even more pronounced in rural regions across the globe, where the issue of undocumented land presents a significant barrier to economic and social development. Over 90% of land in rural Africa remains undocumented and unrecognized even by government authorities (Kshetri, 2017). Similarly, in Ghana, 78% of the land lacks formal accounting, and in Nigeria, this figure reaches as high as 97% (Reuters, 2016). Additionally, in India, more than 20 million families reside on land to which they do not have legal title (Kshetri, 2017).

In addition to these inefficiencies and delays, traditional web-based solutions are not entirely secure and are susceptible to cyber-attacks. This vulnerability is vividly illustrated by several high-profile breaches. For instance, the Equifax cyber-attack exposed the personal information of over 145.5 million Americans (McPhee and Ljutic, 2017). Similarly, another breach involved the theft of the usernames and login passwords of 3 billion Yahoo users (McPhee and Ljutic, 2017).

These widespread issues highlight the pressing need for innovative solutions capable of addressing the limitations and weaknesses in current real estate management systems. Aligning with the objectives of this research, there is a critical demand for a secure, traceable, and efficient platform for managing real estate ownership certification and tracking. Utilizing blockchain technology, this research represents a pioneering attempt to tackle these challenges while preserving a careful balance between transparency, privacy, and accountability within a system designed for managing real estate provenance and ownership certification.

1.3 Technologies Overview

1.3.1 Blockchain technology

The development of blockchain began with the introduction of Bitcoin in 2008, which marked its first practical application. Bitcoin was developed by an entity using the pseudonym Satoshi Nakamoto (Nakamoto, 2008). This document outlined a decentralized currency that utilized blockchain as its underlying foundation, which effectively addressed the double-spending problem inherent in digital transactions.

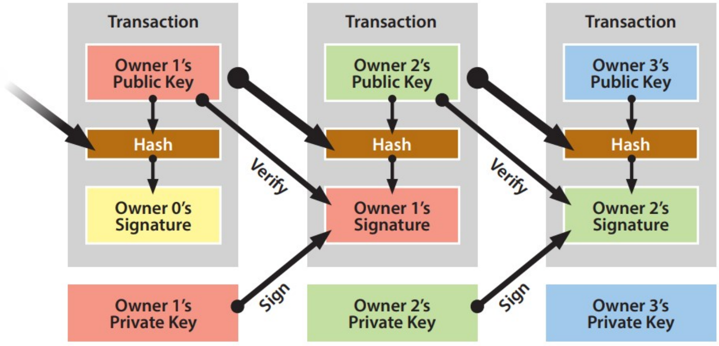

Figure 1.1: Blockchain transactions diagram by Satoshi Nakamoto (Nakamoto, 2008)

Figure 1.1 illustrates the fundamental concept of the transactions within a blockchain, as proposed by Satoshi Nakamoto. Each transaction involves the transfer of digital assets secured through digital signatures. The owner of the digital asset digitally signs the transaction by combining a hashed value of the prior transaction and the public key of the next recipient. This ensures that each transfer is verifiable and secure, which forms an unbreakable chain of ownership as shown in the diagram.

As the technology evolved, it became evident that blockchain could serve as a foundational technology for numerous applications beyond cryptocurrencies. For example the Ethereum platform, which was launched in 2015, is a blockchain-based platform that allows developers to create and deploy smart contracts and decentralized applications. Smart contracts are automated contracts that carry out actions once specified conditions are fulfilled. These innovations have demonstrated how blockchain can transform not just financial transactions but also contractual relationships in several fields such as healthcare, supply chain management, and governance (Zhang et al., 2024a; Queiroz et al., 2020; McGhin et al., 2019).

Blockchain Types

Blockchain technology is classified into several types, each tailored for specific uses and sectors. The main types of blockchains are:

- **Public Blockchains**: These operate autonomously without the need for a central overseeing authority and are characterized by their open and decentralized nature (Pilkington, 2016).
- **Private Blockchains**: These are controlled, centralized systems accessible only to users who have been granted authorization, making them ideal for private organizational use (Yaga et al., 2019).
- **Consortium Blockchains**: Useful in sectors like supply chain management and healthcare, these blockchains enable multiple stakeholders to securely share data and manage operations while maintaining oversight over the shared information (Upadrista et al., 2024).
- **Hybrid Blockchains**: These offer the versatility to adapt blockchain solutions to meet specific business needs, striking a balance between security and broader accessibility (Marar and Marar, 2020).

Table 1.1 illustrates the differences between types of blockchain technologies in terms of access, control, decentralization, and public interaction.

Type	Access	Control	Decentralization	Public Interaction
Public Blockchain	Open to anyone	No central authority	Fully decentralized	High interaction with the public
Private Blockchain	Restricted to specific members	Single organization or consortium of organizations	Centralized or limited decentralization	No direct public interaction
Consortium Blockchain	Restricted to selected group of organizations	Multiple organizations share control	More decentralized than private but less than public	Limited public interaction
Hybrid Blockchain	Combination of private and public access	Controlled by a single organization but interacts with public	Mix of decentralized and centralized	Interacts with public

Table 1.1: Overview of various blockchain types

1.3.2 NFTs

Non-fungible tokens (NFTs) initially appeared as unique digital assets representing ownership or proof of authenticity for specific items or content on the blockchain. Unlike cryptocurrencies like Bitcoin or Ethereum, which are interchangeable on a one-to-one basis (Moro-Visconti and Cesaretti, 2023), each NFT is distinct and cannot be exchanged equivalently with another NFT (Wang et al., 2021). This unique characteristic of NFTs makes them perfectly suited for establishing verifiable ownership of individual items such as digital art, collectibles, and many forms of creative works (Bellagarda and Abu-Mahfouz, 2022).

NFTs originated with the emergence of blockchain technology, particularly with Ethereum, which introduced smart contracts as a foundational element for creating decentralized applications. The first notable NFT project, CryptoPunks, launched in 2017, demonstrated the potential of NFTs by allowing users to own and exchange distinct digital characters (Larva Labs, 2021). This pioneering project laid the groundwork for the burgeoning NFT market, which gained explosive popularity in 2021. That year saw high-profile transactions, such as a digital artwork by Beeple selling for $69 million (Christie's, 2021), capturing mainstream attention.

NFTs operate on blockchain networks such as Ethereum, where smart contracts securely record ownership and transaction history. By leveraging blockchain characteristics, NFTs offer a transparent and tamper-proof method for establishing provenance and verifying ownership. While marketplaces like OpenSea have facilitated the purchase, sale, and exchange of NFTs as unique digital assets (Rehman et al., 2021), these advantages make NFTs similarly useful for representing physical assets such as real estate (Nguyen et al., 2023), event tickets (Regner et al., 2019), and intellectual property rights (Bamakan et al., 2022).

1.3.3 Fractional NFTs

Fractional non-fungible tokens (Fractional NFTs) represent an innovative solution in the NFT ecosystem by allowing fractional ownership of unique assets. This technology emerged in response to the high costs associated with purchasing entire NFTs which often limit access to wealthier individuals or institutions. By enabling multiple owners to hold fractions of a single NFT, fractional NFTs democratize access to valuable assets and make it possible for a broader audience to invest in high-value items (Choi et al., 2024).

The beginnings of fractional NFTs are linked to the expansion of the NFT market, which gained significant traction in 2021. As the NFT ecosystem matured, it became evident that there was a demand for more accessible investment options. Despite being a relatively early technology (Ko et al., 2024), NFTs have led to new innovations like fractional NFTs, which utilize the same underlying blockchain technology. Fractional NFTs employ smart contracts to manage the fractionalization process, allowing multiple owners to hold shares of a single NFT. This increases liquidity and enables a more dynamic trading environment.

1.4 Blockchain Solutions to Real Estate Challenges

As highlighted in the Problem Statement, the real estate sector is hampered by inefficiencies and vulnerabilities inherent in traditional processes. These include lengthy procedures for issuing and verifying ownership titles, compounded by security risks that facilitate fraud and undermine trust in property rights (Wouda and Opdenakker, 2019; Seger and Pfnür, 2021; Shehu et al., 2022). Furthermore, a lack of transparency in ownership provenance history complicates verification processes, leading to disputes and eroding stakeholder trust (Bidabad et al., 2017; Ortega-Rodríguez et al., 2020). Cost variability and the indirect expenses associated with legal and administrative fees exacerbate the unpredictability and inefficiency

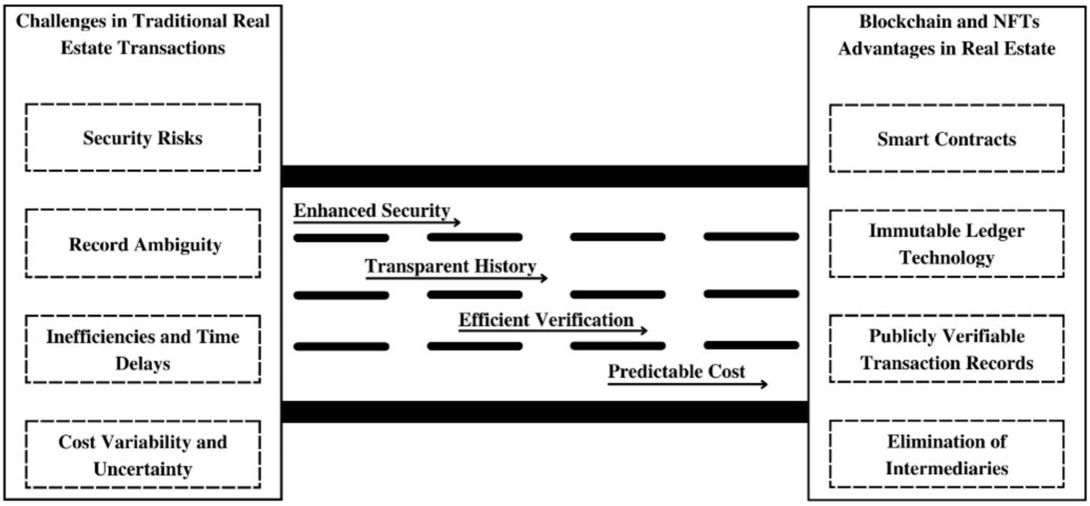

Figure 1.2: Potential solutions to traditional real estate challenges through using the advantages of blockchain and NFTs

of the sector (Collett et al., 2003). These challenges underscore the need for a more efficient, secure, transparent, and traceable system for managing real estate transactions.

As shown in Figure 1.2, one potential technological solution to these challenges is blockchain technology, which offers a secure and decentralized ledger for recording transactions (Shuaib et al., 2021; Yli-Huumo et al., 2016). This innovation can significantly streamline the verification process, thereby addressing the inefficiency in ownership verification by reducing the time and complexity involved (Yang, 2022; LiBin et al., 2021). By utilizing NFTs within the blockchain framework, security vulnerabilities in ownership records can be mitigated (AlKhader et al., 2023), as NFTs provide a unique and immutable proof of ownership (Hasan et al., 2022; Saeidnia and Lund, 2023; Bamakan et al., 2021), enhancing the security and authenticity of property rights. Furthermore, blockchain technology inherently promotes transparency (Babaei et al., 2023), offering a clear and accessible history of ownership transactions (Brau et al., 2024). This capability can effectively overcome the challenges of a lack of transparency in ownership history, ensuring that all stakeholders have access to accurate and reliable property provenance information.

1.5 Significance of the Research

This section outlines the significant contributions made by this research to the field of real estate management and blockchain technology by detailing both scientific innovations and social impacts.

1.5.1 Scientific contribution

1. This research presents the first detailed review of the literature, utilizing an extensive nine-step systematic literature review methodology and a comprehensive General, Specific, Alternative (GSA) keyword strategy to effectively categorize and retrieve all relevant studies.

2. This study is the first to propose a hybrid blockchain-based framework, named the Global Real Estate Platform (GREP), that incorporates real estate provenance, NFTs, and fractional NFTs to provide a secure mechanism that outperforms traditional systems, including paper-based records, which are susceptible to loss, damage, or theft, as well as web-based solutions, which are vulnerable to hacking, corruption, and cyberattacks.

3. This study is the first to implement, validate, and evaluate a universal real estate solution for provenance tracking and ownership certification.

4. This study is the first to propose a hybrid blockchain-based framework that maintains a necessary balance between decentralization, privacy, and accountability in managing and tracing real estate transactions.

1.5.2 Social contribution

1. The study can help address challenges related to undocumented land and inefficient property markets, potentially benefiting economic and social development, especially in rural and underdeveloped regions.

2. This research can contribute to the prevention of common real estate frauds, such as forged documentation and double selling.

3. This research will help reduce the costs and time associated with real estate transactions, streamlining processes and enhancing efficiency across the industry.

4. By providing a secure, trackable, and more reliable real estate system, this study can enhance consumer confidence and promote public trust in real estate markets.

5. This study can open up new possibilities, including serving as a secondary identifier for users and assisting international owners who have no prior data to engage in the market (known as the cold-start problem in recommender systems (Polohakul et al., 2021)).

1.6 Thesis Plan

In this study, we develop and propose the GREP framework, which utilizes blockchain and NFT technologies, including fractional NFTs, to advance the management and certification of real estate provenance and ownership. To thoroughly address the objectives of this study, this thesis is arranged into nine chapters, each chapter described in the following and depicted in Figure 1.3:

- **Chapter 2:** This chapter presents a systematic literature review of existing research on the application of blockchain in the real estate sector. It aims to identify the gaps that this thesis seeks to address.

- **Chapter 3:** This chapter outlines the specific gaps found in the existing literature. It also formulates research questions derived from these gaps and establishes objectives designed to address these questions and fulfill the aims of the thesis.

- **Chapter 4:** This chapter describes the research methodology employed to accomplish the study's objectives, with an emphasis on design science research. It also introduces the solution framework proposed in the thesis.

- **Chapter 5:** This chapter focuses on developing the GREP system for managing real estate provenance, covering Objective 1. It introduces GREP as a hybrid blockchain that integrates the benefits of both private and public blockchains by striking a balance between adequate transparency, data privacy, and accountability. Additionally, this chapter includes the validation and the evaluation of Objective 1, forming part of Objective 4.

- **Chapter 6:** This chapter explains the development and implementation of NFTs within GREP as a reliable method for proving ownership of real estate properties, covering Objective 2. It introduces a secure, transparent, and tamper-proof ownership certification framework by integrating NFTs within a government-regulated hybrid blockchain model, ensuring both decentralized security and regulatory trust. This chapter also includes the validation and the evaluation of Objective 2, which contributes to Objective 4.

- **Chapter 7:** This chapter expands on the GREP framework by integrating fractional NFTs to establish a structured and verifiable method for shared ownership certification, covering Objective 3. It focuses on developing a reliable solution to manage the creation, division, and transfer of a property's ownership record among multiple parties. Additionally, this chapter includes the validation and the evaluation of the shared ownership model, which contributes to Objective 4.

- **Chapter 8:** This chapter presents the prototype implementation of GREP, which contributes to Objective 4 by demonstrating the feasibility of all developed solutions within a unified system. It illustrates system functionality through technical tools, screenshots, and detailed explanations, showcasing how the solutions integrate in a practical environment.

- **Chapter 9:** This chapter finalizes the thesis by addressing the key issues explored throughout the research, detailing the main contributions to the existing literature, and concluding with a section on limitations and future research directions to further enhance and expand upon the developed solutions.

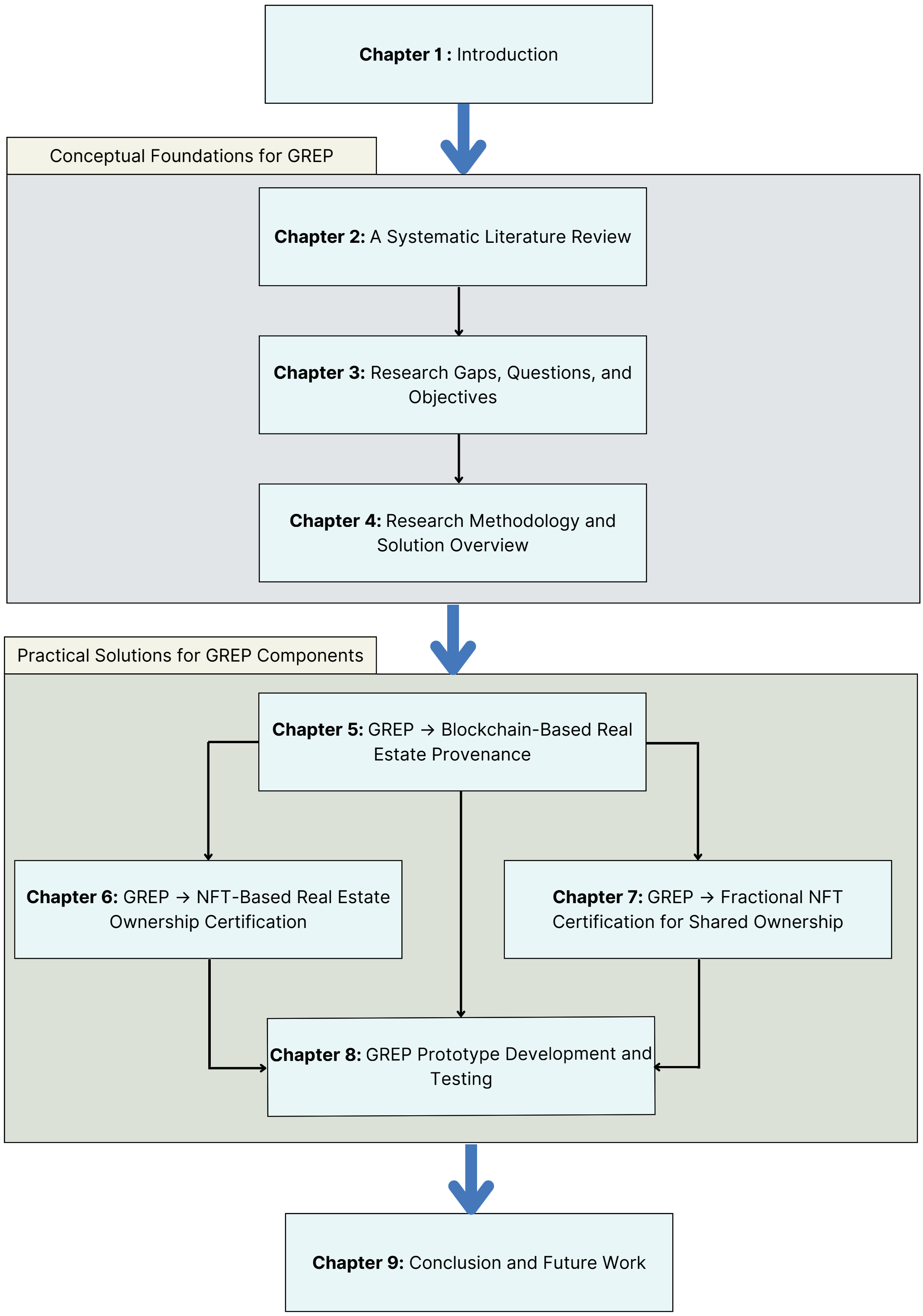

Figure 1.3: Visual representation of the thesis plan

1.7 Conclusion

The first chapter introduces blockchain technology and its potential usability for managing real estate provenance and ownership certification. It begins by presenting the problem statement and discussing the challenges related to real estate ownership and management. The chapter also provides an overview of key technologies such as blockchain, NFTs, and fractional NFTs. Additionally, it explores blockchain-driven solutions designed to enhance transparency, security, and efficiency in real estate transactions. The chapter further outlines the significance of the research by detailing its scientific and social contributions and concludes with a complete thesis plan.

In the next chapter, a systematic literature review is carried out to explore research on blockchain applications in real estate management. The aim is to identify gaps in the current literature and provide a foundation for addressing these challenges through the proposed solutions.

CHAPTER 2

A Systematic Literature Review

2.1 Introduction

The real estate sector faces significant challenges in ensuring secure and efficient transactions. Existing systems for proving real estate ownership are prone to inadequacies, leading to increased risks of fraud, manipulation, and inefficiencies. As highlighted in this systematic literature review, blockchain technology, with its decentralized, secure, and immutable nature, offers a promising approach to overcoming these challenges.

This chapter provides details of a systematic literature review of the related literature on the integration of blockchain technologies in real estate transactions and ownership certification. It introduces a detailed nine-step systematic literature review methodology that incorporates a detailed keyword strategy to ensure comprehensive coverage of relevant research. The process initially identified 505 studies, and through successive filtration stages, 19 studies were identified and selected for further analysis.

All literature is assessed based on specific analytical standards. Based on these standards, further observations, implications, and recommendations are provided for each analytical standard. Beyond offering valuable insights into blockchain applications for managing and tracing real estate transactions and ownership certification, this study's systematic approach provides a robust framework that is applicable to other systematic literature review studies.

The chapter is further organised as follows: Section 2.2 presents the systematic literature review process, which consists of nine subsections. These subsections outline the detailed steps taken during the review: Section 2.2.1 describes the process of searching well-known peer-reviewed databases using related keywords; Section 2.2.2 specifies the criteria for inclusion and exclusion, which define the parameters for including or excluding studies. Sections 2.2.3 through 2.2.6 outline the filtration steps used to refine the search results, namely: Section 2.2.3 applies the 1st filtration by selecting only research whose titles relate to the keywords; Section 2.2.4 applies the 2nd filtration by deleting repeated results in each dataset individually; Section 2.2.5 applies the 3rd filtration by selecting only related results based on the abstract; Section 2.2.6 provides details on a full-text review to assess the studies for final inclusion, and Section 2.2.7 merges all the results and eliminates duplication across databases to consolidate the findings. Section 2.2.8 provides an overview of the analytical standards and results, and Section 2.2.9 discusses the findings and recommendations, offering insights and suggestions. The chapter concludes with Section 2.3.

2.2 Systematic Literature Review Process

Before conducting any research, it is necessary to investigate the existing literature to gain a comprehensive understanding of the current research and to identify trends and gaps. A systematic literature review is a methodology that enables the evaluation of all available research related to the topic (Kitchenham, 2007). It organizes the research process systematically by which all potential existing literature is thoroughly covered, critically analyzed, and synthesized.

This systematic literature review aims to explore the integration of blockchain technologies in the management of real estate transactions and ownership certification. It provides observations on the current state of blockchain applications in real estate, discusses the implications of these findings, and offers recommendations based on the analysis. Additionally, it presents a detailed systematic literature review methodology. In addition to offering valuable insights that can advance the understanding and implementation of blockchain technologies in real estate, the significance of this study extends to its systematic approach, which can be applied to other systematic literature review studies.

Inspired by Kitchenham and Charters (Kitchenham et al., 2007), we refined and expanded our methodology into a nine-step process designed to ensure a detailed and systematic exploration and analysis of all potentially relevant research. The specifics of each step are discussed in the following subsections (see the summary of the nine-step process in Figure 2.1 for an overview).

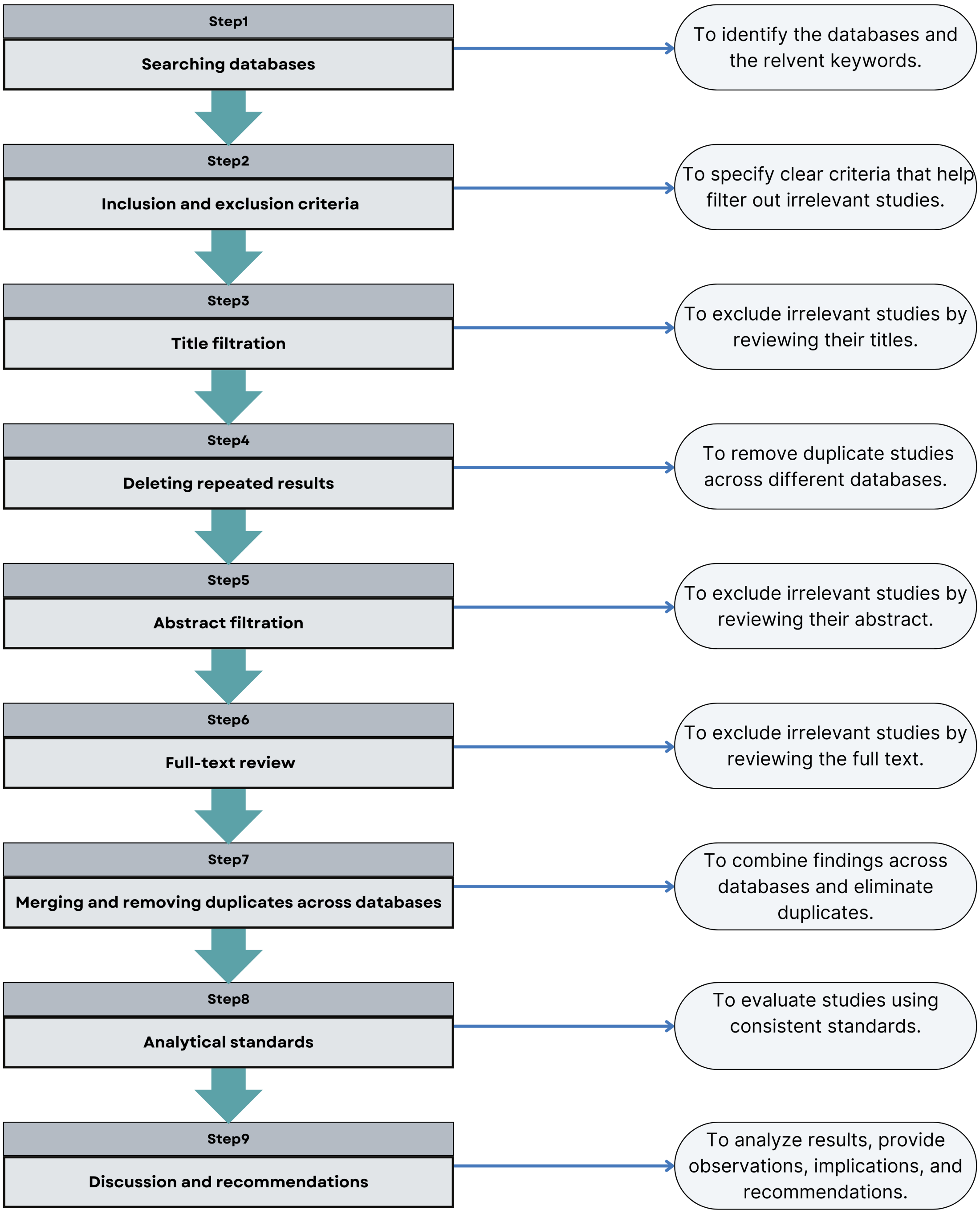

Figure 2.1: Summary of the nine-step process for the systematic literature review

2.2.1 Searching well-known peer-reviewed databases using related keywords

The search was initiated by querying established databases with a set of carefully selected keywords relevant to the study's theme. To review and cover all the related literature comprehensively, the following databases were selected:

1. Association for Computing Machinery Digital Library (ACM DL) accessible at `https://dl.acm.org/`
2. Elsevier ScienceDirect accessible at `https://www.sciencedirect.com/`
3. IEEE Xplore accessible at `https://ieeexplore.ieee.org/Xplore/`
4. Web of Science accessible at `https://www.webofscience.com/wos/`

Determining the right keywords is crucial for retrieving all the relevant studies. To ensure a comprehensive literature review, we devised a GSA keyword strategy that categorizes terms into general, specific, and alternative categories. Table 2.1 below lists the keywords used in the search, along with their intended purpose in the study.

Keywords	**Purpose**
Blockchain AND ("real estate")	*General* inquiry that provides a broad perspective for all related studies on blockchain and real estate management and tracing.
("Non Fungible Token" OR "Non-Fungible Token" OR NFT*) AND ("real estate")	*Specific* inquiry to directly target studies focused on the new blockchain implementation (NFT) and real estate.
("Smart contract*" OR "Distributed Ledger Technology") AND ("property management" OR "property ownership")	*Alternative* inquiry to explore synonymous terms and concepts bridging both general and specific queries.

Table 2.1: Keywords and their purposes. Boolean operators (AND/OR) refine searches by narrowing or broadening results. Quotation marks ("") ensure exact phrase matching, while asterisks (*) capture word variations

The keywords were entered into the selected databases and 505 results were retrieved. Figure 2.2 shows that general keywords account for 61.1% of the total results, reflecting a broad search perspective.

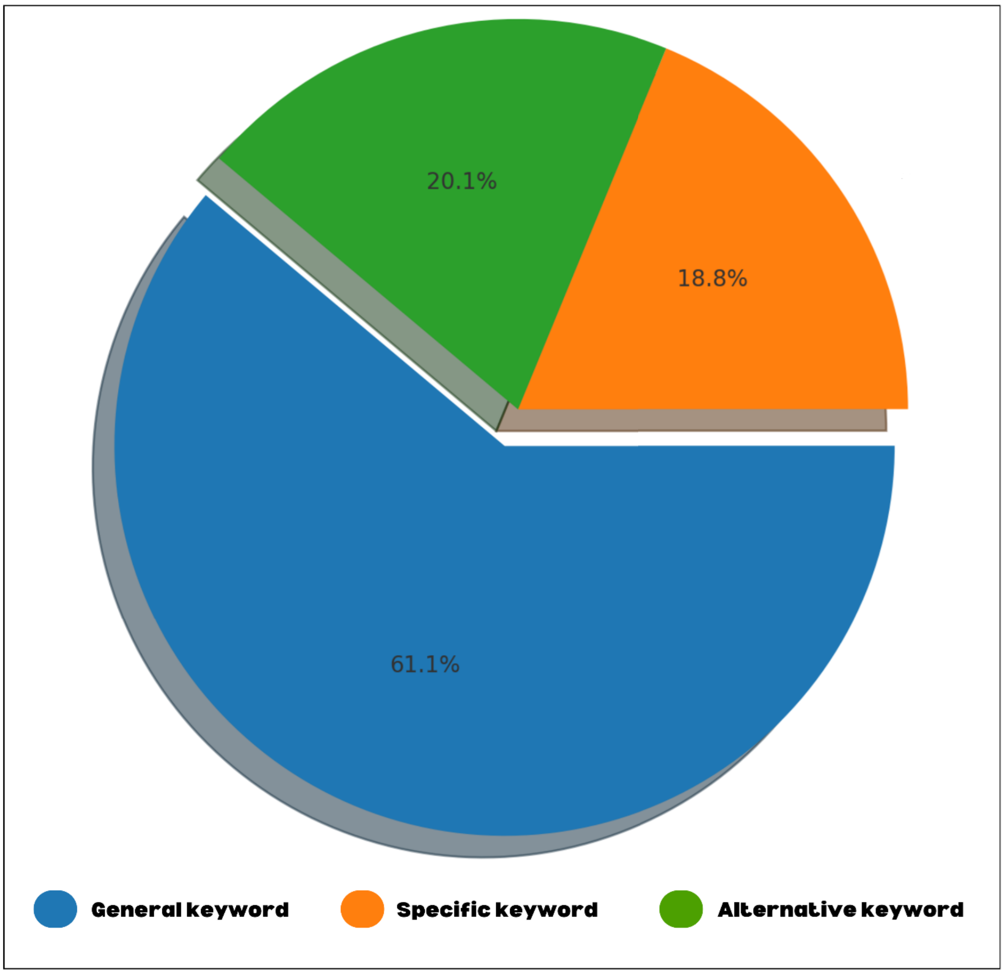

Figure 2.2: Initial keyword distribution

2.2.2 Specifying criteria for inclusion and exclusion

In this step, we set clear criteria for inclusion and exclusion to ensure that only the most relevant studies related to the topic and scope of this thesis are selected. The criteria are as follows:

Inclusion Criteria:

1. **Relevant Literature in Selected Databases:** Include all relevant literature from the selected databases.

2. **Scope of Study:** Only include literature that falls within the defined scope of the study.

3. **Empirical Evidence:** Only include studies that provide empirical evidence or practical applications.

Exclusion Criteria:

1. **Theoretical Proposals Only:** Exclude articles that primarily offer theoretical frameworks, conceptual models, or proposals without empirical study or practical testing results.

2. **Unclear Visualization:** Exclude studies with unclear or inadequate visualizations that hinder understanding.

3. **Off-topic:** Exclude literature that does not pertain to the research objectives.

2.2.3 Applying 1st filtration: Selecting only research titles related to the keywords

The first filtration step involves reviewing the titles of the retrieved studies to determine their relevance, which helps narrow down the pool of studies. Databases tend to show all potential results in any context. As a result, 408 out of 505 results were excluded, leaving 97 relevant studies for further analysis. Figure 2.3 shows the distribution of these studies using the GSA keyword strategy.

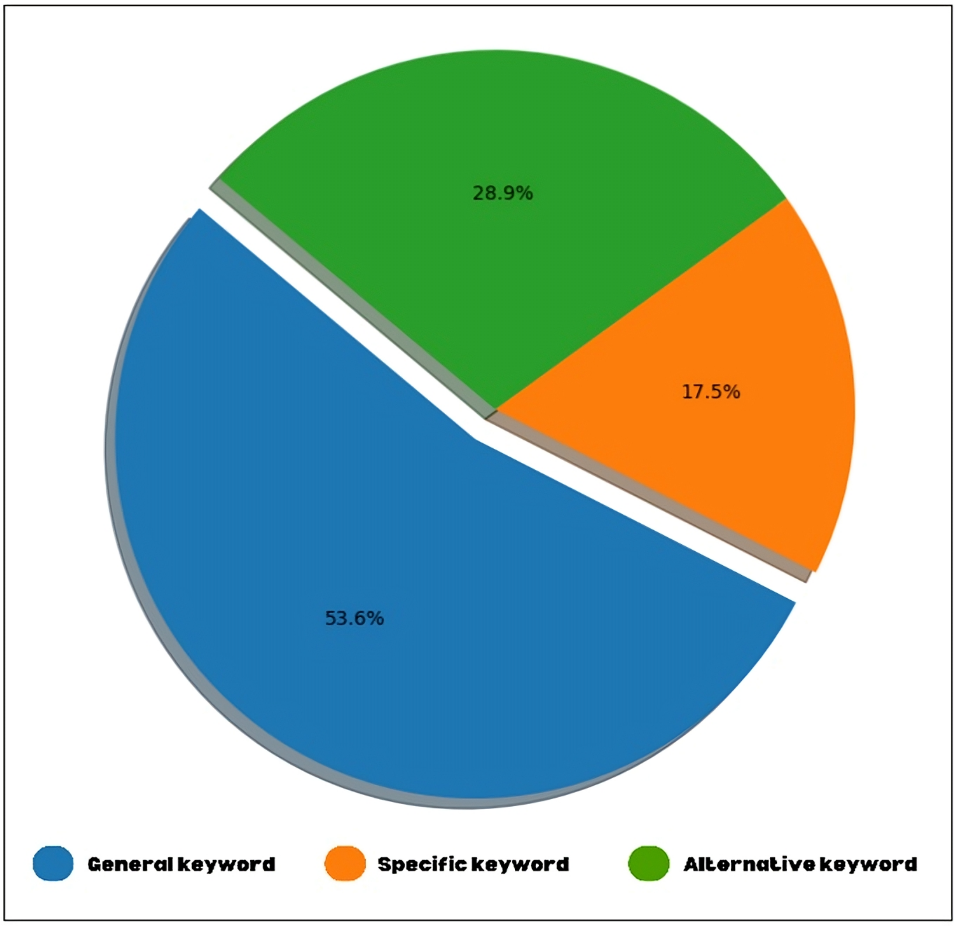

Figure 2.3: Distribution of studies after first filtration using the GSA Keyword strategy. Notably, general keywords yield a broader spectrum of results, accounting for over half of the relevant studies identified, which underscores their crucial role in capturing a wide range of research topics

2.2.4 Applying 2nd filtration: Deleting repeated results in each dataset individually

In this step, we integrate the results obtained through the GSA keyword strategy in each dataset and then remove any repeated results. The focus here is to eliminate duplicate results that arise from the intersections among the GSA keywords. Figure 2.4 displays the percentage of results excluded in this filtration step for each database compared to the total number of results at this stage.

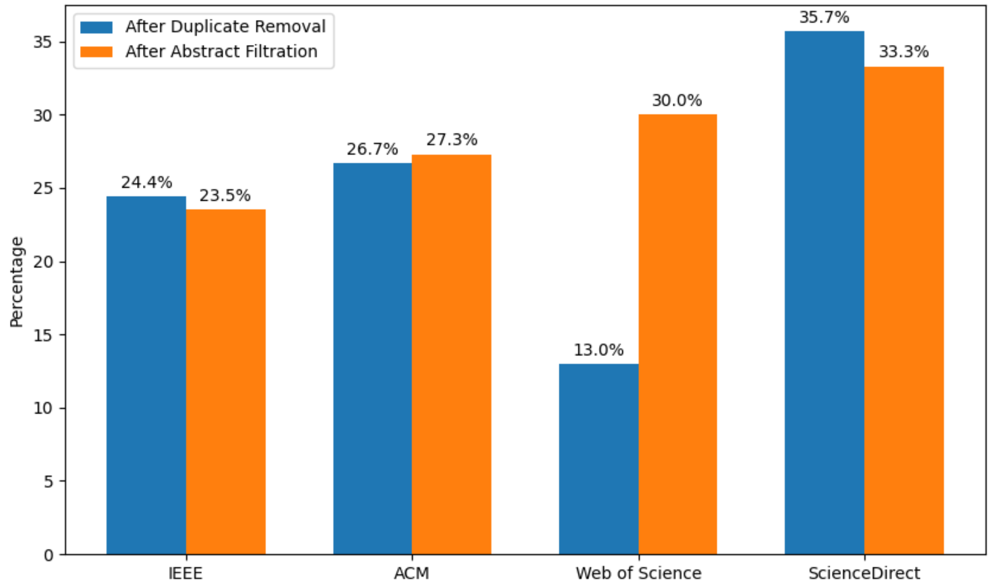

Figure 2.4: Percentage of results excluded after the second filtration in each dataset compared to the total number of results

2.2.5 Applying the 3rd filtration: Selecting only related results based on the abstract

This stage involves a thorough review of the abstracts of the studies that passed the previous filtration steps. The purpose is to assess the relevance of the content in greater detail. Figure 2.6 illustrates the percentage of studies excluded in this filtration step.

2.2.6 Full-text review: Assessing studies for final inclusion

The remaining literature undergoes a full-text review to thoroughly assess its relevance and contribution to the focus of this study. In this phase, we apply the inclusion and exclusion criteria outlined in subsection 2.2.2. After this meticulous review, 23 studies were excluded from the initial 54 for the reasons detailed in Figure 2.5.

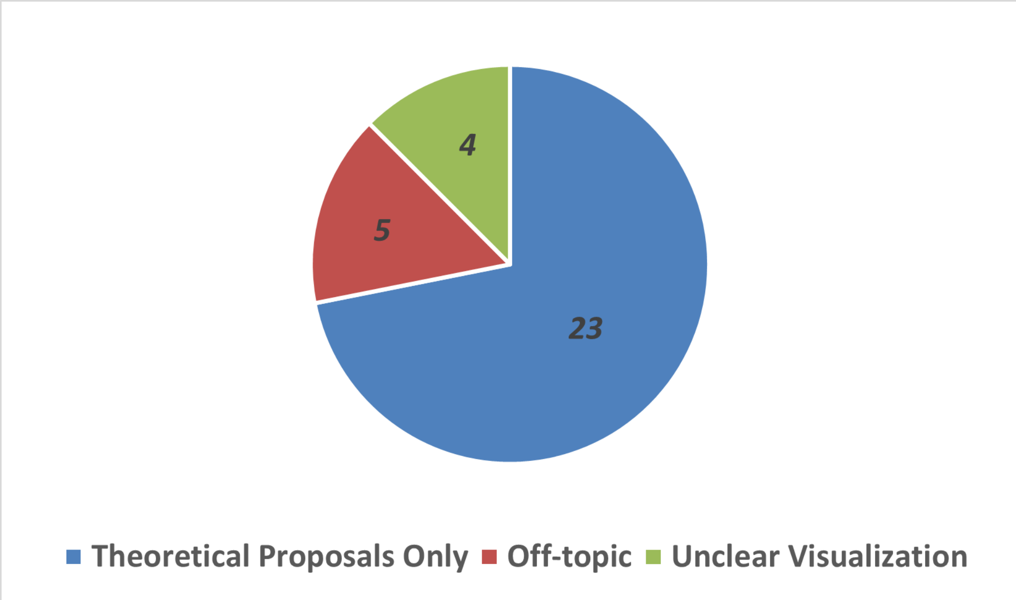

Figure 2.5: Distribution of excluded literature in the full-text review phase. The majority of exclusions (23 out of 32) were due to literature being solely theoretical, highlighting the critical need for this filtration step

Figure 2.6 visualizes the three filtration stages: duplicate removal, abstract review, and full-text assessment. The percentages represent the proportion of studies eliminated at each stage.

2.2.7 Merging all results and eliminating duplication across databases

At this stage, we consolidate the findings from different databases to create a unified dataset ensuring each unique study is counted only once. This step is essential because some databases cooperate, leading to the same literature appearing in multiple databases. We identified three instances where literature had been duplicated across different databases, which highlights the need for this process. Figure 2.7 illustrates the filtration process for all 505 studies, demonstrating the reduction at each stage of our systematic literature review.

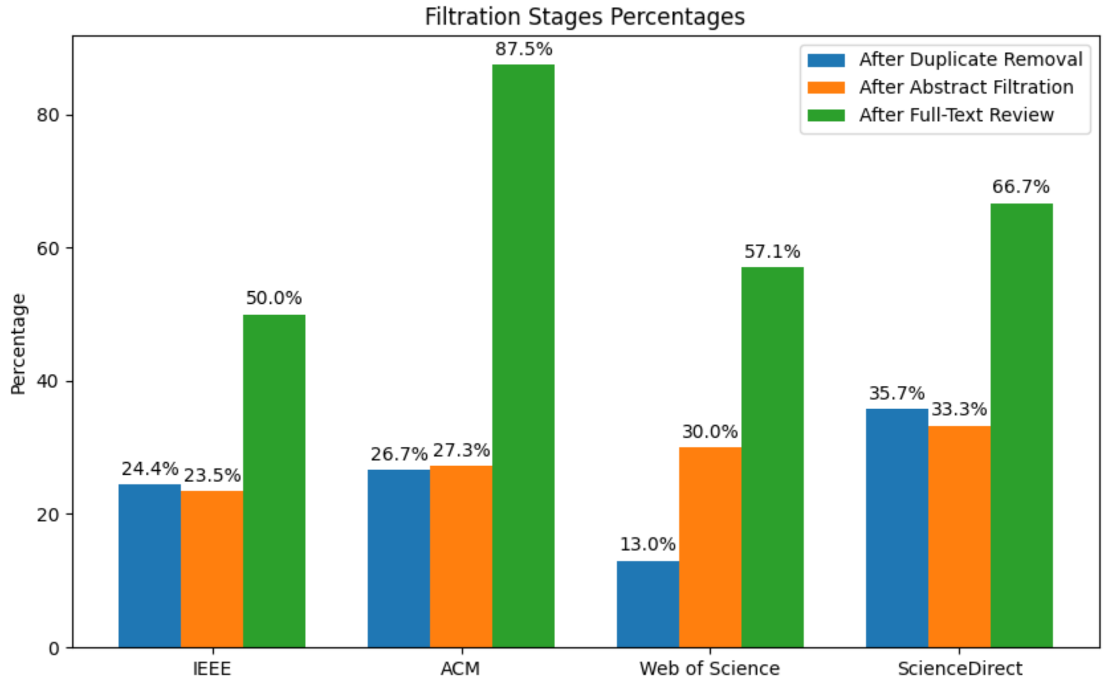

Figure 2.6: Percentages of studies excluded at the three key filtration stages. This underscores the importance of each filtration stage, particularly the full-text review stage, which excluded over 50% of studies

During the process of merging all results and eliminating duplication across the databases, we identified and removed 3 duplicate studies from the initial 22 results obtained through the full-text article filtration. We were left with 19 studies in total. These 19 studies form the core of our analysis. Table 2.2 provides a detailed breakdown of these 19 studies.

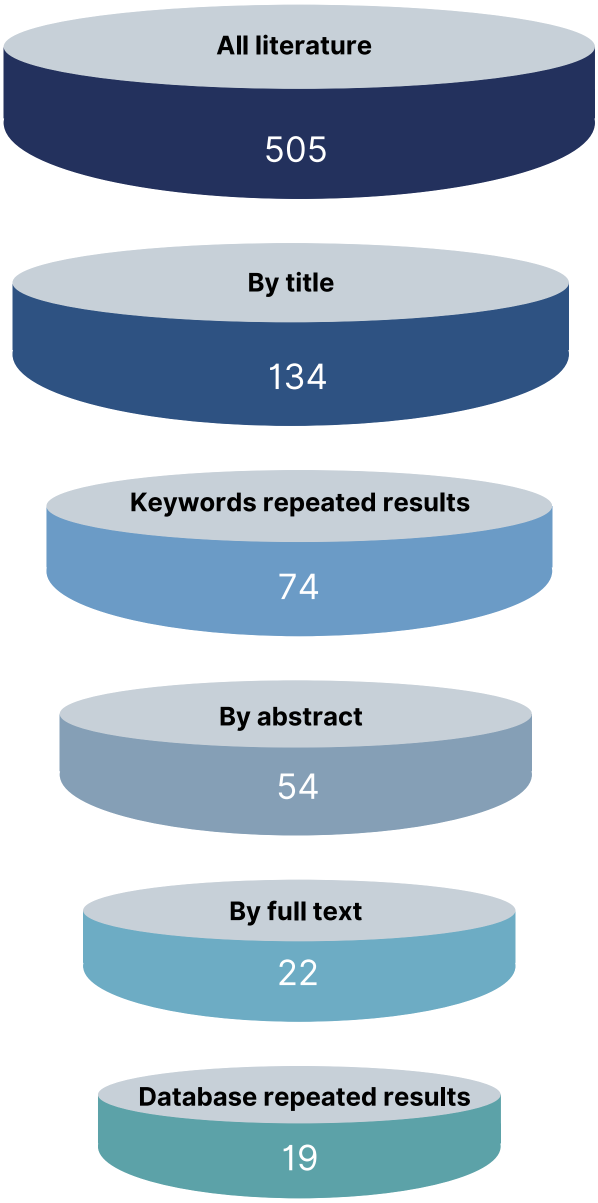

Figure 2.7: The systematic literature review filtration process

Study	Authors and year	Article title
S1	Mohaghegh, M., & Panikkar, A. (2020, November)	A Decentralised Land Sale and Ownership Tracking System using Blockchain technology (Mohaghegh and Panikkar, 2020)
S2	Ali, T. et al. (2020, February)	A Transparent and Trusted Property Registration System on Permissioned Blockchain (Ali et al., 2020)
S3	Sharma, S. et al. (2023, July)	Blockchain Based Property Deeds Repository System (Sharma et al., 2023)
S4	Vivekrabinson, K. et al. (2023, November)	Blockchain Enabled Real Estate Property Transactions using NFT: An Approach (Vivekrabinson et al., 2023)
S5	Bhanushali, D. et al. (2020, February)	BlockChain to Prevent Fraudulent Activities: Buying and Selling Property Using BlockChain (Bhanushali et al., 2020)
S6	Aquib, M. et al. (2020, January)	Blockchain-based Land Record Management in Pakistan (Aquib et al., 2020)
S7	Chand, R. et al. (2023, December)	Blockchain-Based Smart Contracts for Land Title Registry Opportunities and Adaption for Fiji (Chand et al., 2023)
S8	Pocha, N. et al. (2023, October)	Decentralized one stop solution for real estate (Pocha et al., 2023)
S9	Aliti, A. et al. (2023)	Ethereum Smart Contract Deployment for a Real Estate Management System (REMS) Implemented in Blockchain (Aliti et al., 2023)
S10	Jeong, S., & Ahn, B. (2021)	Implementation of real estate contract system using zero knowledge proof algorithm based blockchain (Jeong and Ahn, 2021)
S11	Nguyen, V. et al. (2023, December)	Leveraging Blockchain and NFTs for Collaborative Real Estate Transactions (Nguyen et al., 2023)
S12	Kreppmeier, J. et al. (2023)	Real estate security token offerings and the secondary market: Driven by crypto hype or fundamentals? (Kreppmeier et al., 2023)
S13	Serrano, W. (2022)	Real Estate Tokenisation via Non Fungible Tokens (Serrano, 2022)
S14	Sharma, A. et al. (2024, March)	Real Estate Registry Platform Through NFT Tokenization Using Blockchain (Sharma et al., 2024)
S15	Rakesh, S., & Gargi, N. (2023, June)	Smart Land Registration Using BlockChain (Rakesh et al., 2023)
S16	Zhang, L. et al. (2024)	The real estate time-stamping and registration system based on Ethereum blockchain (Zhang et al., 2024b)
S17	Tan, V. K., & Nguyen, T. (2022, March)	The Real Estate Transaction Trace System Model Based on Ethereum Blockchain Platform (Tan and Nguyen, 2022)
S18	Nguyen, N. et al. (2020, October)	Towards Blockchainizing Land Valuation Certificate Management Procedures in Vietnam (Nguyen et al., 2020)
S19	Hari, M. et al. (2023, January)	T-PASS: A Blockchain-based NFT Enabled Property Management and Exchange System (Hari et al., 2023)

Table 2.2: List of the existing core literature

2.2.8 Analytical standards and results overview

This subsection details the set of analytical standards that guide our evaluation of the 19 remaining studies. These standards should be clearly defined and aligned with the main research questions. This ensures that each study is assessed through a consistent and rigorous methodology within the scope of the study. Our analytical standards include:

- **Q1**: Determines whether the article utilizes blockchain technology to propose a global platform for managing and tracing real estate transactions.
- **Q2**: Determines if the article proposes a formal 'Certificate' or equivalent document as unique evidence for ownership using NFTs or any other form.
- **Q3**: Determines whether the article proposes a proven mechanism for shared ownership using fractional NFTs or any other form.
- **Q4**: Determines if the article discusses the development and evaluation of a universally applicable real estate platform.

These standards are applied to thoroughly assess each study. The results overview is presented in Table 2.3. A detailed analysis and a discussion of these findings are presented in the next subsection.

id	**Q1**	**Q2**	**Q3**	**Q4**
S1				
S2				
S3				
S4		Y		
S5				
S6		Y		
S7				
S8		Y	Y	
S9				
S10				
S11		Y		
S12				
S13				
S14		Y		
S15				
S16				
S17				
S18		Y		
S19				

Table 2.3: Evaluation of the selected studies based on the analytical standards

2.2.9 Discussion of findings and recommendations

In this final stage, we provide further observations, implications, and recommendations based on the results obtained from the previous step, organised by the analytical standards.

Utilization of Blockchain Technology for Real Estate Management and Tracing

Observations:

The analysis, as shown in Table 2.3, reveals a significant gap in the existing literature regarding the comprehensive implementation of blockchain technology in real estate for tracing real estate provenance or even for any management on a global scale. In other words, the table confirms that no existing study has implemented a hybrid blockchain system for managing real estate provenance and ownership certification, which highlights the uniqueness of this research.

One reason for this gap could be the nature of the blockchain type (decentralized vs. centralized) that can fit such a system. In other words, third-party intervention, particularly by the government, is a critical factor in developing the proposed solution.

Table 2.4 provides details of several studies which use various approaches and their applicability to Q1, highlighting the role of government involvement and, where relevant, the choice between public, private, or mixed blockchains.

Study Name	Relation, insights, and applicability to Q1
S1 S4 S14	A public blockchain for real estate trading with no government intervention
S2 S6 S7 S18	A private blockchain for land record management, managed by a local government
S3	A blockchain-based website for property trading where the government verifies sellers' documents
S5 S16 S17	Mixed approach: The verification process is controlled by the government, while trading is conducted on a public blockchain
S8	A blockchain-based website for real estate trading without government intervention
S13	A model for tokenizing real estate information, implemented on a private blockchain

Table 2.4: Studies and their applicability to Q1

The varying levels of government involvement and the choice between public, private, or a mixed approach to blockchains in the studies, as shown in Table 2.4, suggest different implications for scalability, trust, and adoption. In most of the literature, the proposed systems adopted a private blockchain when creating specific systems for certain countries. This includes examples such as in Saudi Arabia (S2, (Ali et al., 2020)), Pakistan (S6, (Aquib et al., 2020)), Fiji (S7, (Chand et al., 2023)), and Vietnam (S18, (Nguyen et al., 2020)).

Moreover, all these studies cover the initial phases in the real estate system, such as land registration, verification, and deed issuance. A similar approach is seen in mixed methods such as (S5, (Bhanushali et al., 2020), (S16, (Zhang et al., 2024b), and (S17, (Tan and Nguyen, 2022)).

Conversely, studies covering later phases in the real estate process, such as trading and exchanging, exclude government intervention, as seen in (S1, (Mohaghegh and Panikkar, 2020)), (S4, (Vivekrabinson et al., 2023)), and (S14, (Sharma et al., 2024)). The same applies to the mixed approach in (S5, (Bhanushali et al., 2020)), (S16, (Zhang et al., 2024b)), and (S17, (Tan and Nguyen, 2022)).

Implications:

- Government involvement is critical in the early stages of real estate transactions for verification and registration, ensuring trust and compliance. However, less intervention is needed in the later stages of trading and exchanging, which can benefit from the efficiency and transparency of blockchain technology. This shift suggests that a holistic blockchain system for managing and tracing real estate transactions cannot be solely public or private.
- Country-based case studies favor private blockchain systems, implying that the practical implementation of a decentralized real estate system is challenging due to regulatory, trust, and scalability issues. This also highlights the disparity between the theoretical ideals and expectations of a public Bitcoin-like system and the practical realities in the real estate sector.
- As there are many studies proposing real estate trade systems that prove the effectiveness of utilizing public blockchain, the adoption of such systems could potentially lead to the loss of jobs for real estate agents, notaries, and other related professions, as their roles might be replaced by automated and decentralized processes.

Recommendations:

- *We suggest that blockchain technology can eliminate the need for most third parties in real estate transactions, except for the government. Therefore, government involvement should be an integral part of any global real estate system, as it maintains control over the registration and verification processes.*

Still, stakeholders can benefit from the advantages of blockchain-based platforms, such as security, provenance history, transparency, and efficiency. Meanwhile, government oversight ensures accountability, trust, compliance with regulations, and facilitates integration with other systems within the platform.

- *We recommend wider adoption of blockchain technology in tracing real estate provenance.*

Real estate provenance can extend beyond ownership records to include comprehensive property information such as electricity bills, water bills, and other business-related transactions. Blockchain technology records all these transactions and provides a transparent and secure history. This significant benefit of blockchain is not yet widely utilized within blockchain-based real estate systems.

Utilization of Blockchain Technology for Ownership Certification

Observations:

The analysis, as detailed in Table 2.3, reveals six studies that implement various methods to ensure ownership verification. These studies, along with their publication years, are summarized in Table 2.5.

Study ID	Year	Methods for Issuing Ownership Certificates
S4	2023	The system uses NFTs to represent ownership.
S11	2023	
S14	2024	
S6	2020	The system issues FORM-II and sales certificates, which are stored on the blockchain and in local storage.
S8	2023	The system uses tokens stored in the owner's digital wallet as proof of ownership.
S18	2020	The system issues paper certificates attached with blockchain-based e-certificates for owners.

Table 2.5: Studies and their applicability to Q2

A noteworthy observation is that the use of tokens as methods for ownership certificates, as seen in (S8, 2023), or in the form of NFTs, as demonstrated by (S4, 2023), (S11, 2023), and (S14, 2024), represents a relatively recent development. This contrasts with more traditional methods such as issuing FORM-II and sales certificates, as used in (S6, 2020), and the issuance of paper certificates attached with blockchain-based e-certificates, as seen in (S18, 2020).

Another observation is that in the studies utilizing NFTs for trading (S4, S11), all these studies promote decentralization and exclude third parties. In contrast, when using NFTs for registering land, as seen in S14, a third party is introduced to verify legal documents.

Implications:

The relatively recent research using NFTs as methods for ownership certificates in real estate indicates a potential trend in scientific studies. This could lead to wider acceptance and adoption of NFTs in real estate applications. Another implication is the decentralized approach for trading and the centralized approach for registering, as seen in the studies, which indicates the crucial role of third-party involvement in the registration process. This highlights the importance of third-party verification and validation in ensuring the accuracy and legitimacy of property registrations, a point previously emphasized.

Recommendations:

- *We recommend wider adoption of tokenization for issuing ownership certificates in real estate.*

These token technologies can replace current deeds and their limitations with more secure, tamper-proof, and immutable alternatives. The adoption of these tokens may take time in the real world as it requires a shift in traditional practices. However, the long-term benefits make this transition worthwhile.

- *We suggest maintaining government involvement for the registration of these certificates.*

It is essential that deeds are legally recognized and government oversight can ensure this. Moreover, at some point, we need accountability from the government to validate and enforce property rights. This is important as it establishes reliable ownership certification mechanisms.

Utilization of Blockchain Technology for Shared Ownership

Observations:

Table 2.3 reveals a significant lack of studies addressing shared ownership in real estate. Only one study, S8, specifically discusses shared ownership. The study emphasizes digitizing real estate assets into blockchain-based tokens to enable fractional ownership, enabling investors to participate in buying and selling fractional ownership of real estate properties.

Implications:

Unlike the increasing volume of published work addressing real estate ownership certificates using blockchain-based systems, there is a significant lack of research on fractional ownership. This implies that research in blockchain-based real estate systems is still in its early stages and does not yet cover all aspects of real estate scenarios. Notably, one article, S8, also proposes tokenization as a method for issuing ownership certificates. This suggests that utilizing tokens that can be fractionalized could be key to addressing shared ownership and potentially other diverse real estate scenarios.

Recommendations:

- *We suggest using divisible tokens to address shared ownership in real estate.*

Tokens that enable fractional ownership offer the benefits of blockchain for shared ownership and any scenario that includes sharing or fractionalizing real estate assets. A form of divisible tokens is fractional NFTs, which provide more reliability than paper-based proofs, which can be lost, stolen, or torn, and offer an extra protection layer compared to web-based proofs, which are vulnerable to cyber-attacks and corruption.

- *The adoption of blockchain in real estate should cover diverse scenarios beyond traditional ownership and trading.*

There is a lack of studies in the existing literature which address these diverse scenarios. While many studies propose effective systems for traditional ownership and trading, other important scenarios such as fractional ownership and property inheritance are almost neglected. To replace the traditional system with a blockchain-based system, diverse scenarios must be validated both theoretically and practically.

Development and Evaluation of a Universally Applicable Real Estate Platform

Observations:

As there are no proposed systems for a global platform, none of the articles have developed or validated such a whole system. However, individually and on a component level, we have noticed several attempts to create and evaluate various systems. These methods of evaluation are presented in Table 2.6.

Study Name	**Applicability for Q4**
S1	Expert evaluation and feedback
S2	Block size, channels, and endorsement policies
S9	Server usage (RAM, CPU, network traffic)
S11	Transaction fees, gas limits, and gas used per transactions
S12	Blockchain transaction data, investor behaviour, and various financial metrics
S13	Mining time and nonce iterations for fixed and variable real estate information using NFT technology
S16	Cost comparison of registration fees and transaction fees between blockchain-based and traditional models
S18	Transaction processing time and throughput during experimental transactions

Table 2.6: Studies and their applicability to Q4

Implications:

Given the complexity and scale of such a complicated system, it is understandable that most researchers focus on evaluating individual components of the real estate system. Although there are only a few studies, diverse approaches are used in these system evaluations. Most studies (S2, S9, S11, S12, S13, S16, S18) use technical metrics and performance indicators, while only one study, S1, focuses on user experience and regulatory compliance.

Recommendations:

- *The evaluation of blockchain-based systems should balance system performance metrics and user experience.*

While it is crucial to evaluate system performance using metrics such as transaction costs, processing times, and resource usage, it is equally important to assess the end user experience, especially given the relatively new adoption of blockchain technology. A general metric to consider is the time taken in the process and the cost, both within the system and for the end user.

2.3 Conclusion

This chapter provides details of a systematic literature review which explored all the related literature on the integration of blockchain technologies in real estate transactions and ownership certification. It introduces a detailed nine-step systematic literature review methodology that incorporates a GSA keyword strategy, categorizing terms into general, specific, and alternative queries. The chapter concludes by providing valuable observations, implications, and recommendations based on the analysis. The systematic approach presented here can also serve as a model for future literature reviews.

Building on the information provided in this systematic review, the next chapter outlines the specific gaps identified in the existing literature. It formulates research questions derived from these gaps and discusses the objectives established to address these questions.

CHAPTER 3

Research Gaps, Questions, and Objectives

3.1 Introduction

One of the key benefits of conducting a systematic literature review is its ability to identify gaps in the existing literature through a structured and systematic approach. These gaps represent open challenges for researchers, offering opportunities for further investigation and innovation. Based on the findings of the systematic literature review, research questions and objectives can be formulated to address these gaps and guide the development of solutions within the research context.

In this chapter, we aim to identify the gaps found in the systematic literature review, along with the research questions and objectives. The remaining sections in this chapter are organised as follows: in Section 3.2, we define the literature gaps. In Section 3.3, we outline the research questions, and in Section 3.4, we set the objectives of this thesis.

3.2 Literature Gaps

In the previous chapter, we conducted a comprehensive nine-step systematic literature review to explore the integration of blockchain technologies in managing real estate transactions and ownership certification. Upon reviewing the current literature in this field, many research gaps have been identified, which shed light on the unresolved challenges and areas which have not yet been thoroughly investigated.

The following are the key gaps we identified during the systematic literature review process:

- **Gap 1:** The lack of a global platform for managing and tracing real estate transactions.

  Several studies propose real estate systems that utilize blockchain technology based on local standards. For instance, local-based systems have been proposed in India (Gupta et al., 2019; Yadav and Kushwaha, 2021), as well as in Saudi Arabia (Ali et al., 2020), Vietnam (Tan and Nguyen, 2022), Pakistan (Humdullah et al., 2021), Thailand (Pongnumkul et al., 2020), Serbia (Stefanović et al., 2022), and South Africa (Tilbury et al., 2019). Nevertheless, a globally applicable platform for managing and tracing real estate transactions has yet to be established.

- **Gap 2:** The lack of research on real estate provenance.

  Provenance tracking in real estate provides a complete history of property ownership, which fosters trust by offering accurate records for buyers, sellers, and regulators. It reduces the risk of fraud by ensuring that all transfers are recorded and verified, which enhances confidence in the legitimacy of transactions. Additionally, provenance data helps ensure compliance with legal and tax requirements, which supports anti-money laundering efforts. This approach also benefits international or remote investors, especially in markets where transaction histories are incomplete or unavailable.

Although the advantages that provenance tracking in real estate provides are clear, there is a lack of studies on real estate provenance. Interestingly, blockchain technology, known for its capabilities in traceability and transparency, has been widely studied and applied to real estate transactions. However, its application in tracking and verifying property provenance remains unexplored, despite its potential.

- **Gap 3:** The lack of a reliable method to prove ownership of a real estate property.

  Through the systematic literature review, the lack of a reliable method to verify ownership of real estate property is evident from different perspectives. On one hand, traditional methods, such as paper-based and web-based certificates, are not reliable for proving ownership. On the other hand, even when more secure methods, like NFTs, are used, the reliability of the issuer is crucial.

  For ownership certification to be trustworthy, the issuing authority must be a reliable and recognized source, which is often not the case with blockchain-based systems. For example, in the study by (Vivekrabinson et al., 2023), the system generates NFTs to represent property ownership, allowing transactions to be conducted securely through a decentralized blockchain network. While this approach offers benefits such as transparency and efficiency, it lacks the formal recognition and oversight of government authorities, which is critical in the real estate industry, where trillions of dollars are at stake.

  In (Nguyen et al., 2023), a blockchain-based system is incorporated where NFTs, smart contracts, and IPFS are used to make the process more efficient.

Unlike traditional real estate management, ownership is proven through NFTs under the supervision of an agency. While this model enhances efficiency and reduces reliance on intermediaries, it raises concerns about the reliability of ownership certification, as the NFTs used to represent property ownership are not issued or backed by government authorities.

In a similar model, in (Sharma et al., 2024), the real estate agency is replaced with an inspector in a process that involves four key roles: the buyer, seller, lender (who lends cryptocurrency if necessary), and inspector (who verifies the legal documents of both parties and ensures the correct transfer of ownership). While this approach incorporates blockchain technology to streamline the transaction, it raises similar concerns about reliability.

A potential argument for excluding traditional authorities from ownership certification stems from the overwhelming success of Bitcoin. This success may have led some researchers to adopt similar government-free solutions in other sectors, including real estate, where blockchain-based systems like NFTs are being explored as alternatives for proving ownership. However, while such approaches offer transparency and efficiency, challenges remain. Traditional methods, such as paper-based and web-based certificates, are unreliable, and even more secure solutions like NFTs still rely on the credibility of the issuer. This underscores the persistent gap in establishing a reliable method to prove real estate ownership.

- **Gap 4:** The lack of a reliable method to prove shared ownership of a real estate property.

  Although many studies have investigated the use of blockchain in real estate transactions, many common scenarios remain unexplored. One significant gap is the lack of research on shared ownership models, where multiple parties own a portion of a property. Currently, shared ownership relies heavily on paper-based systems that are prone to inefficiencies, errors, and a lack of transparency. Despite the advantages that blockchain technology offers, such as immutability and security, its application to managing and proving shared ownership has not been thoroughly investigated.

In the existing literature, we found only one study (Pocha et al., 2023) that discusses the use of tokenization in an investment-focused real estate system. The study proposes the use of digital tokens to represent fractional ownership, which is a type of shared ownership where multiple parties own a defined percentage of a property, typically for investment purposes. However, the study does not address any legal or regulatory aspects, focusing solely on the financial perspective. This highlights the lack of a reliable method to prove shared ownership of real estate property.

- **Gap 5:** The lack of a developed and evaluated real estate platform for managing and tracing real estate transactions.

  This gap originates from the lack of a proposed unified system for managing and tracing real estate transactions. Since no such universal system has been introduced, many uncertainties remain about how such a platform would be developed and evaluated. Without a clear, holistic model, it is difficult to anticipate how to address the complexities of the global real estate system. This gap leaves many questions and concerns unanswered.

  One concern is the lack of balanced evaluation metrics for such a large-scale system. Many studies have developed and evaluated single-purpose systems that focus on specific aspects of real estate transactions, such as tokenization, property registration, or ownership transfer. However, these systems often prioritize technical performance metrics like server usage (Aliti et al., 2023), and transaction fees (Zhang et al., 2024b; Nguyen et al., 2023), while neglecting user experience and scalability. Moreover, these single-purpose systems represent completely different scenarios from what would be required in a universal platform. This highlights the lack of a developed and evaluated real estate platform for managing and tracing real estate transactions.

- **Gap 6:** The lack of empirical studies in the extant literature.

  Despite the extensive theoretical studies that contribute to the potential applications of blockchain technology in real estate, much of the research remains hypothetical and lacks practical implementation. This was evident during the filtration process in our systematic literature review, where out of the 32 excluded studies, 23 were purely theoretical, as shown in Figure 3.1. This underscores the need for more empirical studies that focus on practical testing and the real-world implementation of these models within the real estate sector. Without empirical evidence, it is difficult to fully understand the effectiveness, scalability, and potential challenges of applying blockchain technology in real estate transactions.

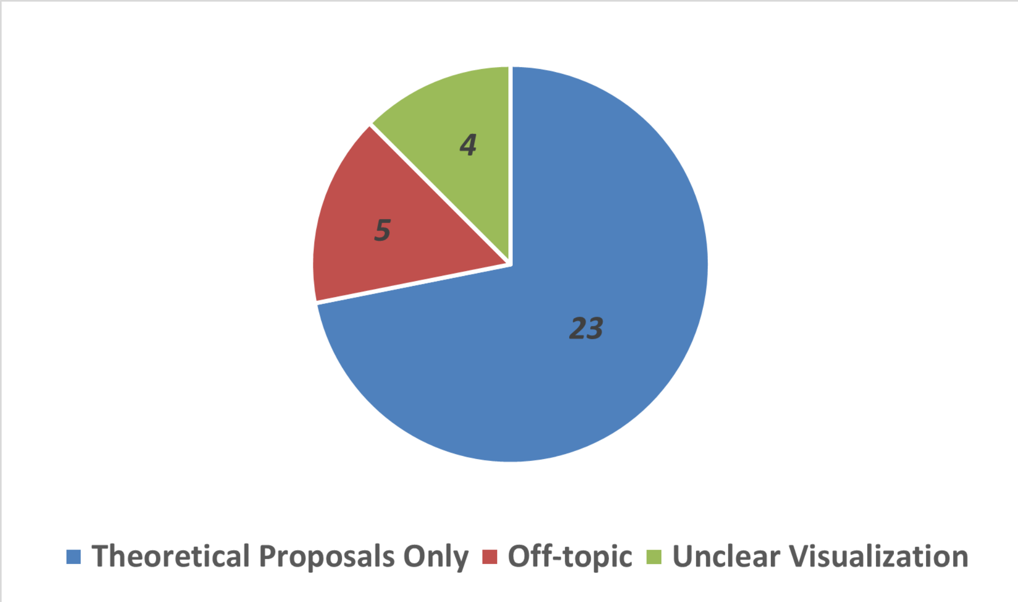

Figure 3.1: Significant exclusion of theoretical studies in the filtration process

3.3 Research Questions

Based on the predefined analytical standards outlined in the systematic literature review and the identified research gaps, the main research questions and sub-research questions have been formulated. These are presented in Table 3.1 and Table 3.2, respectively, along with the corresponding motivations behind each inquiry.

Main research question	**Motivation**
How can real estate provenance and ownership certification be managed and verified globally?	Proposing a secure and global blockchain-based platform for managing real estate provenance and ownership certification.

Table 3.1: The main research question and motivation

Sub-research questions	**Motivation**
1. How do we create a reliable and global platform for managing real estate provenance?	Proposing GREP, which enables real estate provenance to be recorded.
2. How can we provide a unique high-tech distinguisher for property owners that proves their ownership?	Proposing a method that utilizes NFTs as proof of ownership.
3. How do we develop a method to prove shared ownership of a real estate property?	Proposing a method that uses fractional NFTs.
4. How can the proposed methods be evaluated systematically, and their feasibility demonstrated through prototype implementation?	Ensuring reliability and feasibility through use cases, evaluation metrics, and prototype implementation.

Table 3.2: The research sub-questions and motivation

3.4 Research Objectives

Building on the aforementioned research question and sub-questions, the primary objectives of this research are as follows:

- **Objective 1:** To develop a reliable and global real estate platform for managing real estate provenance.

  This objective focuses on creating a reliable global real estate platform for managing real estate provenance. The platform should enable real estate transactions to be conducted in a transparent, trusted, tamper-proof, and traceable environment while ensuring privacy and accountability. It should be able to handle key functions such as managing access rights and managing provenance data, including its entry, retrieval, and updates. The solution's design, implementation, and evaluation for this objective are further discussed in Chapter 5.

- **Objective 2:** To develop a reliable method to prove the ownership of a real estate property.

  This objective focuses on establishing a secure and verifiable method for proving real estate ownership. The method should provide a tamper-proof, immutable, and transparent way to certify ownership, addressing the limitations of traditional paper-based certificates and centralized digital records. It should also ensure that ownership records remain protected from unauthorized modifications while maintaining accessibility and trustworthiness. More details about this objective's design, implementation, and evaluation are further discussed in Chapter 6.

- **Objective 3:** To develop a reliable method to prove shared ownership of a real estate property.

  This objective focuses on developing a reliable method for managing the creation, division, and transfer of a property's ownership record among multiple parties. It should ensure that each owner holds a distinct and verifiable share while upholding trust, accessibility, and accountability in shared ownership scenarios. A detailed discussion, along with the validation and evaluation of this objective, is provided in Chapter 7.

- **Objective 4:** To validate and evaluate the developed solutions (Objective 1 to Objective 3) and demonstrate their feasibility through a prototype implementation.

  This objective focuses on assessing the effectiveness of the developed solutions (Objective 1 to Objective 3). This should include the validation and evaluation of Objective 1, as covered in Chapter 5, Objective 2, as presented in Chapter 6, and Objective 3, as detailed in Chapter 7. Furthermore, the feasibility of the proposed solutions should be demonstrated through a prototype implementation, with its development and integration within a unified system illustrated in Chapter 8.

3.5 Conclusion

In this chapter, we discussed the research gaps identified through the systematic literature review. We then formulated the primary research questions and related sub-questions based on predefined analytical standards. Building on these questions, we outlined the research objectives, which aim to address them by proposing a secure, transparent, and reliable platform for real estate provenance. The proposed approach integrates blockchain technology, NFTs, and fractional ownership mechanisms. Furthermore, we discussed the methodology for validating and verifying the proposed solutions through a proof-of-concept implementation, each of which is explored in its respective chapter.

In the next chapter, we outline the research methodology employed throughout this study, which follows the design science research approach. Additionally, we provide an overview of the proposed solutions, establishing the foundation for the development and validation of each objective.

CHAPTER 4

Research Methodology and Solution Overview

4.1 Introduction

This chapter serves two key purposes: selecting an appropriate methodology for this study and providing an overview of the proposed solutions, which together establish the foundation for achieving the research objectives. By adopting a suitable methodology and presenting a comprehensive overview of the solution components, this chapter lays the groundwork for the development of the GREP system and the objectives outlined in this research.

The chapter is organised as follows: Section 4.2 explains the chosen research methodology. Section 4.3 provides an overview of the solutions, including system workflow and a detailed discussion of solutions for each research objective in subsections 4.3.1, 4.3.2, 4.3.3, and 4.3.4.

4.2 Research Methodology

To achieve the research objectives, it is mandatory to adopt disciplines of a technology-related research method. There are two common research methods, the design science research (DSR) method and the action design research (ADR) method. The steps in the DSR method are shown in Figure 4.1.

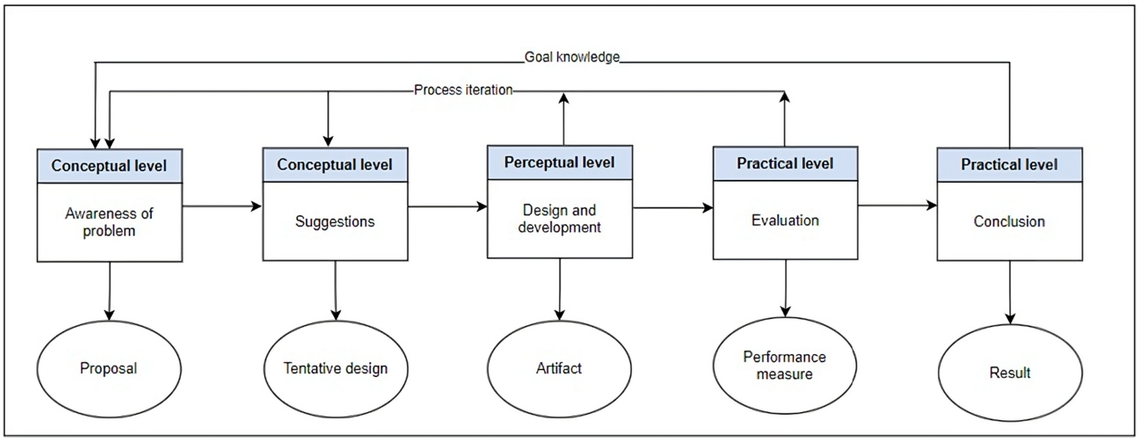

Figure 4.1: Research methodology inspired by (Peffers et al., 2018)

We chose the DSR approach for the following reasons:

Firstly and importantly, the DSR method is used to create new techniques and systems, whereas the Action Design Research method focuses on evolving existing systems, not creating them (Hevner et al., 2004; Sein et al., 2011)

Secondly, we need to validate our chosen methodology, which can be achieved by following the DSR method because the ADR method does not pay attention to the methodology used in creating the system.

Finally, the ADR method tends to be used in real-life organizations and requires professional experience in the intended field. Achieving such a goal can be regarded as future work for this research.

Table 4.1 lists the steps used in the DSR method and also provides a description of each step.

Step	**Description**
Identification of the problem	Brainstorming about all aspects of the real estate industry.
Conceptual level: Literature review	Searching well-known databases to identify the research gaps.
Conceptual level: Problem formulation	Setting the research questions and sub-questions.
Conceptual level: Conceptual solution	Providing a theoretical solution for each gap.
Perceptual level: Methodology development	Choosing the platform, dataset, and setting the rules.
Perceptual level: Implementation and use cases	Setting up the development environment and defining use cases for each developed solution.
Practical level: Assessment and demonstration	Validating each developed solution using the predefined use cases, evaluating their performance with key metrics, and demonstrating feasibility through prototype implementation.

Table 4.1: Steps and description in the DSR method

4.3 Solution Overview

To set the stage for the development of solutions for each objective, this section provides an overview of the system, explaining how it is structured to achieve the research objectives. The GREP platform is designed as a hybrid blockchain-based system that ensures secure, transparent, and verifiable real estate provenance and ownership certification. The system workflow consists of two primary stages:

- **Initialization Stage:** This is the setup phase required before the system's actual operations begin. During this stage, stakeholders undergo enrollment, verification, and credential checks to ensure they meet the necessary requirements before proceeding further. Our system leaves the specific standards and requirements to be defined by the government, allowing for flexibility and global applicability. This approach ensures that the system can be adopted across different jurisdictions without enforcing predefined criteria.
- **Execution Stage:** This is the action phase where the system performs its core functions. It involves managing provenance, proving ownership, and handling shared ownership. Each step in the workflow, as shown in Figure 4.2, is designed to ensure transparency, accountability, and security throughout real estate transactions. A more detailed description of these processes, including technical implementation and evaluation, is provided in subsequent chapters.

The entire system workflow is shown in Figure 4.2, illustrating the process starting from the initial stage to the execution stage, which contains the core objectives of this research.

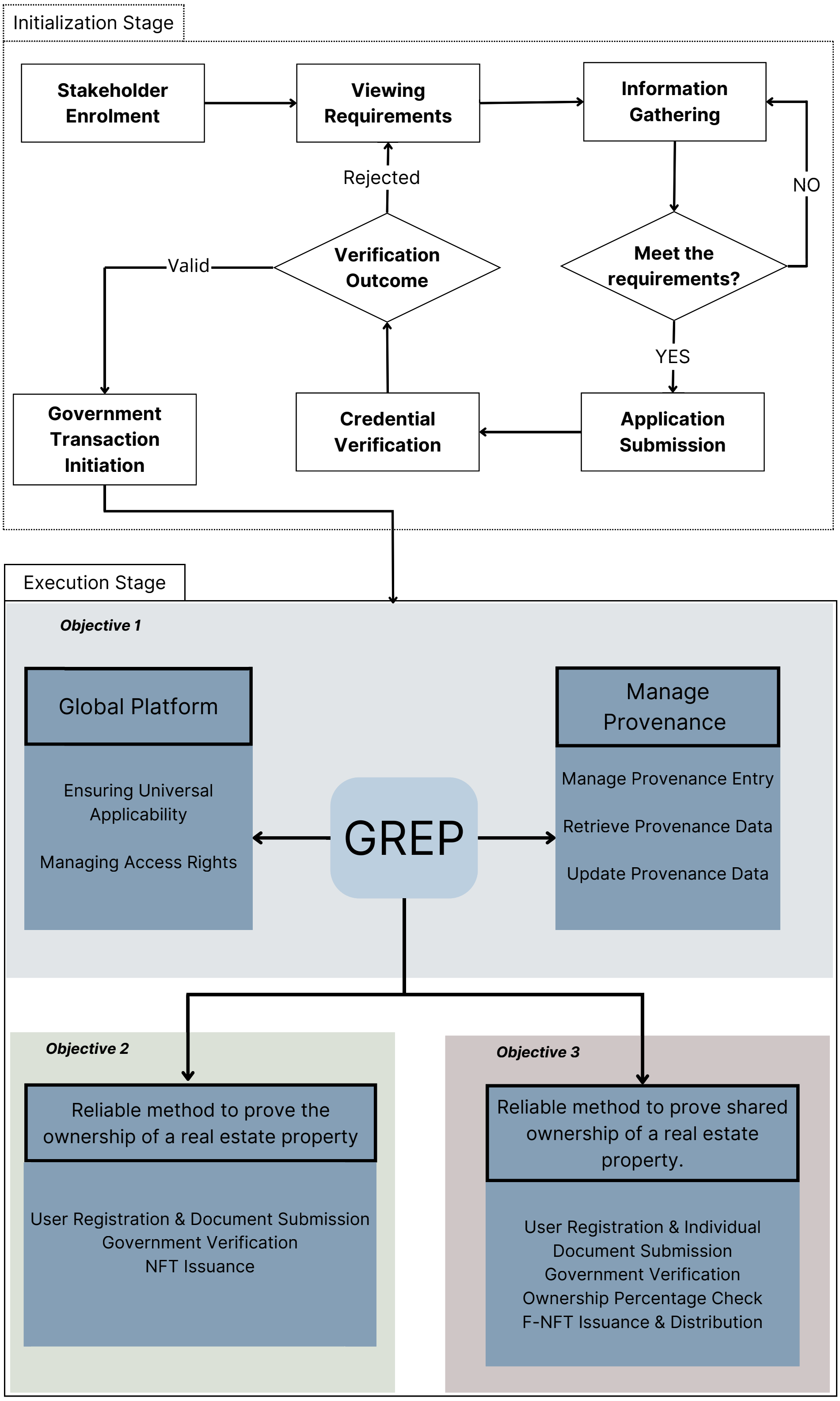

Figure 4.2: Overview of the system workflow

4.3.1 Solution overview for Objective 1

To effectively manage and trace real estate provenance, we propose a hybrid blockchain-based platform called GREP. We utilize Solidity-based smart contracts, which are designed to manage provenance entry, updates, and verification while ensuring data integrity. These contracts enforce an immutable ownership history while allowing authorized updates by regulatory bodies. Additionally, the smart contracts facilitate the secure tracking of ownership records, ensuring transparency and compliance with governance policies.

The total worth of the global real estate market is estimated to be 217 trillion US dollars (Kalyuzhnova, 2018). In such a vast market, government intervention plays a crucial role in preserving trust and accountability, whereas the involvement of intermediaries like notaries is less essential. As a result, we integrate government oversight into GREP to maintain accountability while enhancing transparency and minimizing centralization where it is unnecessary. This approach also promotes scalability and anonymity, advantages that are not available in consortium blockchain architectures (Lu, 2019).

Figure 4.3 overviews the proposed GREP. The platform uses a hybrid blockchain architecture that enables real estate provenance to be managed. The main concept of GREP can be explained as follows:

- Stakeholders are able to submit property provenance inquiries and ownership requests on the system.
- Government bodies are able to review and respond to the requests.

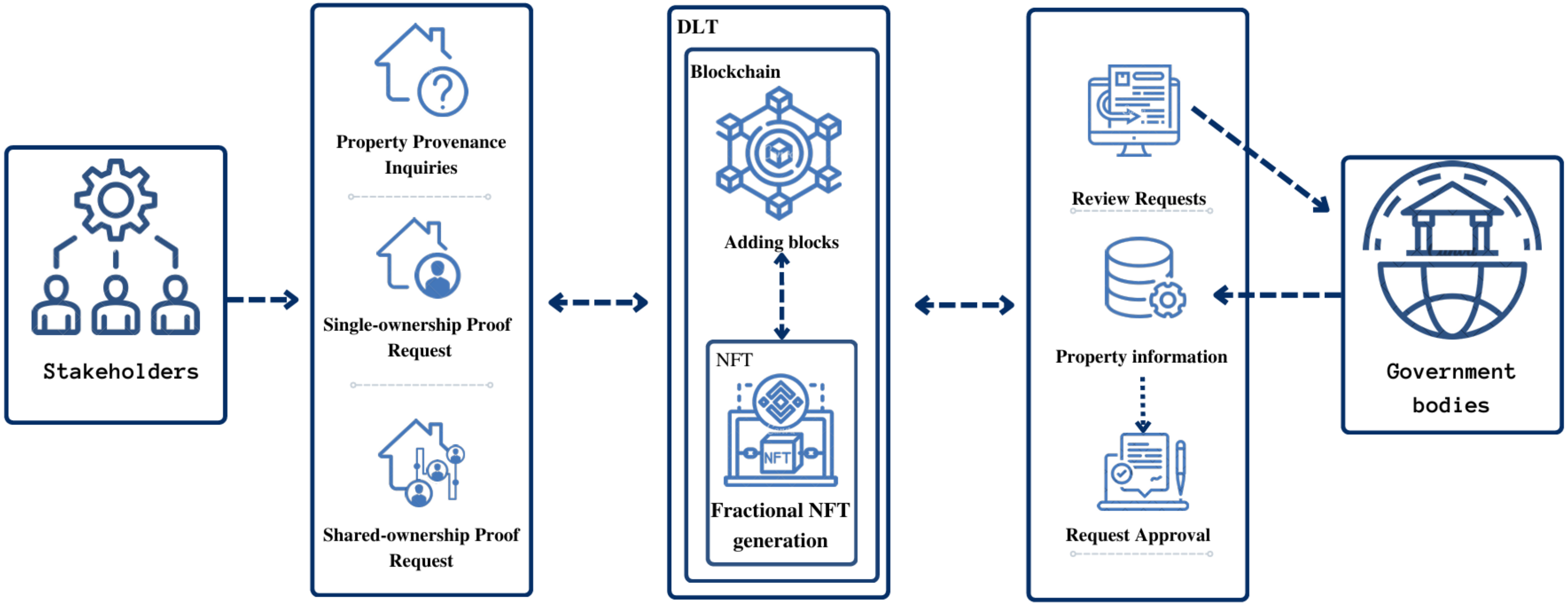

Figure 4.3: Architecture of the proposed platform (GREP)

The proposed GREP is created to represent one reliable place in which:

1. Any user can review property provenance using a special key before making a decision.

2. An owner can receive a unique certificate as proof of ownership, which is neither paper-based nor purely dependent on web servers.

3. Multiple owners of a property are able to receive the same benefits of the unique certificate based on their share percentage.

To provide real-world data for testing our approach for each objective, the research utilizes a public dataset sourced from the Data World website (Data.world, 2016), available at `https://data.world/health/ownership`. This dataset specifically contains ownership records for nursing homes, making it relevant for testing our blockchain prototype's ability to manage real estate provenance and ownership certifications. The dataset includes 180,255 rows, representing individual nursing home records, and 13 columns, each capturing various aspects of ownership and property details, as outlined in Table 4.2.

Column Name	**Description**
Federal Provider Number	Unique identification number for each nursing home assigned by the federal government, used as the Property ID in this project.
Provider Name	Name of the nursing home or care facility.
Provider Address	Street address of the nursing home facility.
Provider City	City where the nursing home is located.
Provider State	State in which the nursing home is situated.
Provider Zip Code	Postal zip code for the nursing home's location.
Role played by Owner or Manager in Facility	Describes the role or position of the individual/entity as the owner or manager (e.g., Director, Managing Employee).
Owner Type	Specifies whether the owner is an individual, an organization, or another type of entity.
Owner Name	Name of the owner or managerial individual/entity of the nursing home.
Ownership Percentage	Indicates the percentage of ownership held (specific percentage, 'Not Applicable', or 'No Percentage Provided').
Association Date	Date from which the listed owner or manager has been associated with the nursing home.
Location	Detailed location of the nursing home, including address and geographical coordinates.
Processing Date	Date on which the particular record or data entry was processed or updated.

Table 4.2: Details of the columns in the dataset used for testing the blockchain prototype

Objective 1 involves managing and tracing real estate provenance using a dataset that provides a structured way to analyze ownership records. As shown in Figure 4.4, it contains historical data indicating how a property has changed ownership over time. In the example, the property has four distinct owners, each with their ownership type, name, and association date. This supports tracing ownership history and validating the blockchain prototype with real-world data, confirming its practical applicability.

	A	B	C	D	E
1	Owner Type	Owner Name	Ownership Percentage	Association Date	Location
17	Individual	THISSE, PETER	NOT APPLICABLE	since 10/08/2004	519 MAIN STREET MEDFIELD, MA 02052 (42.185979, -71.307338)
105	Individual	DAVIS, MARY	NOT APPLICABLE	since 07/24/2001	519 MAIN STREET MEDFIELD, MA 02052 (42.185979, -71.307338)
389	Organization	REHABILITATION ASSOCIATES, INC.	NOT APPLICABLE	since 06/10/1986	519 MAIN STREET MEDFIELD, MA 02052 (42.185979, -71.307338)
625	Individual	THISSE, PETER	NOT APPLICABLE	since 01/03/1990	519 MAIN STREET MEDFIELD, MA 02052 (42.185979, -71.307338)

Figure 4.4: Example of ownership data used from the dataset to achieve Objective 1

4.3.2 Solution overview for Objective 2

To achieve this objective, we use NFT technology as a unique and reliable high-tech distinguisher for property proof of ownership, which is not prone to web server threats, nor can it be lost, torn, or altered unlike paper-based certificates. The uniqueness of an NFT is ensured through its incorporation of distinct property attributes, its immutability via blockchain, and its compliance with the Ethereum request for comments standard, making duplication or tampering impossible. Additionally, NFTs are linked to government-approved property registries within the GREP framework, ensuring regulatory compliance, strengthening public trust, and maintaining a verifiable, tamper-proof record of property ownership.

Figure 4.5 provides an overview of the ownership registration and verification process from the owner's perspective within GREP. The process begins with the owner registering on the government portal and reviewing the ownership requirements. After uploading the required documents and completing the necessary payments, the government verifies the submitted information. If the verification is successful, the ownership details are recorded on the blockchain, and an NFT is issued to the owner's address. This ensures that ownership is permanently secured and can be independently validated.

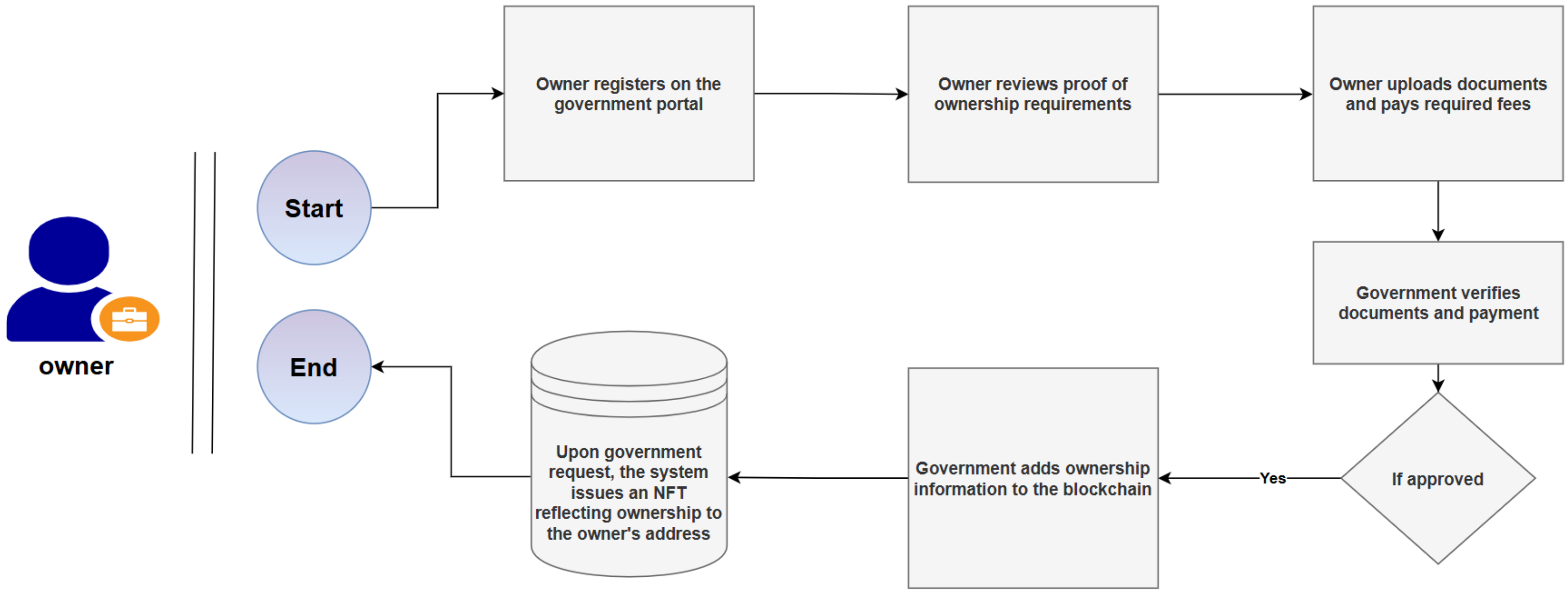

Figure 4.5: The process of NFT ownership issuance from the owner's perspective

The selected dataset offers relevant ownership records that are well-suited for Objective 2. We can utilize the ownership data of properties where individual entities or organizations hold 100% ownership, as shown in Figure 4.6. The dataset includes various properties owned entirely by distinct organizations, detailing essential attributes such as the owner type, name, ownership percentage, and association date. This information is crucial for generating NFTs as proof of ownership and verifying full ownership of real estate properties during the implementation stage.

	A	B	C	D	E
1	**Owner Type**	**Owner Name**	**Ownership Percentage**	**Association Date**	**Location**
45	Organization	GENESIS HOLDINGS LLC	100%	since 02/02/2015	130 ELMORE
85	Organization	WHITTIER HEALTHCARE HOLDING II INC	100%	since 11/04/2011	123 HIGH STREET
94	Organization	WHITTIER HEALTHCARE HOLDING II INC	100%	since 08/01/2009	9 ARBETTER DRIVE
101	Organization	KINDRED NURSING CENTERS EAST LLC	100%	since 10/12/2005	804 EAST 7TH STREET
102	Organization	KINDRED NURSING CENTERS EAST LLC	100%	since 03/12/1998	1200 SUFFIELD STREET
190	Organization	ATRIUM CENTERS, INC.	100%	since 10/01/2007	441 E MAIN ST
267	Organization	KINDRED NURSING CENTERS EAST LLC	100%	since 03/12/1998	1748 HIGHLAND AVENUE
335	Organization	ATHENA HEALTH CARE SYSTEMS MA III LLC	100%	since 06/01/2014	340 THOMPSON ROAD

Figure 4.6: Examples of ownership data used from the dataset to achieve Objective 2

4.3.3 Solution overview for Objective 3

In real-life scenarios, large properties often have multiple owners, each holding a percentage of the total asset. This objective focuses on developing a reliable method to prove shared ownership of real estate properties within GREP. To achieve this, the system integrates fractional NFTs, which inherit the advantages of blockchain technology, including immutability, decentralization, and verifiability.

Blockchain technology has advanced the concept of smart contracts, enabling the automated execution of predefined rules when certain conditions are met. With proper modifications, fractional NFTs can be issued to represent only the owned percentage of a property. Figure 4.7 provides an overview of the shared ownership registration and verification process within GREP.

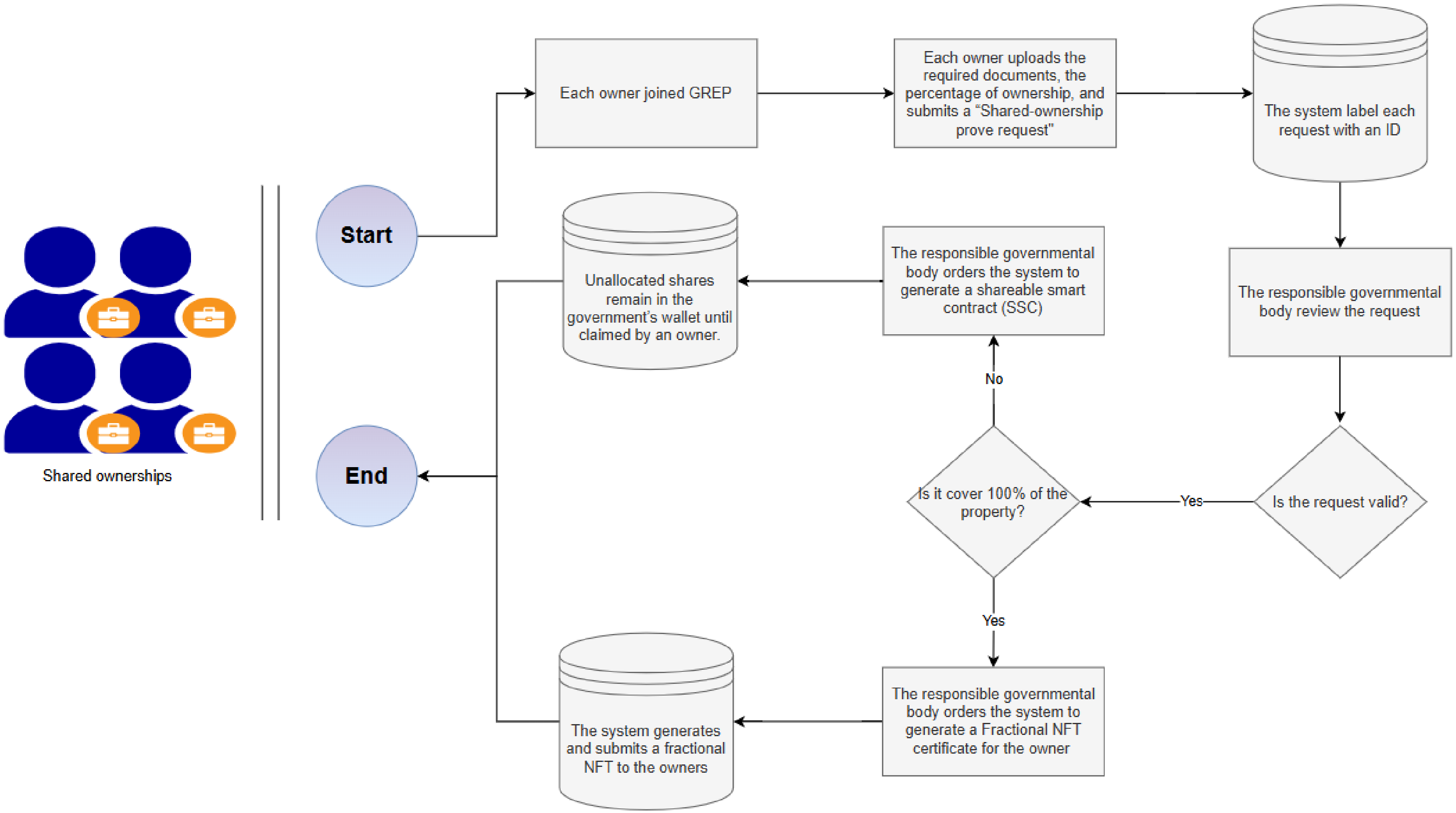

Figure 4.7: Overview of the shared ownership registration and verification process within GREP

The process begins when each owner joins the system and submits a shared ownership proof request by uploading the required documents and specifying their ownership percentage. The responsible governmental body then reviews and validates the request. If approved, the system generates fractional NFTs corresponding to the ownership shares. Any unallocated shares remain in the government's wallet until claimed by an owner, ensuring proper distribution. Once all shares are assigned, fractional NFTs are issued to respective owners.

As shown in Figure 4.8, the selected dataset provides relevant ownership records that effectively support Objective 3. It includes properties with multiple owners, each holding distinct ownership percentages. For instance, in the yellow-highlighted example, one property is co-owned by two individuals, with one holding 30% and the other 70%. This structured ownership data is essential for demonstrating the issuance of fractional NFTs, ensuring that shared ownership percentages are accurately represented on the blockchain.

	A	B	C	D	E
1	Owner Type	Owner Name	Ownership Percentage	Association Date	Location
527	Individual	HANDELSON, STEPHANIE	30%	since 06/26/2013	3 HARVEST CIRCLE
683	Individual	GRAPE, THOMAS	70%	since 06/26/2013	3 HARVEST CIRCLE
3174	Individual	BRUCK, JONAH	30%	since 07/01/2011	8444 ENGLEMAN
3338	Individual	WRONSKI, FRANK	30%	since 04/01/2014	28349 JOY RD
3604	Individual	EISENBERG, LEO	30%	since 04/01/2014	28349 JOY RD
3664	Individual	BRUCK, JONAH	30%	since 04/01/2004	9400 CONANT STREET
3825	Individual	BRANSCUM, JIM	30%	since 12/01/2013	28349 JOY RD
4526	Individual	BRUCK, JONAH	30%	since 05/01/2004	26505 POWERS AVE
5025	Individual	ABRAMSON, DANIEL	30%	since 08/01/2003	21630 HESSEL
5035	Individual	PATEL, AMEE	70%	since 01/01/2010	21630 HESSEL

Figure 4.8: Examples of split ownership data used from the dataset to achieve Objective 3

4.3.4 Solution overview for Objective 4

The validation and evaluation phases are crucial in assessing the quality and reliability of a system. GREP's performance is validated through multiple use cases designed for each objective, and each solution is evaluated using various performance metrics to demonstrate the system's efficiency and reliability. A comparative analysis is conducted between traditional real estate management systems and the blockchain-based GREP framework, highlighting its advantages in terms of time, cost, and predictability. Furthermore, a prototype is implemented to demonstrate the feasibility and effectiveness of GREP in managing real estate provenance and ownership certification.

4.4 Conclusion

In this chapter, we discussed the research methodology chosen for this study, the DSR approach, which is well-suited for developing new techniques and systems. Additionally, we provided an overview of the proposed solutions, covering the system architecture, workflow, and dataset used for implementing and validating the solutions. These foundational components lay the groundwork for achieving the research objectives related to managing real estate provenance and ownership certification, which are explored in greater detail in the following chapters.

The next chapter details the development of the GREP system for managing real estate provenance, aligned with Objective 1. It covers the conceptual design, implementation, and assessment of its core functionalities. Additionally, this chapter includes the validation and the evaluation, forming part of Objective 4.

CHAPTER 5

GREP and Real Estate Provenance

5.1 Introduction

The digital era has profoundly transformed real estate transactions, introducing an era of unprecedented complexity and implications (Naeem et al., 2023; Qian, 2023; Saull et al., 2020). This transformation has catalyzed a major shift towards online platforms, leading the real estate industry to increasingly embrace various electronic business activities. These digital platforms, powered by advanced technology, are essential in improving the accuracy and efficiency of tracking and recording real estate activities (Wouda and Opdenakker, 2019).

Real estate provenance, which captures the documented history of these activities, includes details such as previous ownership, transaction records, or any historical information related to the real estate's origin. Accurate provenance tracking not only ensures transparency (Monahan et al., 2018) and builds trust

(Plass et al., 2023; Grover et al., 2018), but also offers numerous benefits such as fraud prevention, risk mitigation, and support for informed decision-making. Access to accurate and complete historical data further enables market analysis and uncovers investment opportunities. Despite these advantages, the pursuit of maintaining transactional integrity and verifying historical data within real estate transactions introduces several challenges.

These challenges, especially highlighted by the shift to digital platforms, are crucial to address. They emerge primarily from the digital world's complexities and the ongoing evolution of online real estate dealings. The first challenge is ensuring data authenticity in real estate transactions where the risk of fraud and data manipulation is elevated (Saari et al., 2022). In the digital era, the integrity of online-stored property records and histories becomes paramount. Ensuring the authenticity of these documents is crucial for preventing fraudulent activities and ownership disputes. For instance, according to the National Association of Realtors, in the U.S., real estate wire fraud, a specific form of fraud involving the use of the internet to unlawfully divert funds, resulted in estimated losses exceeding $210 million in 2020 (NAR, 2023). This underscores the ongoing challenges and risks associated with electronic business transactions in this sector.

Another challenge in real estate lies in effectively managing access rights, which is a crucial factor that profoundly influences both the security and integrity of the transaction process. Proper access management enhances transaction integrity, which is vital for fostering trust among the parties involved in real estate transactions (Piazolo and Förster, 2019; Mertzanis et al., 2024). Ensuring that only authorized individuals have the ability to view, alter, or approve transactional data is paramount. This not only safeguards against unauthorized access and potential data breaches but also reinforces the reliability of the transaction process. Addressing these challenges in real estate requires the adoption of an innovative technological solution to establish a reliable and anti-fraud environment.

As a potential technological solution, blockchain offers significant advancements in managing real estate provenance. Its decentralized ledger system ensures transparency and immutability in property history records (Witzig and Salomon, 2019; Zhang et al., 2024b), thus enhancing provenance tracking accuracy. Moreover, blockchain's transparency enhances stakeholders' trustworthiness by providing verifiable and tamper-proof transaction records (Johng et al., 2020). Utilizing these features, blockchain significantly improves security in real estate transactions, accordingly reducing the risk of fraud and data manipulation and fostering a trusted environment.

In this chapter, we introduce GREP, a hybrid blockchain that integrates the previously mentioned benefits of blockchain while combining the advantages of both private and public blockchains. This approach effectively addresses blockchain adoption challenges by minimizing disruption and maximizing the benefits of smart contracts (Bennett et al., 2021). While GREP provides a comprehensive framework, this chapter focuses on four key dimensions, which include the following: managing access rights, managing provenance entry, retrieving provenance data, and updating provenance data, addressing the requirements of Objective 1. Additionally, we explore their implementation, validation, and evaluation using various tools and metrics, which contribute to Objective 4.

The rest of the chapter is structured as follows: In Section 5.2, we explore the conceptual development of our framework and address the corresponding challenges in this field. Section 5.3 introduces GREP, outlining its key functional tasks and algorithms in managing real estate provenance. Section 5.4 explores the practical application of GREP through various use cases, assessing system setup, functionalities, and its impact on real estate transactions. Section 5.5 presents a discussion of the findings. The chapter concludes in Section 5.6 by summarizing our findings on GREP's role in real estate provenance management and its alignment with Objectives 1 and 4.

The contents of this chapter have been published in the journal *Service Oriented Computing and Applications* (Springer). The full article can be accessed at: `https://link.springer.com/article/10.1007/s11761-024-00403-0`.

5.2 Developing the Proposed Solution

In our endeavor to develop a system that aims to manage real estate provenance globally, we encounter a variety of challenges. Figure 5.1 displays the primary challenges in developing a global real estate platform. By integrating blockchain technology, we aim to mitigate these key challenges effectively.

Blockchain, with its immutable and tamper-proof ledger, provides a viable answer to the risk of fraud and data tampering prevalent in paper-based systems. In contrast to traditional web-based solutions, which are often vulnerable to cyberattacks and hacking, a blockchain-based approach offers enhanced security and integrity. Leveraging these qualities, the proposed system employs blockchain technology to ensure the authenticity of real estate data.

Central to this framework is the utilization of real estate provenance data. It provides stakeholders with a comprehensive historical record of the property, including previous ownership, transaction history, and any significant events or changes. This approach builds trust, improves data authenticity, prevents fraud, and aids in making better-informed decisions, ultimately enhancing confidence in the real estate market.

In addressing the critical issue of access rights management in real estate, it is essential to understand the required levels of transparency and accountability.

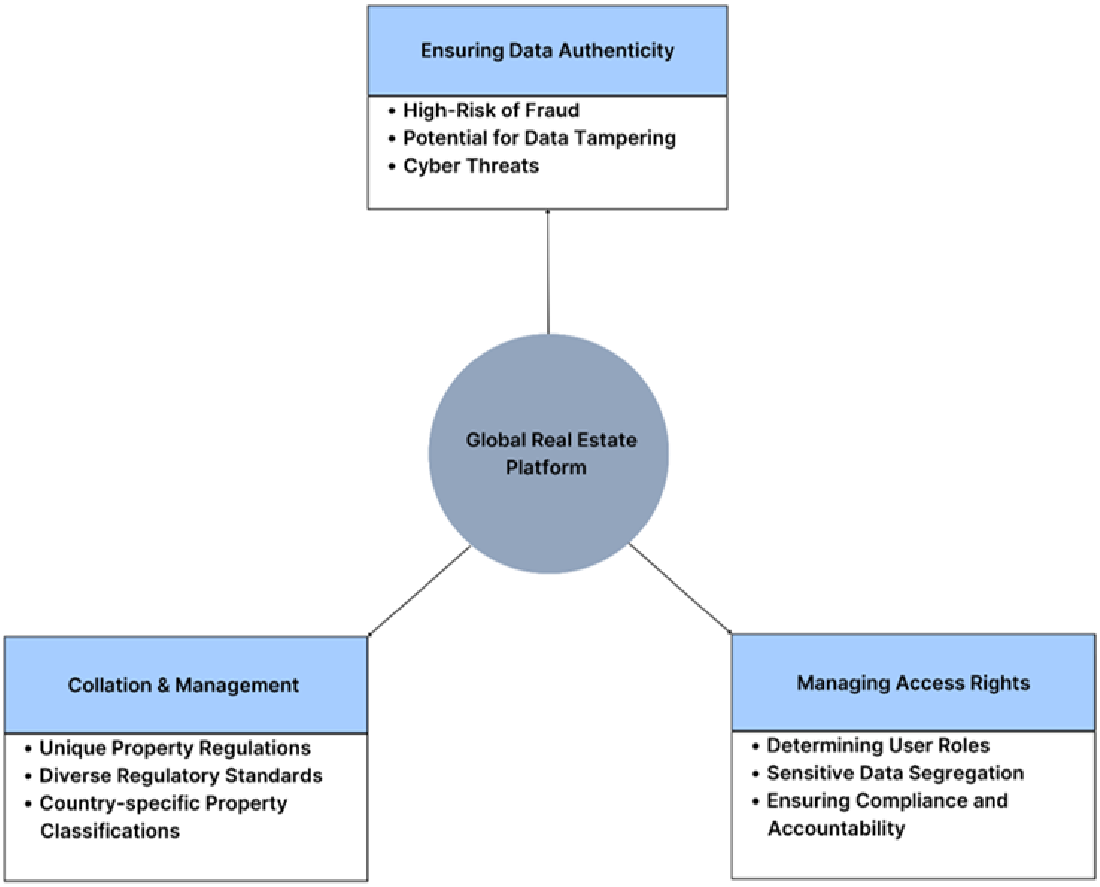

Figure 5.1: Key challenges and sub-issues in developing a global real estate platform

Although a traditional public blockchain inherently offers high transparency (Tyma et al., 2022), this comes with the risk of excessive data exposure (Chang et al., 2020). To strike a balance, the proposed solution ensures adequate transparency while maintaining data privacy.

Furthermore, accountability, especially in real estate transactions, is of paramount importance. Recognizing this, the government's involvement is a key step in reinforcing accountability and establishing public trust. The participation of government entities extends beyond mere regulatory compliance; it is also a realistic decision considering the substantial financial interests that governments have in real estate markets (Singh and Vardhan, 2019).

To strike a balance between transparency, privacy, and accountability, the proposed system adopts a hybrid blockchain model. Part of the data is controlled in a private blockchain, ensuring privacy and accountability, particularly for regulatory compliance and sensitive ownership records. Meanwhile, another part is stored in a public blockchain to ensure transparency without overexposing private data. This approach allows the system to offer both the security of government oversight and the trustlessness of blockchain-based transparency, effectively mitigating risks such as data manipulation and unauthorized access.

Based on these considerations, we propose GREP, a hybrid blockchain system designed to offer conditional transparency while ensuring full accountability. This is achieved through the integration of an authorized entity, as suggested in (Abualhamayl et al., 2023). The establishment of such an entity provides a more secure framework in the context of real estate transactions.

In the conceptual framework of GREP, there are two primary categories of participants:

- **Stakeholders**: This broad category encompasses all parties involved in real estate transactions, including property owners, prospective buyers, and insurance companies. They have the capability to navigate through the system, either to view provenance information or to request the addition of such information, particularly if they are property owners.
- **Government Bodies**: Representing the administrative side, these entities exert control over the system, overseeing and validating transactions.

These participants were previously introduced in Figure 4.3, which presents the architecture of GREP and its key components. Furthermore, Figure 5.2 provides a detailed illustration of the sequential steps that a property owner follows within GREP, from enrollment in the initialization stage to the government's finalization of the transaction in the execution stage. It is worth mentioning that we acknowledge the diverse requirements that different countries may have. Each nation has the autonomy to decide its specific needs and how they are integrated within the framework. This flexibility is crucial for global applicability, ensuring that the system is adaptable to various regulatory environments.

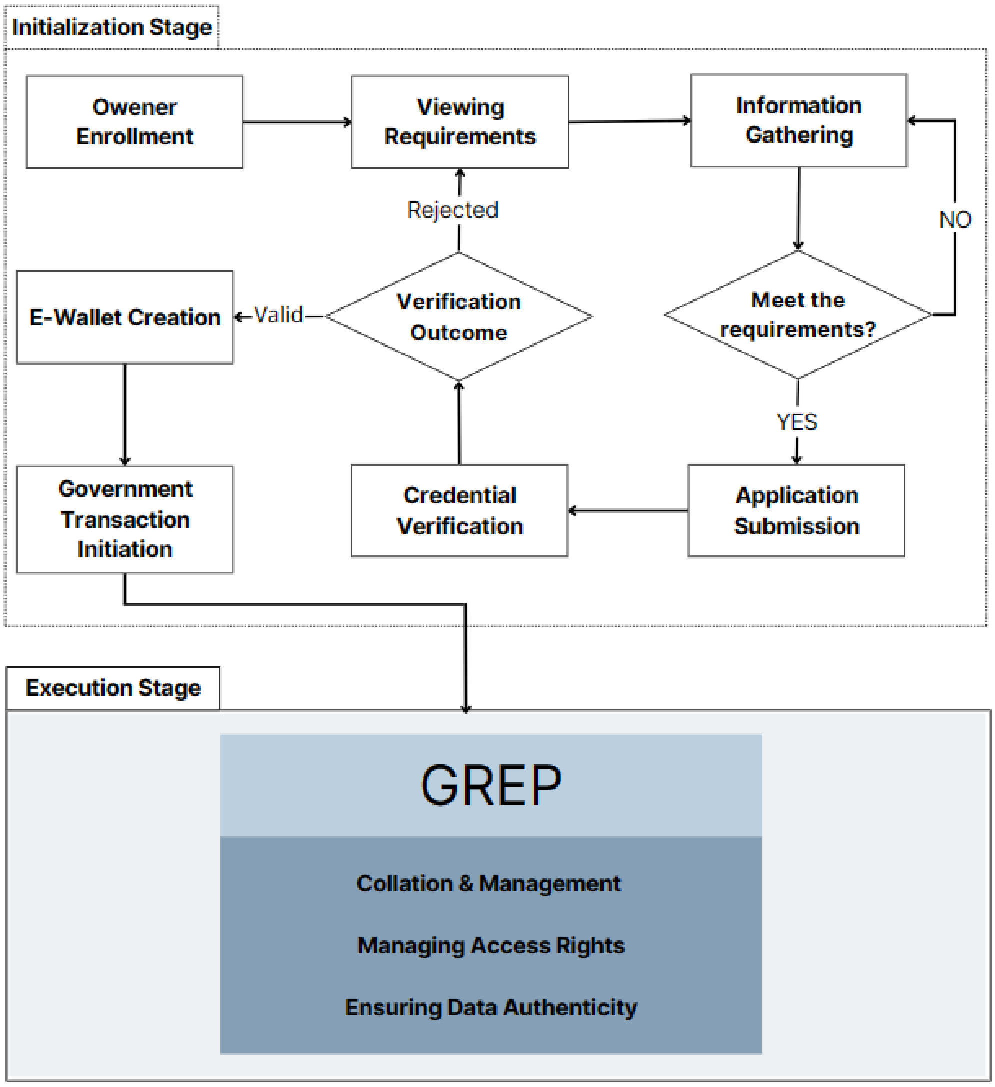

Figure 5.2: Workflow diagram for property owners in GREP

On the other side, government bodies receive and process requests from stakeholders, interacting directly with the smart contract to manage and finalize transactions. Figure 5.3 provides an in-depth system overview, specifically illustrating how GREP facilitates interactions related to real estate provenance management and ensures seamless coordination between stakeholders and government entities.

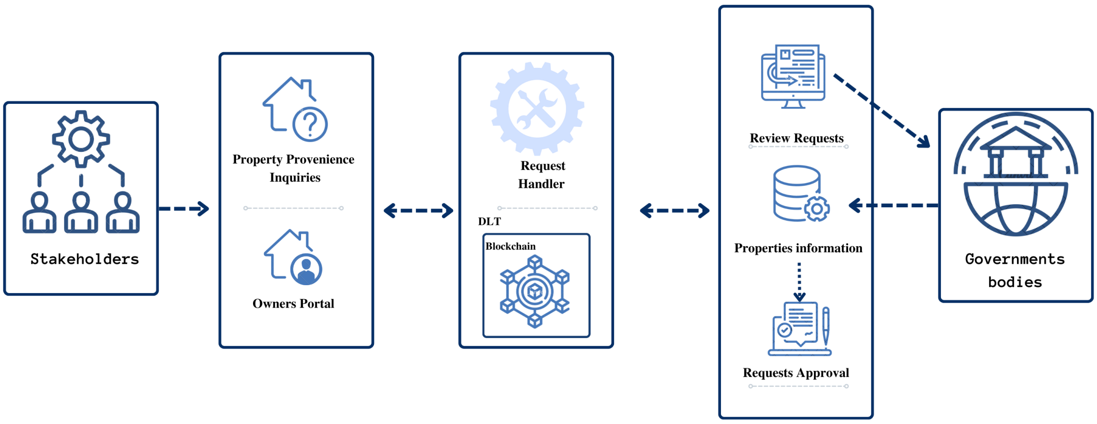

Figure 5.3: Illustration of provenance management within GREP

5.3 GREP: Managing Real Estate Provenance

The Global Real Estate Platform (GREP) is a blockchain-based solution designed to enhance security while maintaining a necessary balance between decentralization, privacy, and accountability in managing and tracing real estate transactions. Some issues are inherently addressed through blockchain adoption, such as preventing unauthorized alterations to property records and enabling the transparent tracing of property ownership history. In the context of provenance data management, GREP is structured around four essential tasks: manage access rights, manage provenance entry, retrieve provenance data, and update provenance data.

5.3.1 Managing access rights in real estate

In response to the challenge of managing access rights in real estate, we employ the role-based access control (RBAC) method (Ferraiolo et al., 1995). Under this model, participants are assigned into three distinct user roles, each with varying levels of authority and system access:

- **Super Admin**: This role is assigned to users who have full authority over the system. Typically, this could be a national government entity.
- **Admin**: Users selected by the super admin to perform specific and limited tasks. This role could be fitting for local government bodies like municipalities.
- **Regular User**: This category includes all other stakeholders, such as property owners, prospective buyers, or any other participants in the real estate transaction process.

Table 5.1 outlines the specific permissions associated with each user role in GREP. Notably, Regular Users are granted viewing access only upon providing a Property ID and a corresponding key, reflecting an additional layer of protection designed to safeguard sensitive data within our system. This structure supports the global nature of our system as it opens the market to foreign investors who may not have direct insights into the properties, allowing them to participate globally.

Role	Deploy Contract	Modify Roles	Access All Data	Modify Records	View Data
Super Admin	Y	Y	Y	Y	Y
Admin		Y		Y	
Regular User					(Requires Property ID and key)

Table 5.1: User role permissions in GREP

5.3.2 Algorithm for managing provenance entry in real estate

After establishing the user roles and permissions, as detailed in Table 5.1, we can now present the specific steps involved in managing provenance entry through a series of algorithms. The algorithm in this subsection is designed to manage provenance entry, ensuring that provenance data is securely handled and accurately recorded within the system. The steps are outlined in Algorithm 5.1.

Algorithm 5.1: Managing Provenance Entry

Inputs:

- **propertyId:** The unique identifier for the property.
- **ownerName:** Name of the property owner.
- **providerName:** Name of the entity providing the property details.
- **ownerType:** Type of ownership (e.g., individual, corporate).
- **propertyLocation:** Location of the property.
- **CityandState:** City and state of the property.
- **associationDate:** Date when the ownership was associated.
- **basicKey:** A basic key for accessing provenance information.
- **detailedKey:** A detailed key for accessing full provenance information.

Output:

- Updated property ownership records for the given *propertyId*.
- Blockchain event *ProvenanceAdded* emitted with property ID, timestamp, and admin address.

Procedure:

```
If msg.sender != superAdmin;
  {
  Return "Error: Only the Super-Admin can call this function."
  }
System stores ← [propertyId, ownerName, providerName, ownerType, propertyLocation,
CityandState, associationDate, basicKey, detailedKey]
Emit ProvenanceAdded Event ← [propertyId, timestamp, Admin's blockchain address]
```

The procedure for managing provenance entry involves several steps, including:

Access Control Verification: The process starts by verifying if the current user is the super admin. If the user lacks the required permissions, the system returns an error message: "Only the Super-Admin can call this function."

Storing Provenance Data: Once access is verified, the system records the provenance details, including the Property ID, owner information, and associated keys. These records are securely stored on the blockchain, ensuring immutability and verifiability.

Emit ProvenanceAdded Event: After the provenance data is successfully stored, the system emits a `ProvenanceAdded` event. This event logs the Property ID, timestamp, and the admin's blockchain address, ensuring transparency and traceability of the record entry.

5.3.3 Algorithm for retrieving provenance data in real estate

After successfully completing provenance entry, we now outline the specific steps for retrieving the entered provenance data within the GREP system through an algorithm. This algorithm ensures that any user with a valid Property ID and key can securely access the provenance data. The steps are presented in Algorithm 5.2.

Algorithm 5.2: Retrieving Provenance Data

Inputs:
- **propertyId:** The unique identifier for the property.
- **key:** Either the basic key or detailed key provided by the user to retrieve the data.

Output:
- **Retrieved provenance data:** Either limited or full, depending on the provided key.

Procedure:

```
System requests ← [propertyId, key]
If key != basicKey && key != detailedKey;
  {
  Return "Error: Invalid key provided.";
  }
If key == basicKey;
  {
  getBasicProvenance(propertyId) ← limited provenance data.
  }
Else if key == detailedKey;
  {
  getDetailedProvenance(propertyId) ← full provenance data.
  }
```

The procedure for retrieving provenance data involves several steps, including:

System Requests Property ID and Key: The process begins by the system requesting both the Property ID and the appropriate key (either the basic key or the detailed key) from the user. This information is required to initiate the retrieval of provenance data.

Validate the Key: Once the key is provided, the system validates it by comparing it against the stored keys associated with the Property ID. If the key does not match the stored basic or detailed key, the system returns an error, indicating an invalid key.

Retrieve Provenance Data: If the provided key matches the stored key, the system retrieves the relevant provenance data. When the basic key is provided, the system returns limited provenance information. When the detailed key is provided, the system retrieves and returns the full provenance data for the property, ensuring the user receives the appropriate level of access and preventing data overexposure.

5.3.4 Algorithm for updating provenance data in real estate

The following Algorithm 5.3 outlines the process for updating provenance data within the GREP system. These steps ensure that only an authorized entity, the super admin, can update ownership information and provenance records, thereby preventing unauthorized modifications to the system.

Algorithm 5.3: Updating Provenance Data

Inputs:

- **propertyId:** The unique identifier for the property.
- **ownerName:** Name of the property owner.
- **providerName:** Name of the entity providing the property details.
- **ownerType:** Type of ownership (e.g., individual, corporate).
- **propertyLocation:** Location of the property.
- **CityandState:** City and state of the property.
- **associationDate:** Date when the ownership was associated.
- **basicKey:** A new basic key for accessing provenance information.
- **detailedKey:** A new detailed key for accessing full provenance information.

Output:

- **Updated provenance records:** New owner information is added and previous ownership history is retained.
- **ProvenanceAdded event emitted:** Logs the new provenance data to the blockchain with the property ID, timestamp, and admin address.

Procedure:

If msg.sender **!=** superAdmin**;**
{
Return "Error: Only the Super-Admin can call this function.";
}
System stores ← [*propertyId*, *ownerName*, *providerName*, *ownerType*, *propertyLocation*, *CityandState*, *associationDate*, *basicKey*, *detailedKey*]
Emit ProvenanceAdded Event ← [*propertyId*, *timestamp*, *Admin's blockchain address*]

The procedure for updating provenance data involves several key steps, including:

Verify Access Control: The process begins by checking if the individual attempting to update the provenance data is the super admin. This step ensures that only authorized entities have permission to modify or update ownership and provenance data, which is essential for maintaining the security and trustworthiness of the system.

Store New Provenance Data: After verifying access control, the system stores the new owner and property details along with the new keys for accessing provenance data.

Emit ProvenanceAdded Event: Finally, after successfully updating the provenance data, the system emits a `ProvenanceAdded` event. This event logs the update, including the Property ID, the timestamp, and the address of the super admin who makes the changes. Emitting this event ensures that the update is transparent and traceable, reinforcing the security and accountability of the system.

5.4 Implementation and Analysis

This section explores the practical implementation of GREP in real estate provenance management through a series of targeted use cases. Our examination covers system setup, specialized functionalities for super admin roles, and the complexities of property information access. We then evaluate the outcomes of these use cases using various performance metrics.

5.4.1 System setup and implementation tools

In the implementation of our hybrid blockchain for real estate provenance, we conducted our experiments on a 64-bit Windows operating system. The setup featured a 13th Gen Intel® Core™ i9-13900H processor and was equipped with 32 GB of RAM.

We used different tools at each level of our system implementation. Remix – Ethereum IDE version 0.38.1 served as our primary development environment for creating and initially testing our smart contracts. Locally, we used Ganache version 2.7.1 to mimic our blockchain behavior and interactions in a controlled environment. Visual Studio Code version 1.84.2 was employed for additional coding and scripting needs, particularly for JavaScript development. Furthermore, for real-time interaction with the Ethereum network, Web3.js was integral, especially its WebSocketProvider functionality, which enabled us to connect seamlessly to the Sepolia testnet via Infura. This was crucial for testing and validating our smart contract's behavior in a more realistic network environment. In these processes, Node.js was utilized as the runtime environment, providing a stable and efficient platform for running our JavaScript code and Web3.js for blockchain interactions. We used Sepolia faucet via MetaMask to perform our transactions, ensuring an authentic and efficient transaction management process. Additionally, HTML was utilized to create visualizations, such as line charts, effectively presenting data and illustrating the outcomes of our blockchain experiments. Table 5.2 provides an overview of the tools and their respective usage in our implementation.

As discussed in Chapter 4, we utilize a public dataset available on the Data World website (Data.world, 2016). As shown in Table 4.2, the original dataset includes several columns that do not contribute to the goals outlined in this chapter. To prepare the dataset, we removed extraneous columns such as 'Processing Date' and 'Ownership Percentage', eliminated redundant entries, and addressed missing data to ensure the dataset reflects the key scenarios necessary for system functionality and evaluation.

Tool	**Description/Usage**
Remix - Ethereum IDE v0.38.1	Primary environment for smart contract development and testing.
Ganache v2.7.1	Simulates local blockchain for testing and interaction control.
Visual Studio Code v1.84.2	Used for coding and scripting, especially in JavaScript.
Web3.js v1.3.6	Facilitates real-time Ethereum network interaction, using WebSocketProvider.
Node.js v20.9.0	Runtime environment for JavaScript and Web3.js scripts.
Infura v3	Gateway for connecting to the Sepolia testnet for network testing.
MetaMask v11.4.1	Wallet for managing Ethereum transactions.
Sepolia Faucet	Provides test Ether for Sepolia testnet transactions.
HTML5	Utilized for data visualization and presentation, like line charts.

Table 5.2: Summary of tools and technologies used in the blockchain implementation with their respective versions and usage

5.4.2 Use case demonstration

This subsection presents three pivotal use cases that encapsulate the core functionalities of GREP. The first use case demonstrates blockchain's ability to securely manage property provenance records, a fundamental step in establishing trustworthy real estate transactions. By leveraging blockchain's immutability, GREP ensures that property records cannot be altered, duplicated, or forged, effectively preventing fraudulent activities such as forged documents and double selling. Each transaction is permanently recorded and cryptographically secured, making unauthorized modifications impossible. The second use case highlights its role in providing controlled access to property information, ensuring security and privacy. The final use case illustrates dynamic user role management, including the promotion and demotion of admins, reinforcing system adaptability and data integrity. Together, these use cases showcase GREP's effectiveness in enhancing security and trust in real estate transactions, fulfilling its requirements for managing real estate provenance.

Use Case 1: Super admin adds property records

In the first use case, we focus on the execution stage where a super admin, an authorized entity in our proposed system, adds property records, as visualized in Figure 5.2. Given the original dataset's considerable size, we extracted sub-datasets, each containing 3–13 rows of provenance information for a single property. These sub-datasets were used to realistically simulate the provenance data entries. Reflecting our system's authoritative structure, only the super admin is granted the privilege to deploy the smart contract.

Our experimentation was divided into two separate sections:

Local-based test environment

In a controlled test environment, we tested our smart contract initially using Remix VM and subsequently with Ganache. The deployment began in the Remix VM environment, where the super admin's address was used to deploy the smart contract. We then entered the extracted sub-datasets, which were initially ordered by property location. To mitigate any potential acceleration of data entry due to this ordering, we randomized the sub-datasets to form a more realistic scenario. After compilation using Remix's built-in compiler, the smart contract was deployed locally. Figure 5.4 specifically illustrates a successful data entry for the seventh transaction by the super admin, showing the decoded input for property "265,177", while Table 5.3 summarizes the first seven transactions of property data entry.

```
          [vm]from: 0x5B3...eddC4
          to: GlobalRealEstatePlatform.addProvenance
          (uint256,string,string,string,string,string,string,string,string)
          0xd91...39138 value: 0 wei data: 0x70d...00000 logs: 1 hash: 0xd83...d328f
status    0x1 Transaction mined and execution succeed
transaction hash    0xd8319e90a2f6f59d71729f80c38b54eb6a174e34347d18251a9793fb931d328f
block hash          0x75e3fba565906ccc603ce2b3f7bc1887bcebdb7379d06218bc0b420bae67ed30
block number        7
from      0x5B38Da6a701c568545dCfcB03FcB875f56beddC4
to        GlobalRealEstatePlatform.addProvenance(uint256,string,string,string,
          string,string,string,string,string)
          0xd9145CCE52D386f254917e481eB44e9943F39138
decoded input       {
          "uint256 propertyId": "265711",
          "string ownerName": a,
          "string providerName": b,
          "string ownerType": "Orgnization",
          "string propertyLocation": c,
          "string CityandState": "Fenton, Mo",
          "string associationDate": d,
          "string basicKey": "666",
          "string detailedKey": "777"
```

Figure 5.4: Detailed view of the seventh property data entry

We also tested our smart contract on Ganache, a tool that enables developers to create a private Ethereum blockchain, which can be used for testing and development purposes. Differing from Remix VM, Ganache provides a more realistic blockchain environment suitable for use on a local machine.

Transaction No.	Initiated by Super Admin	Transaction Hash	Timestamp	Property ID
1	0x5B38...eddC4	0xadc3ec63ca65bea03d58686946a99585e6644704 1efdde90ea08c771825e56e3	-	-
2	0x5B38...eddC4	0x834b7fdf872260e80668abab583860cd8ee9f38a 233ad7df1eabe6281ab07fef	1701701941	75329
3	0x5B38...eddC4	0x1e5766e9edb189579826ed52514c4447c4439049 da59c24c8a9b43334f0384a1	1701702099	395502
4	0x5B38...eddC4	0xd95529b01ead9fcdcdf212e62236784ca8f9bb7 9998aa8558aef3a575b6210b3	1701702232	265711
5	0x5B38...eddC4	0xc4c21d4a89f990066cea5a432409f499df4d13a 59048f1fbe5622af8af4af02d	1701702364	75329
6	0x5B38...eddC4	0x555fb5b690bf9fb56aa871d4b5dd27e29be6436 3df91a85edca45c3be5e289a0	1701702472	395502
7	0x5B38...eddC4	0xd8319e90a2f6f59d71729f80c38b54eb6a174e3 4347d18251a9793fb931d328f	1701702612	265711

Table 5.3: Summary of first seven property data entry transactions

We began by integrating the smart contract environment with Ganache, adjusting the Remix environment to connect via Ganache's JSON-RPC endpoint. To ensure the highest data accuracy and automate the timestamp collection, we utilized event listeners. By employing the Ethers.js library, we efficiently recorded the timestamp of each property data entry, specifically those emitting the 'ProvenanceAdded' event from our smart contract's 'addProvenance' function.

For data analysis, we initially collected these transaction timestamps in Unix format. Subsequently, using a JavaScript conversion code implemented in Visual

Studio Code, we transformed them into a human-readable date and time format. After the conversion, we calculated the duration of each transaction by subtracting the start timestamp from the end timestamp. This process allowed us to determine the total time taken for each transaction. The line charts in Figures 5.5 and 5.6 display the timestamps and durations for data entry across nine transactions, starting from the first transaction.

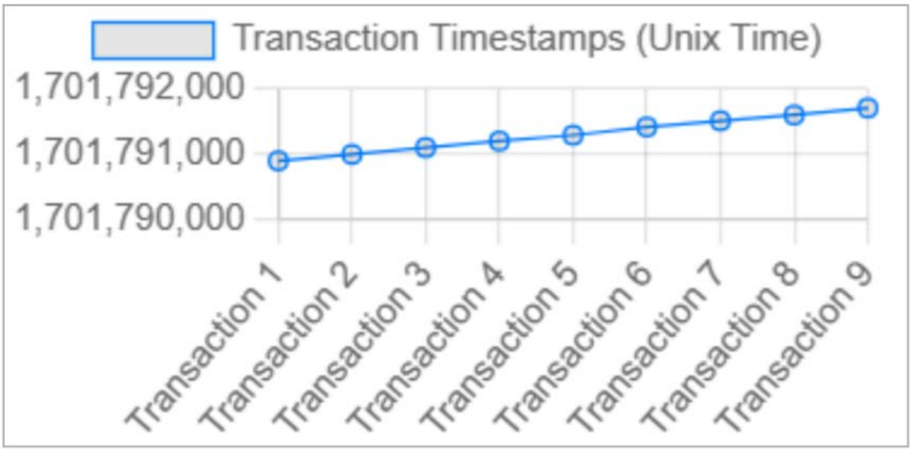

Figure 5.5: The timestamps for each transaction conducted by the super admin in a local-based test environment

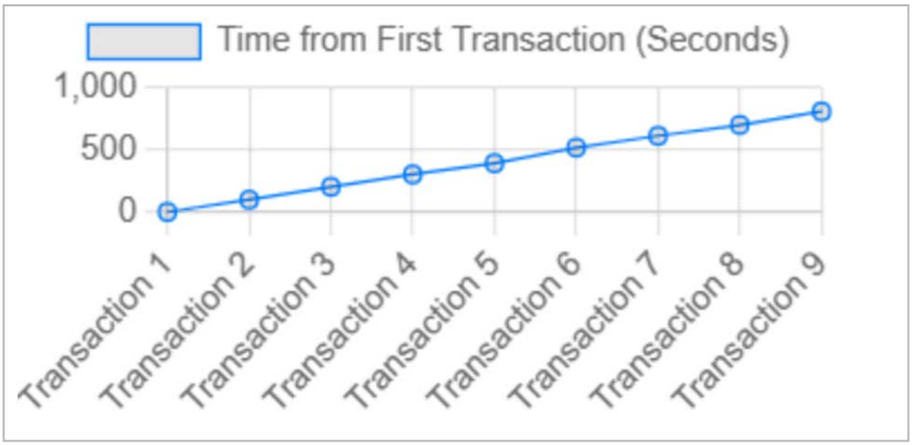

Figure 5.6: The time taken for each transaction relative to the first in a local-based test environment

Network-based test environment

In this section, our objective is to elevate our testing environment to encompass more realistic scenarios. We initiated this advanced phase by integrating our smart contract with MetaMask, a popular Ethereum wallet and gateway to blockchain applications. MetaMask facilitates direct interaction with Ethereum's blockchain via a web browser, making it ideal for simulating real-world user interactions. To utilize MetaMask in a test network mode, we selected the Sepolia test network, which closely mimics the Ethereum mainnet's functionalities.

For our experiment, we created three different accounts within MetaMask, representing a super admin, an admin, and a regular user. Each account was funded with Ethereum from the Sepolia faucet, a necessary provision for executing transactions on the test network. This setup was instrumental in realistically simulating transactional processes among various user roles within our blockchain environment.

Furthermore, we integrated Infura into our setup. Infura provides a scalable infrastructure that is crucial for ensuring reliable and efficient access to the Ethereum blockchain. This integration played a pivotal role in facilitating the complex interactions that are typically encountered in decentralized environments.

By integrating MetaMask with the Sepolia test network and our smart contract, we established a realistic blockchain test environment, crucial for simulating a super admin's role in securely adding property records. By employing event listeners and the provided tools, we conducted a targeted assessment of the blockchain transactions. Key metrics recorded included the timestamps of each transaction, illustrated in Figure 5.7, the time elapsed from the first transaction, shown in Figure 5.8, gas prices, depicted in Figure 5.9, and the overall transaction costs, presented in Figure 5.10.

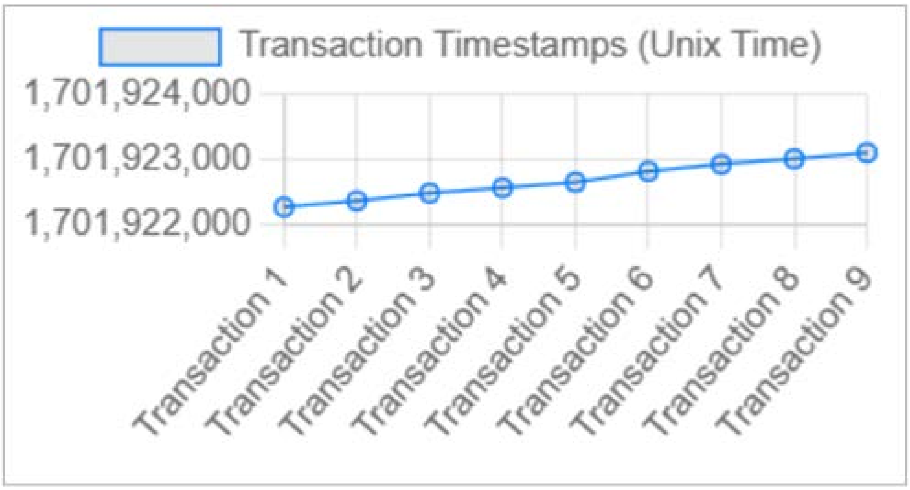

Figure 5.7: The timestamps for each transaction conducted by the super admin in a network-based test environment

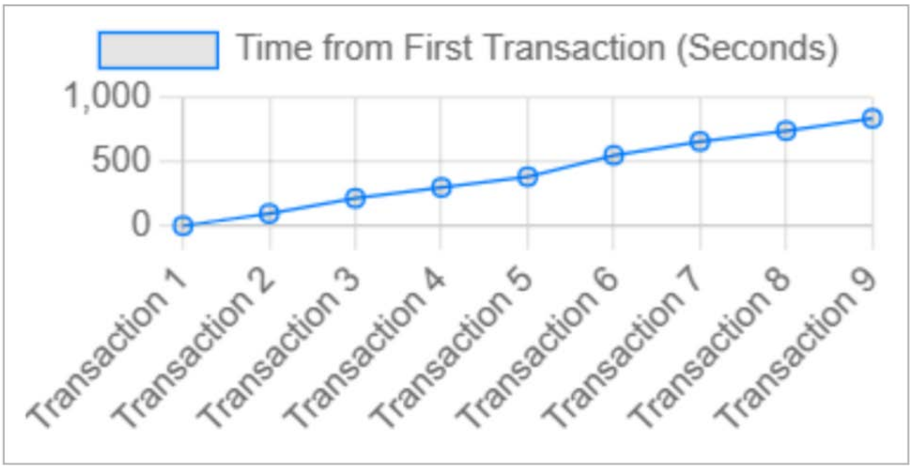

Figure 5.8: The time taken for each transaction relative to the first in a network-based test environment

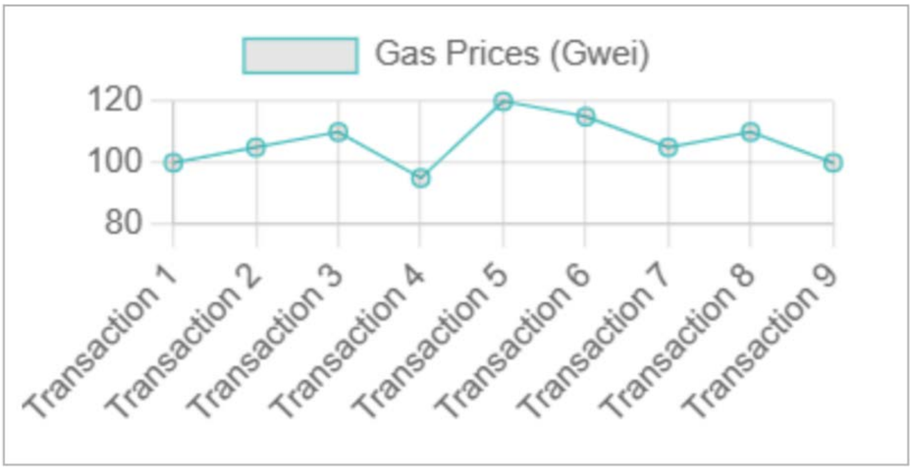

Figure 5.9: The gas costs for each transaction

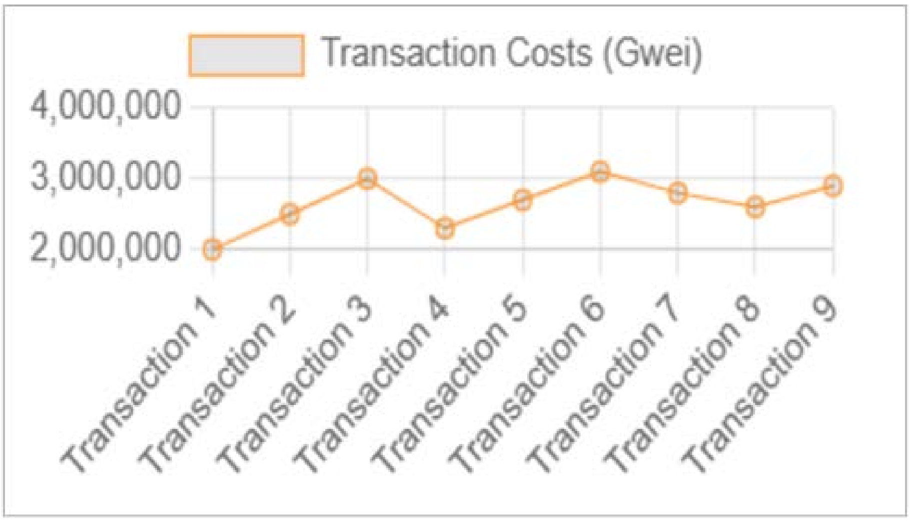

Figure 5.10: The overall costs of each transaction

Use Case 2: User access to property Information

In the second use case, we address the crucial aspect of displaying property provenance information to regular users within GREP. The expected output of this use case is a two-tiered access system that allows users to view property provenance information based on their level of access. This system is designed to regulate information exposure and prevent potential data leaks.

The setup for this experiment utilizes the property information entered by the super admin in the first scenario. We divided the property information into two levels: basic and detailed.

Access to Basic Details: In the basic level, users with a basic key can access fundamental details about real estate provenance. This level is specifically designed for scenarios where a property owner prefers to share limited information with less trusted parties. For instance, an owner can share the basic key, along with the property's identification number, with a prospective buyer who does not require detailed data. This allows the buyer to access and claim essential provenance data through the system using this basic key, effectively balancing information accessibility with security.

Table 5.4 illustrates this process by providing a detailed view of a typical transaction, including the interaction method, user and contract addresses, and the specific data exchanged when accessing basic property information.

Access to Detailed Information: In the second level, users with a detailed key can access comprehensive information about real estate provenance. This level is tailored for situations where a property owner fully trusts another party and opts to share in-depth property details. A typical scenario could involve an owner providing the detailed key, along with the property's identification number, to an insurance

Feature Showcase: User Access Basic Property Information		
Detail	**Value**	**Description**
Call Function	`GlobalRealEstatePlatform.getProvenance (uint256, string)`	Indicates the contract method being called for retrieving property information.
From (Caller)	`0xC13ec36b7a178C510360B047B2E484351bd 33E71`	The Ethereum address of the regular user attempting to access property information.
To (Contract Method)	`GlobalRealEstatePlatform.getProvenance (uint256, string)0x71dF8CEcC5d5aB76402 7498Cdafb6018EFA7D67`	Specifies the contract and method attempted by the user to retrieve information.
Decoded Input	`{"uint256 propertyId": "75329", "string key": "222"}`	The input data, where users provided the Property ID "75329" and the key "222" to access the property information.
Decoded Output	`{"0": "string: Owner: A, Property Location: B==== Owner: C, Property Location: B==== Owner: D, Property Location: B"}`	The output data, showing the limited information about the property provenance with the basic key "222".

Table 5.4: Basic provenance information retrieval details

company seeking extensive data on the property's history and condition. This access enables such entities to review all available provenance data within the system, using the detailed key.

Table 5.5 offers a detailed view of a transaction involving the detailed key and showcases the comprehensive property information accessed in this process. It details the specific data exchanged, including the interaction method, as well as the user and contract addresses involved in accessing this deeper level of property provenance information.

To evaluate the efficiency of our system in handling different access levels, we measured the response times for accessing both basic and detailed provenance information. This was achieved using a function that calculated the time elapsed from initiating to completing each provenance information request.

	Feature Showcase: User Access Detailed Property Information	
Detail	**Value**	**Description**
Call Function	`GlobalRealEstatePlatform.getProvenance (uint256, string)`	Method for calling to retrieve detailed property information.
From (Caller)	`0x2C0449898062532Ce5A3826f219a32B94D7F08bb`	The Ethereum address of the trusted user.
To (Contract Method)	`GlobalRealEstatePlatform.getProvenance (uint256, string)0x71dF8CEcC5d5aB764027498Cdafb6018EFA7D671`	Specifies the contract method and address the user interacted with to retrieve information.
Decoded Input	`{"uint256 propertyId": "75329", "string key": "333"}`	The user used Property ID "75329" and the key "333" to access the detailed information.
Decoded Output	`{"0": "string: Owner: A, provider Name: B, Owner Type: Organization, Property Location: C, City and State: Bristol, CT, Association Date: Since 01/01/1984 ==== Owner: D, provider Name: B, Owner Type: Individual, Property Location: C, City and State: Bristol, CT, Association Date: since 01/01/2003 ==== Owner: E, provider Name: B, Owner Type: Individual, Property Location: C, City and State: Bristol, CT, Association Date: since 01/01/2005"}`	The output data, showing extensive information about the property provenance with the detailed key "333".

Table 5.5: Detailed provenance information access details

Figure 5.11 presents this data in a line chart format, visually comparing the response times for accessing basic and detailed provenance information and including the average response time for both.

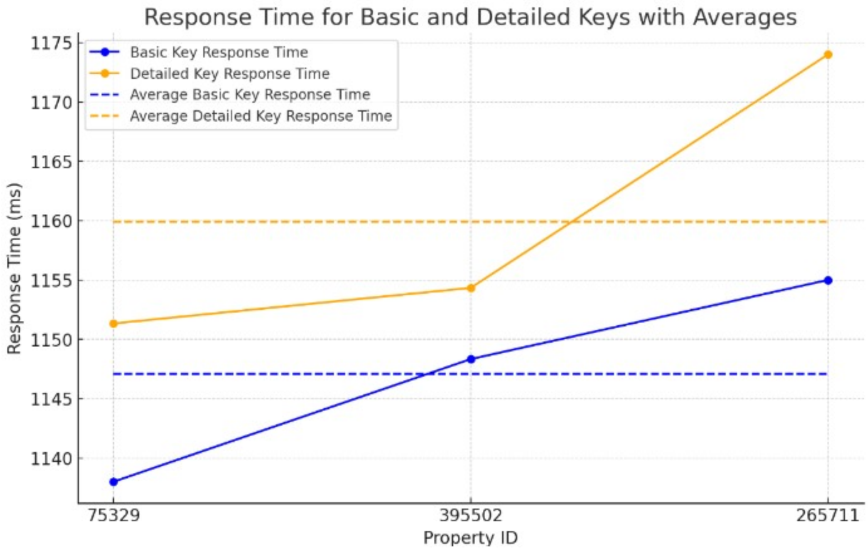

Figure 5.11: Provenance information response time visualization

To illustrate the results of Use Case 2, Figure 5.12 shows the improved ERC-721 standard that we used to achieve a solution for Objective 1. Figure 5.13 illustrates the provenance retrieval using the Property ID and the basic key, while Figure 5.14 illustrates the provenance retrieval using the Property ID and the detailed key within our system.

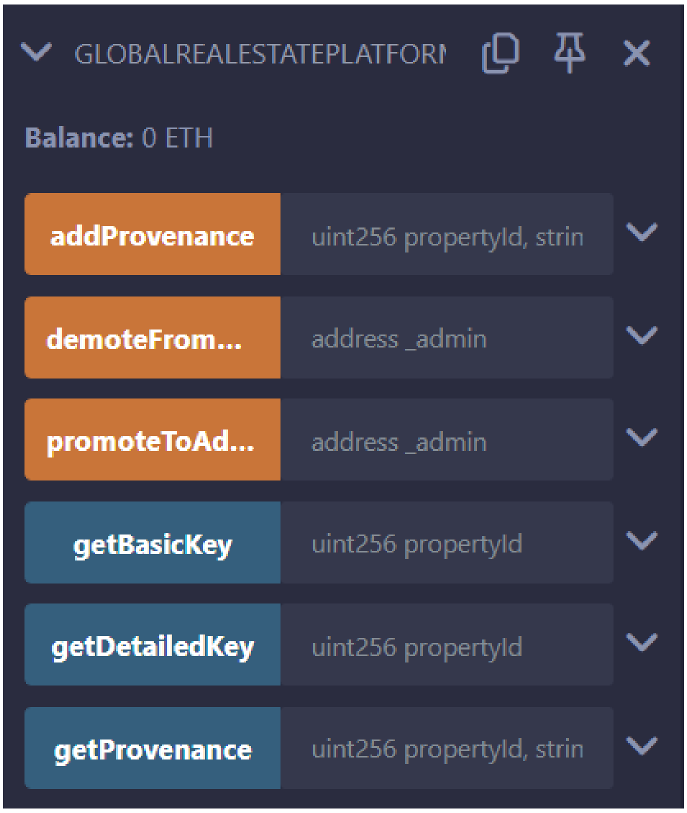

Figure 5.12: Improved ERC-721 standard implementation.

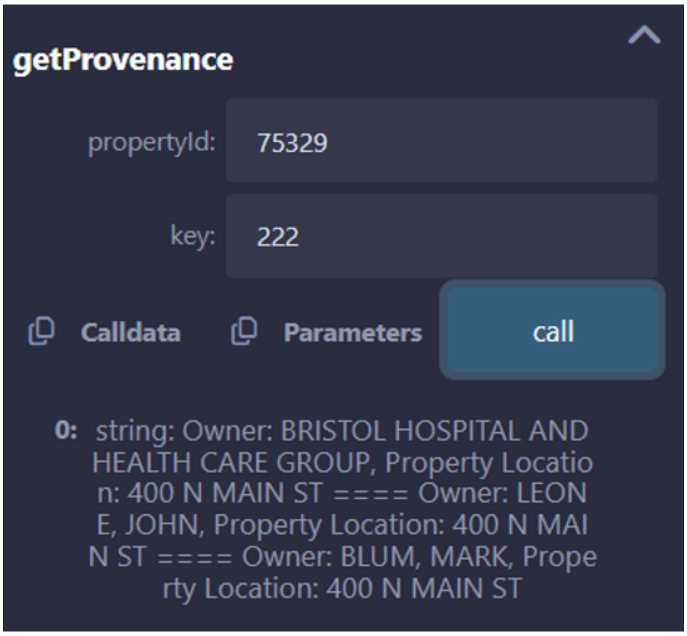

Figure 5.13: Provenance retrieval using Property ID and basic key

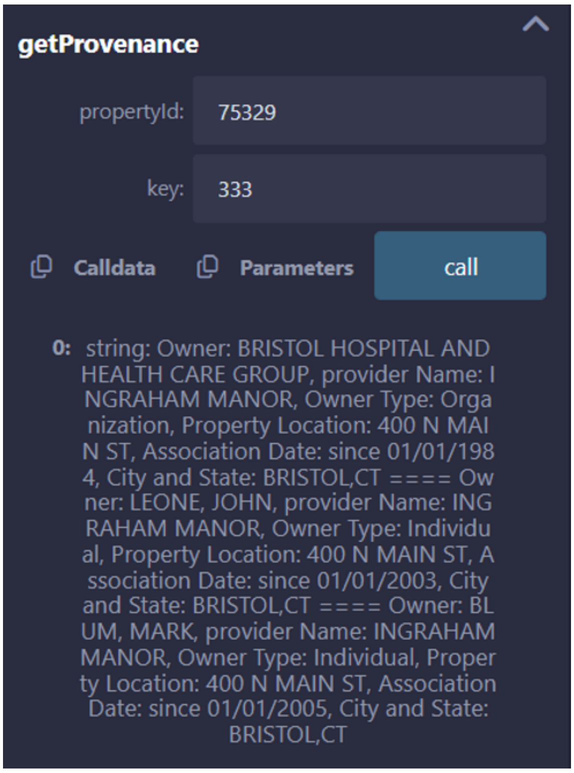

Figure 5.14: Provenance retrieval using Property ID and detailed key

Use Case 3: Promoting and demoting admins

In our third use case, we explore the super admin's authority within GREP to promote regular users to admin roles and to demote them, as detailed in Table 5.1. This case aims to demonstrate effective user role management, emphasizing the crucial role of admins in maintaining privacy and controlling access to sensitive functions.

This experiment builds upon the first scenario where the super admin added property provenance, including a detailed key. To illustrate this experiment, we incorporated the 'getBasicKey' function into our smart contract. This function is critical as it allows access to light-weight property information, yet only authorized entities like super admins or admins can use it, whereas regular users cannot. The aim of this test is to validate the system's role-based access control mechanisms, particularly focusing on the super admin's ability to promote a user to an admin status and the newly promoted admin's ability to access the 'getBasicKey' function.

The actual verification in this scenario begins with the super admin promoting a specific regular user to an admin role. A detailed visualization of this transaction is demonstrated in Table 5.6.

Following the promotion, this new admin address gains the right to call the 'getBasicKey' function and access its contents. Table 5.7 demonstrates the execution of this function by the newly promoted admin.

The super admin has the capability to demote admins back to regular user status. In our experiment, we demonstrated this by demoting the same user who was previously promoted to an admin. This process is depicted in Table 5.8. As a result of the demotion, when that user attempted to call the 'getBasicKey' function, an error message was triggered, stating "execution reverted: only an admin or super admin can call this function." This confirms that the user had effectively lost admin privileges.

To assess the system's efficiency in managing user role changes in Use Case 3, we monitored the system's performance through a series of role modification transactions. This involved a sequence of user promotions and demotions to evaluate the system's responsiveness during these critical operations. We recorded the timestamps of each transaction to analyze the time dynamics involved in these role changes. Figure 5.15 visually presents the timestamps for each of these transactions.

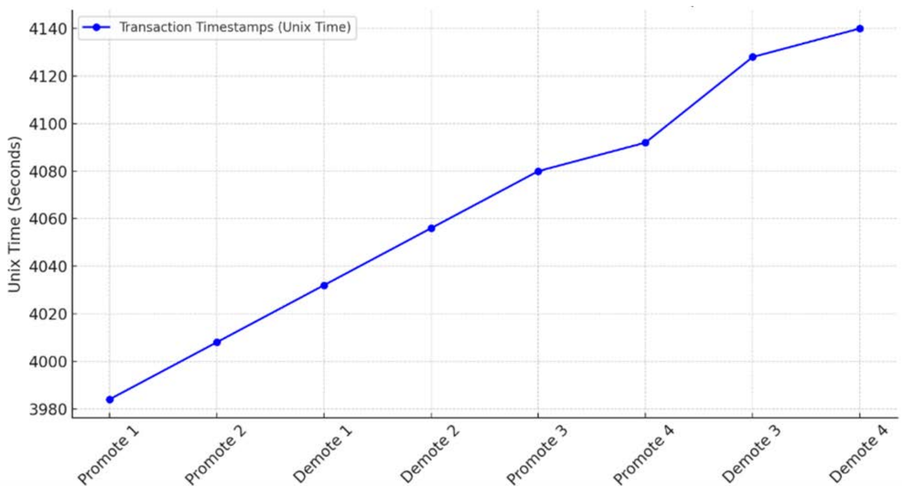

Figure 5.15: Timestamps for user role modification transactions

Feature Showcase: Super Admin Promoting a User		
Attribute	**Value**	**Description**
Transaction Hash	`0x8d35c021a8737c931435e062fcc2820fe7 c0ba0f488 ee0deb7509b48582d8589`	Unique identifier of the transaction.
From (Sender)	`0x8d642c343998d03628AcE3F3CdbFb7dBc8 8f9b6a`	Ethereum address of the super admin initiating the transaction.
To (Contract Method)	`GlobalRealEstatePlatform.promoteTo Admin(address)`	Smart contract method called to promote a user to admin.
Decoded Input	`{"address_admin": "0x2C0449898062532Ce5A3826f219a32B94 D7F08bb"}`	The input data, specifying the admin address being promoted.

Table 5.6: Admin promotion transaction visualization

Feature Showcase: New Admin Performing a Call		
Attribute	**Value**	**Description**
From (Sender)	`0x2C0449898062532Ce5A3826f219a32B94D7F08bb`	Ethereum address of the new admin performing the call.
To (Contract Method)	`GlobalRealEstatePlatform.getBasicKey(uint256)`	Smart contract method called to retrieve a basic key.
Decoded Input	`{"uint256 propertyId": "75329"}`	The input data, showing the Property ID for which the basic key is requested.
Decoded Output	`{"0": "string: 222"}`	The output data, showing a successful retrieve for the basic key.

Table 5.7: Details of the new admin performing a call to retrieve the basic key

Feature Showcase: Admin Demotion and Access Check		
Detail	**Value**	**Description**
Status	`0x1 Transaction mined and execution succeed`	Indicates the transaction was successfully processed.
Transaction Hash	`0x31cd16502cff8ac89d8dc54fa81187a46022563d3938b40c993c3c3df38e765c`	Unique identifier for the transaction.
From (Sender)	`0x8d642c343998d03628ace3f3cdbfb7dbc88f9b6a`	The Ethereum address of the super admin initiating the demotion.
To (Contract Method)	`GlobalRealEstatePlatform.demoteFromAdmin (address)0x71df8cecc5d5ab764027498cdafb6018efa7d671`	Indicates the contract method being called for demoting an admin.
Decoded Input	`{"address_admin": "0x2C0449898062532Ce5A3826f219a32B94D7F08bb"}`	The input data, specifying the admin's address to be successfully demoted.
Call Function (Attempt)	`GlobalRealEstatePlatform.getBasicKey(uint256)`	The demoted admin's attempted call to the "getBasicKey" function.
Error Message	`execution reverted: Only an Admin or Super-Admin can call this function`	Transaction failed as explained in the error message.

Table 5.8: Failure call execution for demoted admin

5.5 Discussion

This section provides a detailed analysis of the outcomes of our experimentation in each use case. We explore the key findings, the challenges encountered, and the impact of these results.

Use Case 1: We conducted multiple tests to analyze the process of a super admin adding property records across various environments. Every entry made by the super admin was carefully compared with the original dataset to ensure accuracy and consistency. Figure 5.4 and Table 5.3 illustrate the details of the information entered by the super admin in the Remix local VM. Additionally, Tables 5.4 and 5.5 confirm the successful and accurate data entry on our system, as evidenced by the comparison with the original dataset.

To evaluate the effectiveness of this solution, we extended these tests to a local-based and network-based environment. A key metric we focused on was the recording of timestamps for each transaction, which are crucial for tracking the exact moment each transaction is processed within the blockchain. Although slightly less critical in controlled environments, they provide essential insights into system performance. Figures 5.5 and 5.7 illustrate the timestamps in local and network environments, respectively.

The analysis reveals that the network environment, as shown in Figure 5.7, demonstrates an increasing trend with less stable increments, which can be reasonably attributed to the increased transaction time associated with local addresses compared to those using the MetaMask wallet. This direct comparison highlights the impact of network conditions on transaction times. Similarly, the metric of time elapsed from the first transaction provides instrumental insights into activity patterns and internal processing efficiency, as depicted in Figures 5.6 and 5.8.

Shifting our focus to financial aspects, we considered the following two metrics for budgeting and financial planning:

1. **Gas prices**: Figure 5.9 presents a line chart of gas prices for 9 transactions within our government-controlled hybrid blockchain system, with all transactions maintaining gas prices between 90 to 120 Gwei. This relatively narrow range demonstrates the effectiveness of our regulatory mechanisms in stabilizing gas prices, despite the inherent fluctuations typical in blockchain systems. The consistency observed in the gas price range underscores our system's ability to provide a predictable environment for financial planning and budgeting in blockchain-based transactions.

2. **Transaction Costs**: Similarly, Figure 5.10 illustrates the transaction costs associated with the same set of transactions and shows that despite fluctuations, the costs stay within a relatively predictable range. This predictability mirrors the stability observed in gas prices and underscores our hybrid blockchain's ability to provide financial predictability and stability.

In Use Case 1, we encountered the following challenges during the implementation:

- **Tool compatibility and downgrading**: During our implementation phase, a major challenge was compatibility issues in our development stack, as shown in Table 5.2. We faced errors suggesting incompatibilities between different versions of our tools and libraries. This issue was particularly apparent with ethers.js, where we encountered functionality problems due to unresolved bugs and unsupported changes in its newer versions. Similar compatibility issues were experienced with Node.js versions, web3.js, and the Solidity compiler. Our solution often involved downgrading to more stable versions of these tools.

Notably, the versions of the tools outlined in Table 5.2 are not the latest, implying the complexities inherent in blockchain development.

- **Managing smart contract complexity and security**: In addressing the security concerns related to data exposure, our focus extended beyond mere data entry to encompass the expected outputs of the system. We implemented features to show provenance using both basic and detailed keys, which were set by the super admin. While these enhancements were crucial for ensuring data security and preventing unwanted consequences later, they inevitably led to a more complex and heavier smart contract.

- **Realism in data entry**: During our implementation, we faced a challenge in the data entry process. The original dataset is extensive, and when sorted by provider location and date, it provided the provenance data for specific properties. However, entering this data in a sorted order could unrealistically speed up the process, as certain parameters such as Property ID, Provider Name, and Provider Location would be repeatedly used without change. To avoid creating an unrealistic scenario and to better mimic real-world conditions, we randomized the sub-datasets, resulting in the data being unsorted.

While this use case primarily focuses on managing provenance data entry, it establishes a foundation for future advancements in secure and efficient real estate transactions. As part of Objective 4, our evaluation for this part includes timestamps, gas prices, and transaction costs, providing insights into the system's effectiveness, stability, and overall performance.

Use Case 2: In Use Case 2, we developed a two-tiered access system to display property provenance information. Users, such as foreign investors, can access basic details with a basic key, which is ideal for limited information sharing. For more comprehensive data, a detailed key enables access to in-depth property information. Our approach successfully called both keys with the desired and accurate output, as demonstrated in Tables 5.4 and 5.5 respectively. This not only demonstrates the functionality of this use case, but also validates the successful data entry process started in Use Case 1.

To evaluate the efficiency of our system in Use Case 2, we selected response time as our key metric. In a hybrid blockchain, assessing response times helps in benchmarking the system's performance. This is especially important for government-controlled environments, where efficiency and reliability are paramount. Figure 5.11 offers a visual comparison of the response times for accessing basic and detailed provenance information across a network test environment, including the average response time associated with each key type. Notably, the response times for accessing detailed information are understandably longer due to the greater volume of data involved.

A primary challenge we faced was the detection and tracking of function calls within the blockchain environment. Unlike event listeners that readily capture and log transactions, as seen with adding provenance data in Use Case 1, tracking function calls required a more intricate approach. Our approach involved implementing an asynchronous function to measure response times accurately. However, this method demanded rigorous execution to ensure precise monitoring and analysis, which highlighted the complexities of function call tracking.

Use Case 2 in our study represents an important step toward secure and trustworthy real estate transactions. The implementation of a two-tiered access system for property provenance information on GREP notably advances the security and trustworthiness of online transactions. It achieves this primarily by ensuring balanced transparency and full accountability, a critical aspect that directly tackles our primary challenge of effectively managing access rights. This innovative system not only grants users access to information based on their authorization levels but also could serve as a secondary identifier to boost security protocols. The importance of such features is increasingly recognized in preventing fraud. Additionally, this system enables foreign investors, who may not have direct insights into local properties, to actively participate in the market, thereby significantly enhancing the global accessibility of the real estate market. Ultimately, Use Case 2 validates and evaluates GREP's ability to efficiently manage access rights while maintaining a necessary balance between decentralization, privacy, and accountability, demonstrating the transformative potential of hybrid blockchain in the real estate industry.

Use Case 3: In Use Case 3, we effectively demonstrated role-based access control within GREP, specifically highlighting the super admin's ability to promote and demote user roles. Initially, a regular user, identified by an address ending in 'F08bb,' was promoted to an admin role. This promotion enabled access to specific functions like 'getBasicKey' and 'getDetailKey', which were previously inaccessible. The successful transition and newly granted access were clearly demonstrated, as shown in Table 5.6. Further, when this user, now an admin, called 'getBasicKey' for property '75329', the system correctly returned the basic key '222', as depicted in Table 5.7. Continuing the experiment, we demoted this user back to regular status and attempted to access the 'getBasicKey' function again. As expected, the system effectively prevented the now regular user from obtaining the basic key, reinforcing the access control measures, as presented in Table 5.8.

In our analysis, which focused on evaluating the system's performance in managing user role changes, we mainly monitored performance through a series of role modification transactions. These transactions included sequences of user promotions and demotions, which were aimed at assessing the system's responsiveness during these critical operations. To gain insights into the time dynamics involved, we recorded the timestamps of each transaction. The line chart, as illustrated in Figure 5.15, indicates that both promotion and demotion transactions consistently maintained a near-constant time. This consistency suggests a high level of predictability in the system's response, which highlights its reliability in efficiently managing user role changes.

Notably, we encountered a challenge due to testnet faucet limitations. Previously accessible test networks that used to offer up to 100 ETH were no longer available, leading us to a faucet that provided only 0.5 ETH every 24 hours. While this limitation did not substantially slow our progress, it imposed a sense of caution and consideration with each transaction we conducted.

In Use Case 3, the effective management of user permissions is crucial in addressing both key challenges: managing access rights and ensuring data authenticity. This strategic approach is vital in preventing unauthorized access and ensuring the authenticity of real estate provenance information, as a result encouraging confidence in the system's capabilities. Building on the advancements demonstrated in Use Case 2, Use Case 3 validates and evaluates GREP's ability to enforce secure role-based permissions. These combined efforts verify GREP's flexibility, resilience, and operational efficiency in property provenance management.

5.6 Conclusion

In conclusion, this chapter introduces GREP, a hybrid blockchain framework that provides a comprehensive foundation for real estate provenance and ownership certification while maintaining a balance between decentralization, privacy, and accountability. This chapter addressed GREP and real estate provenance with a focus on four key dimensions: managing access rights, managing provenance entry, retrieving provenance data, and updating provenance data. Through a structured approach, we examined the implementation, validation, and evaluation of these functionalities using various tools and metrics, which collectively demonstrate the effectiveness of GREP in real estate provenance management, which aligns with Objective 1 and contributes to Objective 4.

The next chapter explains the conceptual model and implementation of NFTs within GREP as a reliable method for real estate ownership certification, aligned with Objective 2. Additionally, this chapter includes the validation and the evaluation of this objective, contributing to Objective 4.

CHAPTER 6

GREP and Real Estate Ownership Certification

6.1 Introduction

The process of issuing and verifying real estate ownership certification is complex yet crucial, as it involves several parties and ensures that property rights are clear and undisputed (Wolniak et al., 2020; Abdullah et al., 2011). Nowadays, modern technology, including artificial intelligence, machine learning algorithms, and big data, offers an unprecedented opportunity to simplify the complexities and transform the landscape of traditional real estate transactions (Wei et al., 2022; Oluwatofunmi et al., 2021; Pai and Wang, 2020). These tools introduce a level of speed, accuracy, and transparency previously considered beyond reach. Despite the promising potential of these technological advancements, the process of issuing and verifying real estate ownership faces numerous challenges.

These challenges arise from the inherent limitations of traditional methods. The traditional processes are severely hindered by inefficiencies, where complex and time-consuming practices result in significant delays in both issuing new ownership titles and verifying existing ones (Wouda and Opdenakker, 2019; Seger and Pfnür, 2021). Moreover, security vulnerabilities in the ownership records further exacerbate these challenges, as they invite fraud and unauthorized alterations (Shehu et al., 2022), shaking the foundation of trust in property rights. These vulnerabilities compromise the integrity of ownership records, posing a substantial risk to the stability of property markets.

Another challenge in this field is the lack of transparency in ownership history, which hinders the ability of buyers, sellers, and legal entities to access comprehensive and precise information. This opacity often leads to potential disputes and erodes trust among stakeholders (Bidabad et al., 2017; Ortega-Rodríguez et al., 2020), thereby complicating the verification process. Additionally, the cost variability and uncertainty associated with ownership authentication not only affect the direct and unstable expenses related to legal, registration, administrative fees, and other intermediaries but also extend to encompass the broader financial implications of a lengthy process. This includes the indirect costs stemming from the consumption of time and resources (Collett et al., 2003), which can significantly fluctuate and contribute to the overall unpredictability of the process. Tackling these challenges necessitates the implementation of an advanced technological approach to develop a reliable method for proving and verifying real estate ownership that is more efficient, secure, and transparent. As shown in Figure 6.1, blockchain technology has the potential to revolutionize the real estate sector by providing a decentralized and secure ledger for recording transactions (Shuaib et al., 2021; Yli-Huumo et al., 2016). This innovation can significantly streamline the verification process, thereby addressing the inefficiency in ownership verification by reducing time and complexity

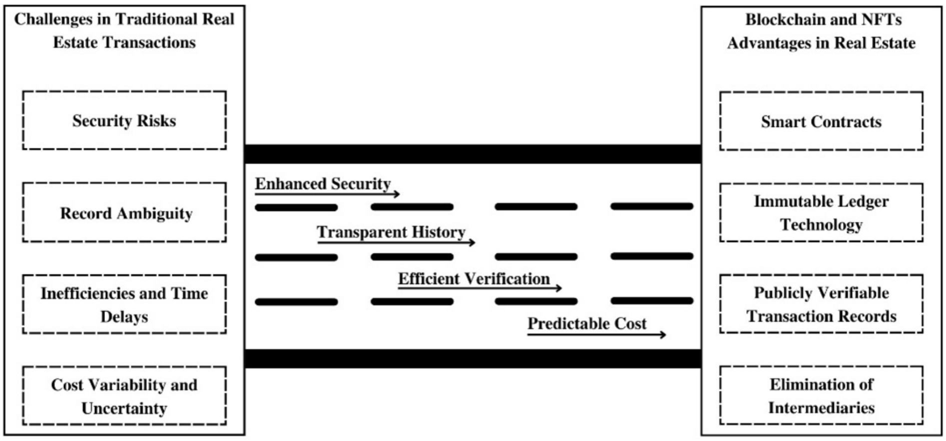

Figure 6.1: Potential solutions to traditional real estate challenges through blockchain and NFTs advantages

involved (Yang, 2022; LiBin et al., 2021). By utilizing NFTs within the blockchain framework, security vulnerabilities in ownership records can be mitigated (AlKhader et al., 2023), as NFTs provide a unique and immutable proof of ownership (Hasan et al., 2022; Saeidnia and Lund, 2023; Bamakan et al., 2021), which improves the security and integrity of property rights. Furthermore, blockchain technology inherently promotes transparency (Babaei et al., 2023), offering a clear and accessible history of ownership transactions (Brau et al., 2024). This capability can effectively overcome the challenges of a lack of transparency in ownership history, ensuring that stakeholders have access to complete and accurate information.

Taking advantage of the aforementioned benefits of blockchain technology and NFTs, we introduce another functionality of GREP that employs NFTs to establish a reliable, secure, and tamper-proof ownership certification framework. The hybrid nature of GREP combines the decentralized security and transparency advantages of blockchain with the regulatory and trust-enhancing capabilities of governmental control. The rationale for a government-regulated hybrid model stems from the essential need for accountability and enhancing public trust in the verification process. Moreover, government involvement serves as a strategic response to the significant economic interests that governments have in the real estate sector (Higgins, 2023), in addition to their ability to ensure regulatory compliance and stability.

This chapter makes the following contributions:

- Advancing Objective 2 by developing a reliable method for proving real estate ownership within GREP using NFTs, which ensure secure, transparent, and immutable property certification.
- Implementing a blockchain-based system for proving real estate ownership, along with its validation and evaluation, which contribute to Objective 4.
- Developing key algorithms for NFT-based certification within GREP's certification framework, which defines the processes of adding an owner to property history, minting NFTs for property ownership, and verifying the current NFT owner.
- Addressing key sector challenges, which include inefficiencies, security vulnerabilities, lack of transparency, and cost variability in ownership certification.
- Providing a quantitative analysis of the newly introduced GREP functionality, which examines cost efficiency and processing time in real estate ownership certification issuance.

This chapter is organised as follows: In Section 6.2, we discuss the benefits of NFTs for real estate provenance, highlighting their role in enhancing ownership verification and transaction efficiency. Section 6.3 explores the conceptual foundations for developing a reliable real estate ownership method, including the

ERC-721 standard and its improvements as applied in GREP. Section 6.4 introduces the key algorithms for generating NFTs within GREP's certification framework, detailing the processes of adding an owner to property history, minting NFTs for property ownership, and verifying the current NFT owner. Section 6.5 presents the implementation process, covering the development tools and ownership validation workflow used in GREP. Section 6.6 evaluates the system's performance, focusing on transaction costs and the time required to issue ownership proof. These indicators provide insight into the system's efficiency and practical viability. Finally, Section 6.7 concludes the chapter by summarizing our findings and transitioning to the next objective of shared ownership verification within GREP.

6.2 Benefits of NFTs for Real Estate Provenance

The adoption of NFTs in real estate represents a significant innovation in property provenance and transaction management. NFTs function as digital certificates of ownership, leveraging blockchain technology to provide secure, transparent, and immutable verification of property rights. This transformative approach addresses key inefficiencies and vulnerabilities inherent in traditional real estate transactions (Bhambri, 2024). As the NFT market continues to evolve, its role in real estate is expected to expand, unlocking new investment opportunities and ownership models previously unattainable (Dume, 2023).

Table 6.1 outlines how NFTs address key challenges in real estate provenance by ensuring the security, transparency, and traceability of property records.

Table 6.1: How NFTs address challenges in real estate provenance

Challenge	**How NFTs Enhance Provenance Management**
Inaccurate or incomplete provenance records	Traditional record-keeping systems may contain inaccurate, incomplete, or conflicting property history. NFTs enable the secure storage and retrieval of immutable provenance records on a blockchain, ensuring accuracy and consistency in property data.
Risk of record tampering	Paper-based records can be altered, forged, or lost, and centralized databases are vulnerable to cyber-attacks. NFTs create a tamper-proof, cryptographically secured history of property transactions, preventing unauthorized modifications.
Limited traceability of ownership transfers	Property ownership changes are often fragmented across different registries, making verification difficult. NFTs enable real-time, transparent tracing of all ownership transfers on a decentralized ledger.
Unverified property history	Buyers and investors face uncertainty due to the lack of verified ownership history. NFTs provide an auditable, publicly accessible record of all previous transactions, reducing disputes and fraud.

Beyond ownership verification, NFTs unlock new models for real estate provenance, such as fractional ownership and tokenized property investment, enhancing market accessibility and liquidity (Serrano, 2022; Abualhamayl et al., 2023).

6.3 Conceptual Foundations for Developing a Reliable Real Estate Ownership Method

To effectively implement GREP's certification mechanism, we need to adopt Ethereum standards as the foundation for our solution. We have chosen the ERC-721 standard as our primary framework since it aligns with GREP's goal of providing a secure and verifiable ownership certification system. In the following subsections, we first outline the original ERC-721 standard, including its functions and events. This is followed by the introduction of the enhanced ERC-721 standard, which has been tailored specifically to meet the unique requirements of real estate ownership and property management within GREP. Finally, we discuss the conceptual solution overview, which ensures a reliable and secure method for proving real estate ownership.

6.3.1 Original ERC-721 standard

The Ethereum blockchain supports the creation of NFTs through specific token standards, known as Ethereum Request for Comments (ERC) standards. These standards define how NFTs can be created, managed, and transferred on the Ethereum network, ensuring interoperability and functionality across various platforms and applications. There are several token standards, including fungible standards like ERC-20, which enable the creation of tokens that are interchangeable and identical, and non-fungible standards such as ERC-1155 and ERC-721, which allow the creation of unique and indivisible digital assets, suitable for showcasing distinctive items such as digital artworks, rare collectibles, and virtual properties.

The ERC-721 standard allows for the creation of unique identifiers for each token, ensuring that no two tokens are the same (Nam and Kil, 2022), and the tokens are transferable (Cabot-Nadal et al., 2022). This standard guarantees both the uniqueness of each real estate asset and the immutability of records while allowing mobility. Consequently, we adopt the ERC-721 as a foundational standard for our development in Objective 2.

Figure 6.2 shows the original functions and events within the ERC-721 standard, as proposed in (Entriken et al., 2018), that enable the secure management and transfer of unique assets.

ERC-721

```
event Transfer(address indexed _from, address indexed _to, uint256 indexed _tokenId);
event Approval(address indexed _owner, address indexed _approved, uint256 indexed _tokenId);
event ApprovalForAll(address indexed _owner, address indexed _operator, bool _approved);

function balanceOf(address _owner);
function ownerOf(uint256 _tokenId);
function safeTransferFrom(address _from, address _to, uint256 _tokenId, bytes data);
function safeTransferFrom(address _from, address _to, uint256 _tokenId);
function transferFrom(address _from, address _to, uint256 _tokenId);
function approve(address _approved, uint256 _tokenId);
function setApprovalForAll(address _operator, bool _approved);
function getApproved(uint256 _tokenId);
function isApprovedForAll(address _owner, address _operator);
```

Figure 6.2: ERC-721 standard functions and events

6.3.2 Improved ERC-721 standard for real estate ownership certification

The improved ERC-721 standard builds upon the original ERC-721. While the original ERC-721 standard provides the foundational functions for managing and transferring NFTs, this improved version introduces additional features specifically tailored for real estate applications. The enhancements in the improved standard focus on providing more robust support for provenance tracking, ownership history, and secure token minting.

The improved ERC-721 standard introduces the following new event and functions:

ProvenanceAdded

This event logs the addition of an ownership record for a property, including information such as the owner's name, provider, property location, and other key attributes. It plays a crucial role in maintaining a transparent and immutable property history on the blockchain.

addOwner

This function adds a new owner to the property history, generating a unique token ID for the owner and recording details such as the owner's name, property location, and association date. It also triggers the ProvenanceAdded event to log the ownership change.

mintNFTForLastOwner

This function mints an NFT for the most recent owner of a property, linking the ownership record to the NFT and associating it with a URI for metadata storage.

getCurrentOwnerAddress

This function retrieves the address of the current owner of a property, simplifying the process of verifying the current ownership status of the property.

Figure 6.3 illustrates the functions and events of the improved ERC-721 standard. These additions align with the objective of developing a reliable method to prove ownership and manage real estate provenance effectively.

Improved ERC-721 standard

```
event ProvenanceAdded( uint256 indexed propertyId, string ownerName, string providerName,
        string ownerType, string propertyLocation, string cityAndState, string associationDate,
        uint basicKey, uint detailedKey, address ownerAddress, uint256 tokenId);
event Transfer(address indexed _from, address indexed _to, uint256 indexed _tokenId);
event Approval(address indexed _owner, address indexed _approved, uint256 indexed _tokenId);
event ApprovalForAll(address indexed _owner, address indexed _operator, bool _approved);

function addOwner(uint256 propertyId, string memory ownerName, string memory providerName,
          string memory ownerType, string memory propertyLocation, string memory cityAndState,
          string memory associationDate, uint basicKey, uint detailedKey, address ownerAddress);
function mintNFTForLastOwner(uint256 propertyId, string memory tokenURI);
function getCurrentOwnerAddress(uint256 propertyId)
function balanceOf(address _owner);
function ownerOf(uint256 _tokenId);
function safeTransferFrom(address _from, address _to, uint256 _tokenId, bytes data);
function safeTransferFrom(address _from, address _to, uint256 _tokenId);
function transferFrom(address _from, address _to, uint256 _tokenId);
function approve(address _approved, uint256 _tokenId);
function setApprovalForAll(address _operator, bool _approved);
function getApproved(uint256 _tokenId);
function isApprovedForAll(address _owner, address _operator);
```

Figure 6.3: Functions and events of the improved ERC-721 standard - improved (in green) and original (in blue)

6.3.3 Conceptual solution overview

In response to the challenges outlined in Table 6.1, which collectively contribute to Objective 2, we propose the integration of GREP with NFTs as a certification mechanism for real estate ownership. This newly introduced functionality within GREP leverages blockchain technology to streamline and automate the verification processes, thereby reducing time and complexity. The security vulnerabilities in ownership records are mitigated through the use of blockchain's immutable ledger, further enhanced by the hybrid model's integration of government oversight, which adds an additional layer of credibility and trust. NFTs play a crucial role in securely representing property ownership, ensuring each record is unique and tamper-evident, thereby safeguarding against cyber-attacks. The lack of transparency in ownership history is addressed by the blockchain's transparent nature, with government control ensuring that the system operates within the regulatory frameworks and standards. Finally, the cost variability and uncertainty traditionally associated with methods of ownership verification are directly addressed in our hybrid blockchain environment. Our approach stabilizes verification costs by eliminating the need for intermediaries and their associated excessive fees. Additionally, the system's design, which does not require miners and allows for a fixed gas price, enhances cost stability. These improvements make the overall cost of transactions more predictable and the real estate verification process more accessible and efficient. By tackling these challenges, our solution provides a verifiable and reliable proof of ownership.

To explain our conceptual solution, we present Figure 6.4, which offers a visual representation of our proposed system. For clarity, the system is divided into two sections: **external components** and **internal components**.

External components: The external components encompass entities that interact with the system from an external standpoint. These include: *Owner.* An individual or entity that holds property rights and seeks to authenticate and verify their ownership through the system. *Prospective entity.* This term encompasses a wide array of stakeholders, including potential buyers, insurance firms, real estate agents, and financial institutions. Each has a vested interest in confirming ownership for various reasons.

It is worth mentioning that while our current focus is on the externals associated with ownership verification, our system has the ability to accommodate a broader range of externals in the future. This includes buyers, sellers, and other key participants in the real estate market.

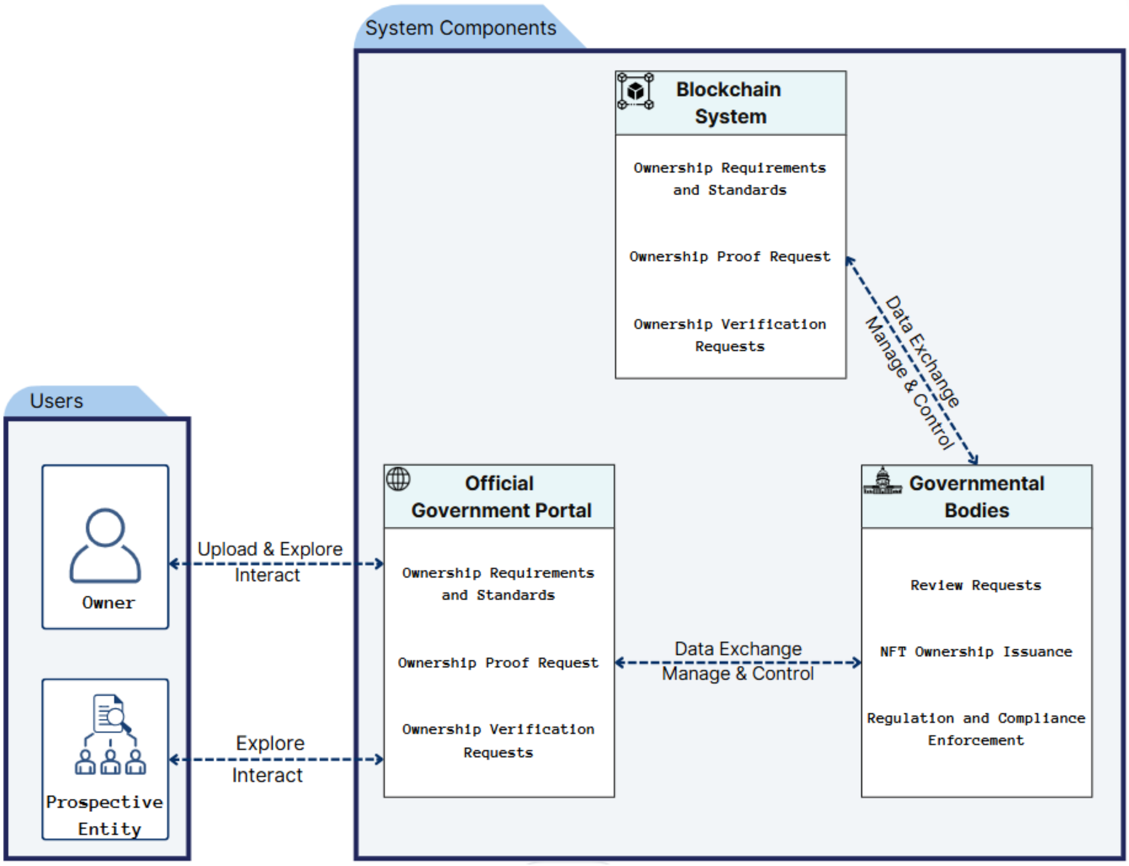

Figure 6.4: System architecture for real estate ownership verification

Internal components: Different from the external components, the internal components category encompasses entities and infrastructures that form the backbone of the system. These integral elements directly enable and manage its operations, ensuring the system's functionality, security, and reliability. They encompass: *Official government portal.* Serving as the main interface between external entities and the system's core functionalities, the official government portal allows external users to submit documents and inquire about ownership. Moreover, it enables each country to set the requirements and standards they consider necessary. *Governmental bodies.* Tasked with a critical oversight role, they enforce regulatory standards, examine submissions for accuracy and compliance before any transaction is recorded on the blockchain system, and, upon validation, authorize the issuance of NFTs as digital proofs of ownership. *Blockchain system.* The core of our solution, the hybrid blockchain system implemented in GREP, accessible exclusively by government administrators, plays a central role in recording all transactions and ownership details. Notably, we opt to record the ownership data on-chain, a strategic decision aiming to maximize security and fraud resistance. This approach contrasts with off-chain methods, which, while potentially offering benefits in scalability and speed, are not governed by the inherent security mechanisms of blockchain technology and thus could be at greater risk. Additionally, the system issues NFTs as a secure and fraud-resistant proof of ownership and maintains a transparent ledger for verification purposes.

Recognizing the safety mechanisms inherent in our solution, it is essential to understand that even if the government web portal is compromised, the system's reliability remains unshaken from two critical perspectives. On one side, the ownership transactions recorded on the blockchain are immune to theft, alteration, or tampering. On the other side, for users, the NFT steadfastly serves as irrefutable proof of ownership. This resilience highlights how GREP ensures the security, reliability, and immutability of real estate ownership certification.

6.4 Algorithms for Generating NFTs in Real Estate Certification

To ensure secure and verifiable ownership certification within GREP, we propose a series of algorithms that define the key steps involved. These algorithms establish a structured approach for recording ownership on the blockchain, minting property-linked NFTs as proof of ownership, and verifying ownership to prevent fraudulent transactions. By leveraging blockchain's immutability and transparency, these algorithms enhance the efficiency and trustworthiness of real estate ownership certification under GREP.

6.4.1 Algorithm for adding an owner to property history

Algorithm 6.1 outlines the steps for securely adding an owner to the property history. This process is essential for establishing ownership provenance records by leveraging blockchain technology, which supports secure record-keeping and improves data traceability. By maintaining an authenticated ownership history, this step strengthens GREP's certification mechanism, ensuring secure and fraud-resistant transactions.

As part of this process, the algorithm generates a unique token ID by combining the Property ID with a sequence number, ensuring distinct ownership records. This token ID is fundamental for verifying and managing ownership, serving as a core component of NFT-based property certification, which contributes to the solution for Objective 2.

Algorithm 6.1: Add Owner to Property History

Inputs:

- **propertyId:** The unique ID of the property.
- **owner details:** (name, provider, owner type, location, city and state, association date, keys).
- **ownerAddress:** The blockchain address of the new owner.

Output:

- **Updated ownership history:** The owner is added to the property history with a unique token ID.
- **ProvenanceAdded event emitted:** Logs the addition of the owner to the blockchain.

Procedure:

sequence ← *propertyToNextTokenId[propertyId]++*
tokenId ← *propertyId * 1000 + sequence*
newOwner ← *creates Owner structure with input details and tokenId*
Insert *newOwner* **to** *propertyHistory[propertyId]*
Emit ProvenanceAdded(propertyId, owner details, tokenId)

The procedure for adding an owner to the property history involves several key steps, including:

Retrieve Next Available Token ID: The process begins by fetching the next available token ID for the specific property using `propertyToNextTokenId[propertyId]`, which keeps track of the token sequence for each property. The sequence is incremented to generate the next token ID.

Generate Unique Token ID: A unique token ID is then generated by combining the Property ID with the sequence number, following Equation 6.1, ensuring that each token ID remains unique.

$$\text{tokenId} \leftarrow \text{propertyId} \times 1000 + \text{sequence} \tag{6.1}$$

Create New Owner Structure: The new owner's information, including their name, property details, and the generated token ID, is used to create a new owner structure.

Insert Owner to Property History: This new owner structure is then appended to the property's ownership history, ensuring that the ownership chain is securely stored on the blockchain.

Emit ProvenanceAdded Event: Finally, the `ProvenanceAdded` event is emitted to log the addition of the ownership record on the blockchain. This event plays a critical role in maintaining the transparency and immutability of the ownership records.

6.4.2 Algorithm for minting an NFT for property ownership

Algorithm 6.2 details the process of minting an NFT for the most recent owner of a real estate property within GREP. Once the ownership history is established, the algorithm ensures that the most current owner is represented on the blockchain through the minting of a unique NFT. This step verifies the ownership status, generates a digital asset associated with the property, and assigns it a metadata reference (tokenURI) for linking additional metadata to the property.

By securely minting NFTs for property owners, this process directly supports Objective 2, which is to provide a trustworthy and reliable method for ownership certification.

Algorithm 6.2: Mint NFT for Last Owner

Inputs:

- **propertyId:** The unique ID of the property.
- **tokenURI:** Metadata link associated with the NFT.

Output:

- Minted NFT for the last owner.
- Updated token URI associated with the NFT.

Procedure:

If propertyHistory[*propertyId*].*length* == **0**;
{
Return "Error: Property has no owners."
}
Retrieve lastOwner ← last entry in propertyHistory[propertyId]
Mint NFT to *lastOwner.ownerAddress* **with** *lastOwner.tokenId*
Set the token URI for *lastOwner.tokenId* **using** *tokenURI*

The procedure for minting an NFT for the last owner involves several key steps, including:

Check if the Property has Owners: The process begins by verifying whether the property has any recorded owners by checking the length of the `propertyHistory[propertyId]` array. If no owners exist, the algorithm returns an error message indicating, *"Property has no owners."* This ensures that an NFT is only minted for properties with an established ownership history.

Retrieve Last Owner Information: If the property has owners, the algorithm retrieves the most recent (last) owner from the `propertyHistory` array. The last owner represents the current holder of the property, and their details are crucial for the next steps.

Mint NFT for the Last Owner: The NFT is minted for the last owner using their wallet address (`lastOwner.ownerAddress`) and the unique token ID (`lastOwner.tokenId`). This step uses the `_safeMint()` function to securely mint the NFT, linking it to the owner's blockchain address.

Set Token URI for Metadata: After minting the NFT, the final step involves associating the token with metadata. The algorithm sets the `tokenURI` for the `lastOwner.tokenId`, which links the NFT to additional descriptive data about the property.

6.4.3 Algorithm for verifying the current NFT owner

Although we achieved the core of Objective 2 in Algorithm 6.2, which focuses on minting NFTs to represent property ownership, it is also crucial to ensure that the current holder of the NFT is indeed the rightful and most recent owner. Algorithm 6.3 addresses this concern by providing a method to verify that the individual holding the NFT is actually the last owner of the property within the GREP framework. This procedure is essential in preventing situations where a previous owner may attempt to sell the property again, thereby avoiding double selling or fraudulent transactions. By verifying ownership through this process, we add an additional layer of security to our system.

Algorithm 6.3: Retrieve Current Owner

Inputs:
- **propertyId:** The unique ID of the property.

Output:
- **ownerAddress** : The blockchain address of the current (most recent) owner of the property.

Procedure:

If propertyHistory[*propertyId*].*length* == **0**;
{
Return "Error: Property has no owners."
}
currentOwner ← last entry in propertyHistory[*propertyId*]
Return *currentOwner.ownerAddress*

The procedure for retrieving the current owner of the property involves several steps, including:

Check for Ownership Records: The process begins by checking if the property has any recorded ownership history. If the `propertyHistory` array for the given Property ID is empty, the system returns an error, indicating that there are no owners associated with the property.

Retrieve the Most Recent Owner: If ownership history exists, the algorithm retrieves the last entry from the property's ownership history, representing the most recent owner.

Return Owner's Address: Finally, the blockchain address of the most recent owner is returned, which serves as a verifiable link to the current legitimate owner. This step ensures that the rightful owner is recognized and helps prevent fraudulent activities such as double selling or ownership disputes.

Before proceeding with implementation, it is useful to recall that the entire process of NFT ownership issuance requires the owner to have a digital wallet, such as MetaMask, to receive and manage their property NFTs. This wallet acts as a secure repository for the digital asset representing their real estate ownership. The process for obtaining the NFT is illustrated in Figure 4.5.

6.5 Implementation

6.5.1 Development tools and blockchain environment

To support the implementation and evaluation of GREP's real estate ownership certification, we conducted experiments on a system running a 64-bit version of the Windows operating system. This configuration included a 13th Generation Intel® Core™ i9-13900H CPU and was supported by 32 gigabytes of RAM.

In the construction of this system, we employed a variety of tools to facilitate the development process. The primary environment for the development and preliminary testing of our smart contracts was the Remix - Ethereum IDE, specifically version v0.44.0. This integrated development environment enabled us to code, compile, and deploy our smart contracts effectively. Our smart contract was constructed using Solidity, employing the improved ERC-721 standard to mint NFTs, which distinctively represents real estate ownership on the Ethereum blockchain. Furthermore, to execute our transactions, we integrated our environment with MetaMask, serving as the injected provider. Within MetaMask, we established ten accounts, one of which was designated as the government account, holding control over the entire system as designed. This account was funded with Ethereum from the Sepolia faucet, enabling it to conduct transactions effectively. This approach ensured that we could simulate real-world transaction processes within a controlled environment.

6.5.2 Real estate ownership validation workflow

In this part, we detail the essential processes that form GREP's blockchain-based certification framework to authenticate real estate ownership. This workflow is structured around three key operations: blockchain owner addition, where we integrate new owners into the blockchain; NFT minting as a digital proof of ownership, which generates an NFT as a secure and enduring record of ownership; and the ownership validation process, where we confirm the legitimacy of ownership claims. The integration of these operations collectively forms our ownership validation process.

Blockchain ownership addition

We initiate this process by strategically creating ten accounts within MetaMask, nine of which are designated to represent the wallet addresses of various property owners, and one which is exclusively reserved for government operations. This government account is granted unique privileges, enabling it to deploy the smart contract, add owner information to the blockchain, and mint NFTs. Given that these transactions require a fee, the government account is funded with Ethereum from the Sepolia faucet.

After preparing our dataset, we utilized its real-world data to execute nine transactions from the government account on the blockchain to the nine owner accounts in MetaMask. In this phase, each transaction, referred to as "Add Owner", incorporates essential data such as Property ID, owner name, ownership type, property location, and association date. These transactions reflect the process of transferring ownership information onto our blockchain system. Table 6.2 offers a detailed view of these transactions, confirming the effective execution of the initial phase of our hybrid blockchain solution.

NFT minting as a digital proof of ownership

The minting process is a crucial step in GREP's real estate ownership certification framework. It begins after an "Add Owner" transaction has been added to the blockchain by the government account. During this phase, this administrative account inputs the Property ID and initiates the "Mint NFT For Last Owner" operation. The smart contract then creates a new NFT and assigns it to the most recent property owner who was added to the blockchain using the "Add Owner" function. This NFT acts as a digital proof of ownership for a specific real estate asset. Table 6.3 illustrates the detailed transactions involved in minting the NFT for the latest property owner on the blockchain.

It is worth mentioning that the timestamps for each 'Mint NFT for Last Owner' transaction in Table 6.3 also encompass the time taken for the respective 'Add Owner' transaction. This indicates that the reported durations reflect both the addition of owners and the creation of their NFTs.

Table 6.2: Transaction details for the Add Owner" operation

Transaction Type	Property ID	Transaction Hash	Transaction Cost (Gas)	Timestamp
Contract Creation	N/A	0x0d9d531c2e1d26850b95 1abc37661e17	377645	Feb-18-2024 08:34:00 PM
Add Owner (1st)	753239	b3e8b33b7b5f9b10ec99 638a4bf9aae2	312693	Feb-18-2024 08:36:00 PM
Add Owner (2nd)	395502	f3d6938d9aae9d793549 53b4fa1eaeee	312741	Feb-18-2024 08:39:00 PM
Add Owner (3rd)	265711	c7b79b6ab962a16d18e5 1a355e55b	335045	Feb-18-2024 08:43:00 PM
Add Owner (4th)	753239	ed36c5277341231728d4 10a430b5fda	278445	Feb-18-2024 08:45:00 PM
Add Owner (5th)	395502	x090ae3c734ff5768eff 863c05e3493862	278541	Feb-18-2024 08:48:00 PM
Add Owner (6th)	265711	f3dc34d06c59bab1b69 2beba19d357e90	300917	Feb-18-2024 08:51:00 PM
Add Owner (7th)	753239	x58730623e90ee2o2666 2c1d54cb9899a	300857	Feb-18-2024 08:53:00 PM
Add Owner (8th)	395502	x590f705e1ca054620a0 d266055fe13d2	278457	Feb-18-2024 08:56:00 PM
Add Owner (9th)	265711	x0233e696d5c606151b6 9626920ba03e6	278541	Feb-18-2024 08:58:00 PM

Table 6.3: Transaction details for the Mint NFT for Last Owner" operation

Transaction Type	Property ID	Transaction Hash	Transaction Cost (Gas)	Timestamp (UTC)
Mint NFT For Last Owner (1st)	75329	0x2444827dae682221 beeba6ddc03bce44b	171045	Feb-18-2024 08:37:00 PM
Mint NFT For Last Owner (2nd)	395502	0x52d529036dd44f4c add65e4e3a8503ae	171045	Feb-18-2024 08:40:00 PM
Mint NFT For Last Owner (3rd)	265711	0x71c7452f41a0f972 7af5123822341534	171035	Feb-18-2024 08:42:00 PM
Mint NFT For Last Owner (4th)	75329	0xd500a7c48970ae3d e94879e48077c43	171045	Feb-18-2024 08:44:00 PM
Mint NFT For Last Owner (5th)	395502	0x068181c53c1a2feb 961a43c260b9f7580	171045	Feb-18-2024 08:46:00 PM
Mint NFT For Last Owner (6th)	265711	0xe089bb4667ec1f18 a3a79eb0f940	171045	Feb-18-2024 08:51:00 PM
Mint NFT For Last Owner (7th)	75329	0xacc58b2a6034b1fb e99e2e4f5a396ed1	171045	Feb-18-2024 08:54:00 PM
Mint NFT For Last Owner (8th)	395502	0x9787320e6634f5da cf853a54b2530	171045	Feb-18-2024 08:56:00 PM
Mint NFT For Last Owner (9th)	265711	0x21cc2fc7f01b40a0 ee76e954a750a3	171035	Feb-18-2024 08:59:00 PM

Ownership validation process

The final and crucial phase in this process is the ownership validation process. This process is designed to confirm the authenticity of property ownership recorded by our system. Following successful "Add Owner" and "Mint NFT For Last Owner" operations, ownership validation can be conducted using one of two methods:

Validation via Transaction Hash: Ownership can be verified by utilizing the unique transaction hash. These hashes are detailed in Table 6.3 and can be used on the Sepolia Testnet via Etherscan to verify the ownership of the NFT. Figure 6.5 shows an example of a minted NFT for the 9th owner, verified using the transaction hash on the Sepolia Testnet Explorer through Etherscan.

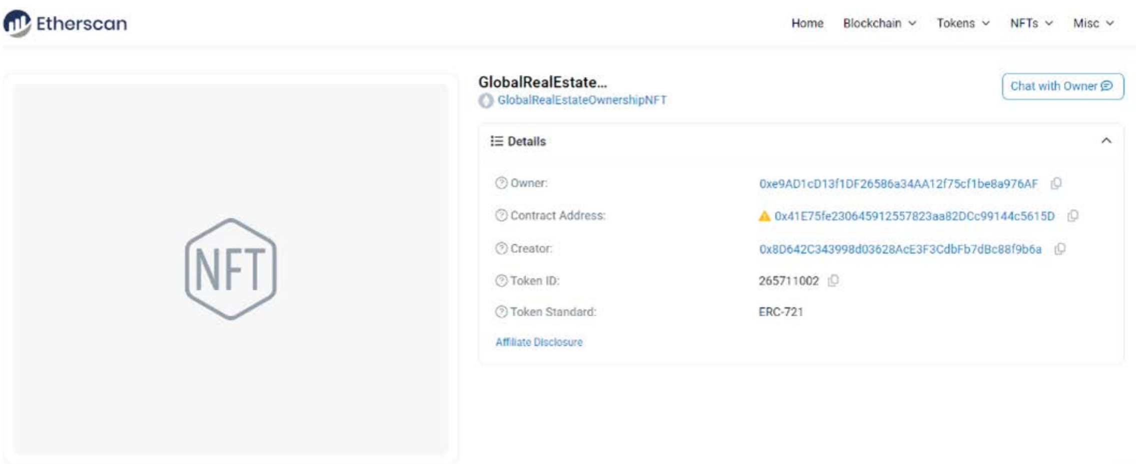

Figure 6.5: An example of validation via transaction hash

Validation via the Token ID: Ownership verification can alternatively be carried out using the token ID in our system. The token ID is a unique numerical identifier assigned to each NFT, encapsulating the ownership information of a specific property. Unlike relying solely on the Property ID, which is unique to each property, our system employs a special formula to generate a distinct token ID for each instance of ownership. This ensures that every change in ownership for a property is uniquely recorded. As shown in Equation 6.1, the token ID is generated by combining the Property ID and the ownership sequence number, reflecting the chronological order of ownership for the property.

Table 6.4 illustrates the unique token IDs generated for the first three ownership instances of various properties, as described in Equation 6.1.

Table 6.4: Illustration of token ID creation across various properties for initial owners

Property ID	**Ownership Order**	**Token ID**
75329	1st owner	75329000
395502	1st owner	395502000
265711	1st owner	265711000
75329	2nd owner	75329001
395502	2nd owner	395502001
265711	2nd owner	265711001
75329	3rd owner	75329002
395502	3rd owner	395502002
265711	3rd owner	265711002

For the validation process, our platform enables direct verification of token IDs. For instance, consider the verification of token ID 265711002, as depicted in Table 6.4. Any user can access our verification system to input this specific token ID. Upon submission, the system retrieves and displays the associated ownership address, which is also presented in Figure 6.6. This figure illustrates the owner of token ID 265711002, along with their wallet address, confirming the information shown in Figure 6.5.

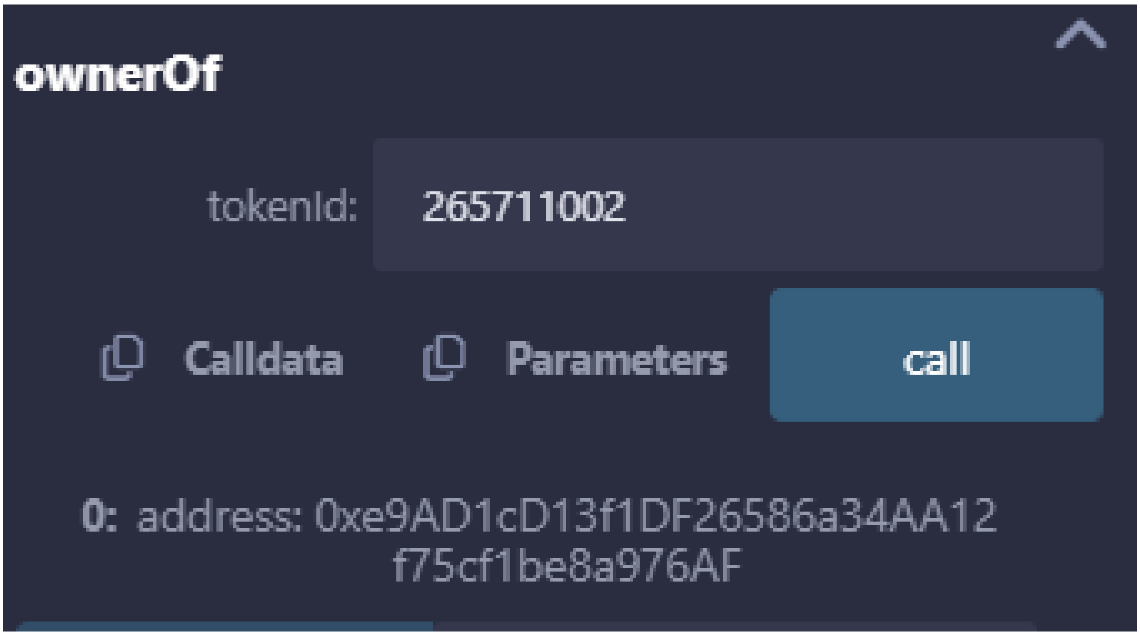

Figure 6.6: Querying token ID 265711002 in our system reveals the owner's address '0xe9AD1cD13f1DF26586a34AA12f75cf1be8a976AF', matching the address shown in Figure 6.5

It is crucial to emphasize that users are responsible for conducting thorough investigations to acquire a deep knowledge of a property's ownership. This includes reviewing NFT metadata and transaction history. As a step forward in enhancing our system's usability, we introduced the `getCurrentOwnerAddress` function. This function simplifies the process of checking current ownership, allowing users to verify the latest owner's address by simply entering the Property ID, as illustrated in Figure 6.7.

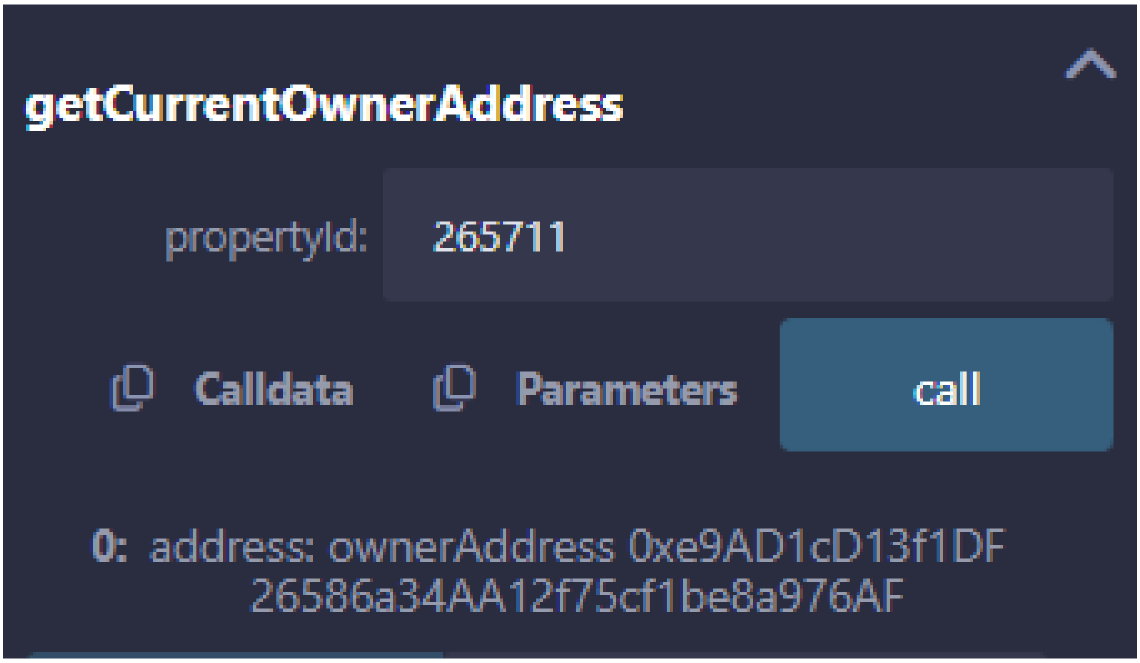

Figure 6.7: Demonstrating the 'getCurrentOwnerAddress' function to verify ownership by Property ID

Through these practical implementations, from setting up our development environment to integrating real-world data and testing our hybrid blockchain solution, we conducted a verification of the system to ensure it met our expectations. Although our results confirm the system's effectiveness at a functional level, more critically, they address two significant challenges: the security vulnerabilities in ownership records, mitigated by issuing tamper-proof NFT ownership proof, and the lack of transparency in ownership history, tackled by providing a verification system that any user can access and utilize the token ID to verify ownership. These developments significantly contribute to our goal of developing a reliable method for proving and verifying real estate ownership.

6.6 Evaluation and Discussion

This section evaluates the performance of GREP's real estate ownership certification framework. Our analysis focuses on two essential metrics: transaction cost and time required to issue ownership proof. These indicators are pivotal for understanding the system's effectiveness and suitability for practical real-world scenarios.

6.6.1 Transaction cost

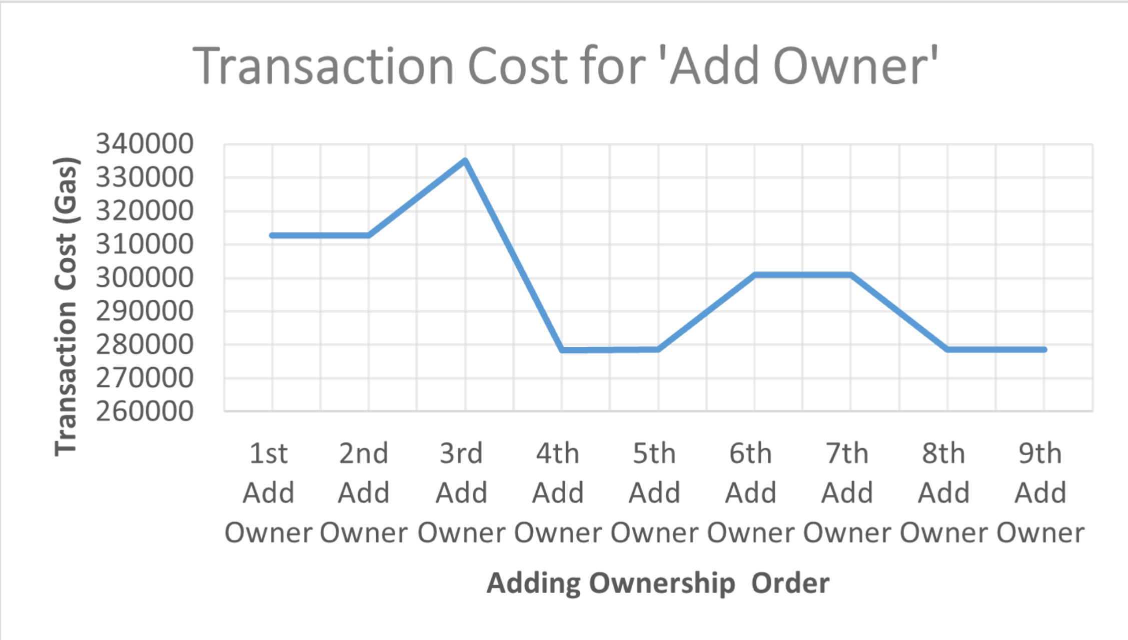

Figure 6.8: Transaction costs (in gas) for nine 'Add Owner' operations

In evaluating our blockchain solution's practicality, we examine the transaction costs related to the 'Add Owner' operations, as shown in Figure 6.8. These costs, measured in gas—which is the internal pricing for executing transactions on Ethereum—show a variation from a low of 278,445 to a high of 335,045. To translate these gas units into a more tangible measure of cost, we apply the formula for converting gas to ether (ETH):

$$\text{Cost}_{\text{ETH}} = \text{Gas Used} \times \text{Gas Price}_{\text{Gwei}} \times 10^{-9} \tag{6.2}$$

Based on the historical average gas price of 23.89 Gwei, derived from Etherscan data between 1 September 2023 and 1 September 2024, and the average ETH to USD exchange rate of $2690.73 for the same period, we use the following formula to calculate transaction costs:

$$\text{Cost}_{\text{USD}} = \text{Cost}_{\text{ETH}} \times \text{Rate}_{ETH-USD} \tag{6.3}$$

The calculated average transaction cost for the Add Owner operations is approximately $19.11 USD, based on an average gas usage of 297,360 gas units. The transaction costs range from $17.90 USD to $21.54 USD, leading to a variation of about $3.64 USD, which reflects the fluctuation from the lowest gas usage of 278,445 to the highest gas usage of 335,045.

It is essential to acknowledge that the rates applied in our calculations are subject to variation due to the volatile nature of gas prices, which significantly influence transaction cost fluctuations. Notably, in our experiment, the elevated cost for the third 'Add Owner' operation highlights a period of peak gas usage. Conversely, the lower and more stable costs noted in subsequent transactions indicate times of reduced gas prices.

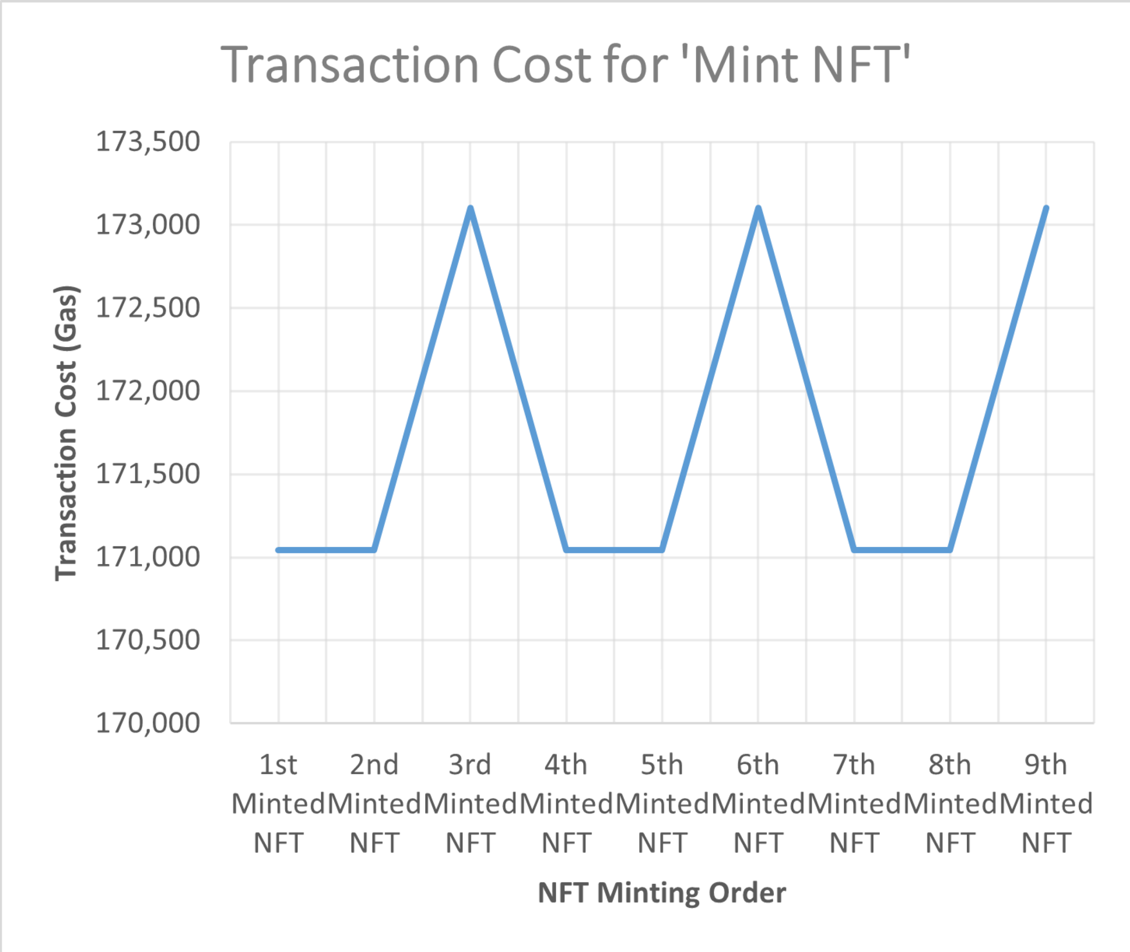

Figure 6.9: Transaction costs (in gas) for nine 'Mint NFT For Last Owner' operations

With reference to the transaction costs associated with minting NFTs, which serve as the digital proof of ownership in the real estate context and a key focus of this paper, we observe notable consistency, as shown in Figure 6.9. The transactions (denoted as T_s where s represents the sequence number of the operation) for minting NFTs are specifically grouped as (T_1, T_4, T_7), (T_2, T_5, T_8), and (T_3, T_6, T_9), exhibiting a pattern of stability. Within these groupings, each transaction represents the minting of an NFT for a new owner of the same property, showcasing our system's reliability in maintaining consistent costs across different ownership transfers.

To validate the reliability of our findings, we conducted the minting process multiple times across different periods, which consistently yielded similar results, as documented by the transaction hashes. The transaction costs, 171045 Gas for groupings (T_1, T_4, T_7) and (T_2, T_5, T_8), and a marginally increased 173105 Gas for groupings (T_3, T_6, T_9), reinforce the high level of reliability and predictability in the minting costs of NFTs.

To translate these gas units into a more tangible measure of cost, we applied the formulas for converting gas as outlined in Equation 6.2 and Equation 6.3. Based on the historical average gas price of 23.89 Gwei and the historical average exchange rate of $2690.73 USD per ETH, the results show that for the operation *Mint NFT For Last Owner*, with an average gas usage of 171,732, the calculated average transaction cost is approximately $11.04 USD. Although the difference in transaction costs, due to a variation in gas usage of 10 gas units, amounts to a very small difference of roughly $0.00064 USD more or less, our analysis suggests that the cost for each ownership transaction within the same property remains consistent, as illustrated in Figure 6.9.

Results Discussion To understand the complexity behind the cost variability and uncertainty in real estate transactions, a recent report on the Pricer website (Pow, 2024) highlights that the estimated cost for legal services can range from $50 to $200 USD. However, this fee does not represent the total payment, as there are additional fees including costs for recording, taxes on transfers, legal services, shipping or mailing fees, document drafting, mortgage settlement charges, and various other property-related legal fees. Interestingly, all these fees may fluctuate based on the property's location and value, introducing further variability and uncertainty into the overall cost. The report also estimates related fees in the transfer of ownership deeds, among them:

Attorney Fees: The cost for drafting the new deed, performing title searches, and offering legal advice ranges from \$200 to \$2000 USD, while costs specifically for deed preparation range from \$150 to \$300 USD.

Title Search Fees: A company specializing in reviewing titles examines the property records to verify the ownership history. The fees for this service can vary from approximately \$200 to \$500 USD.

Deed Type Fee: The cost for a basic deed transfer, without legal protection, ranges from \$100 to \$250 USD, while more complex deeds can incur fees of \$500 USD or more.

In comparison, in our experiment, the total cost of adding ownership to the blockchain and subsequently issuing proof of ownership in the form of an NFT is approximately \$30.15 USD, with a potential variation of about \$3.64 USD, more or less. Our solution, in these settings, eliminates the need for intermediaries such as attorneys, allows users to explore property records to verify ownership history at no cost (since the call function doesn't require any fee), and standardizes the deed type by providing a secure deed for each owner. Collectively, these factors help mitigate cost variability and uncertainty, demonstrating a significant potential enhancement in the real estate ownership system.

It is worth mentioning that our hybrid blockchain provides a solution to gas price volatility. Unlike public blockchains, where market dynamics determine gas prices and contribute to inherent volatility, our government-managed hybrid blockchain allows for greater control over gas usage through the implementation of fixed gas prices for transactions. This approach not only stabilizes costs but also has the potential to lower them, thereby enhancing the cost efficiency and financial predictability of the system, potentially introducing new challenges that warrant further exploration.

6.6.2 Time taken to issue ownership proof

The second metric we utilized for the evaluation is the time taken to issue an ownership proof, an NFT, on our system. Although the timestamp for each transaction is documented in Table 6.2, we chose not to include the time the system takes to add ownership on the blockchain for several reasons. Firstly, the time required to input information on the blockchain cannot be directly compared to traditional systems. Traditional systems may take months to verify ownership, which implies a difficulty in measuring a comparable system. Secondly, we assume in our experiment that all information is correct and does not need authentication, which could be inaccurate as real-world scenarios often take longer. Thirdly, our focus is on measuring the time taken once all information is authenticated and no further steps are required. Consequently, we opted to measure the time taken to issue ownership proof in the form of an NFT and exclude the preliminary steps to provide a more accurate assessment of the system's efficiency in issuing verified ownership.

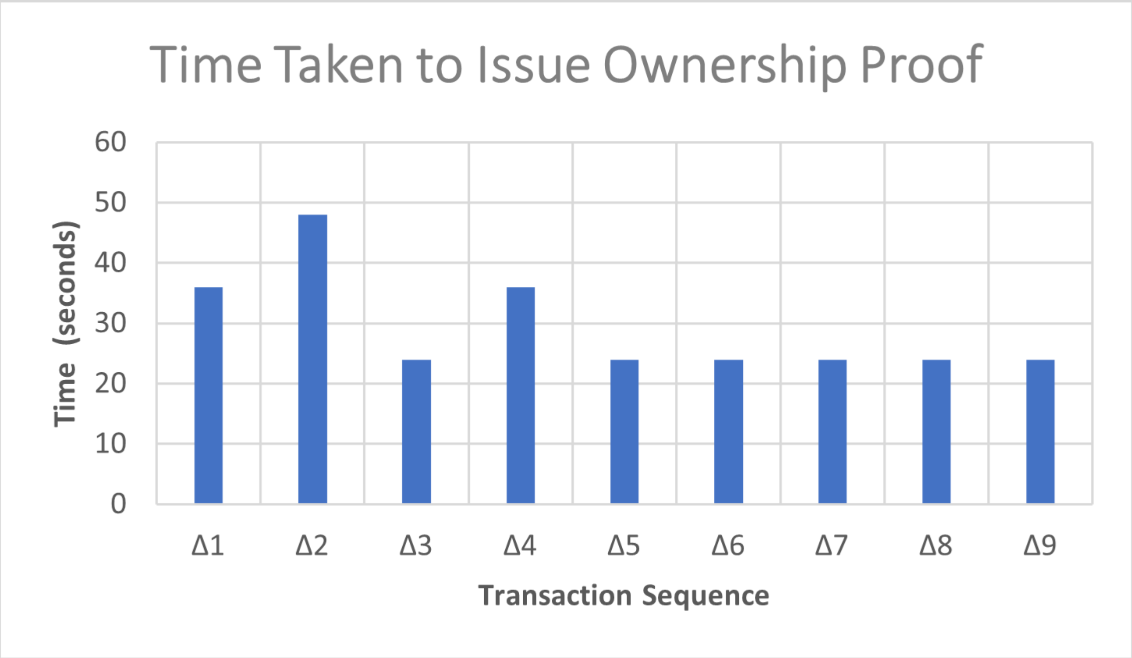

Figure 6.10: Actual processing time for ownership proof issuance

Figure 6.10 illustrates the time difference, in seconds, from the completion of each 'Add Owner' transaction to the issuance of the following respective 'Mint NFT For Last Owner' transaction. To calculate this time difference, we use the following formula:

$$\Delta\text{Time}_\text{s} = \text{TS}_\text{Mint NFT} - \text{TS}_\text{Add Owner} \tag{6.4}$$

Results Discussion According to the report from the Pricer website, the county recorder's office may take 1 to 2 weeks to process a deed transfer. However, the legal review and preparation conducted by attorneys prior to deed submission could extend from 2 weeks to as long as 2 months. This variability particularly reflects the time-consuming and inconsistent pattern that contributes to inefficiencies in ownership verification.

The results from our analysis of the time taken to issue ownership proofs reveal a high degree of consistency and efficiency within our blockchain system. The frequent occurrence of a 24-second processing time for the majority of transactions underscores the system's optimized performance and predictability. Such regularity in processing times enhances the system's efficiencies in ownership verification.

Evaluation Summary Our evaluation of the hybrid blockchain-based system across two critical metrics, transaction cost and time taken to issue ownership proof, underscores its effectiveness. The system facilitates the addition of ownership and issuance of NFT-based proof of ownership at an estimated cost of $30.15 USD and an estimated 24-second processing timeframe across most transactions. These figures respectively address the challenge of the cost variation of ownership authentication and the inefficiencies in ownership verification, thereby aligning with our objective of developing a reliable method to prove the ownership of real estate property.

This assessment is part of the evaluation process outlined in Objective 4, ensuring that the system meets key performance benchmarks. While acknowledging the need for more transactions and further optimization, it is important to highlight that our system, although still in its prototype phase and not yet a finalized product, has successfully demonstrated a high degree of efficiency, consistency, and predictability. These attributes are indicative of the system's potential even in its prototype stage.

6.7 Conclusion

In this chapter, we introduced the integration of GREP with NFTs to develop a reliable framework for real estate ownership certification and verification aligning with Objective 2. Our solution addressed several key challenges, including inefficiencies in ownership verification, security vulnerabilities, lack of transparency, and the high costs of ownership authentication. We developed and implemented a conceptual solution that integrates critical system components and introduced key algorithms to streamline ownership verification and provenance tracking. Our solution was built on the improved ERC-721 standard. By evaluating transaction costs and the time required to issue proof of ownership, our system demonstrated consistency and efficiency, processing ownership verification in approximately 24 seconds and maintaining predictable costs of around $30.15 USD. These evaluations, which contribute to Objective 4, prove that our system can provide a secure, transparent, and efficient method for proving and verifying real estate ownership, successfully mitigating the traditional challenges in this field.

The next chapter primarily explores Objective 3, focusing on the development of GREP's framework for shared real estate ownership certification. To achieve this, we leverage fractional NFTs to facilitate the collective holding and management of property ownership. Additionally, this chapter includes the validation and the evaluation of the shared ownership model, which also contributes to Objective 4.

CHAPTER 7

GREP and Shared Real Estate Ownership Certification

7.1 Introduction

For many individuals, owning a home or investing in property remains financially out of reach due to high costs and complex legal procedures. One approach to addressing this challenge is shared ownership, which allows multiple participants to co-own a property and distribute costs and responsibilities. However, the traditional real estate market, characterized by high entry barriers, legal complexities, and the involvement of multiple intermediaries such as brokers, legal professionals, and financial institutions (Kania and Kmieć, 2022), often makes shared ownership cumbersome and difficult to manage. These obstacles highlight the need for innovative solutions that simplify property transactions while expanding accessibility.

Shared ownership provides a viable alternative for making real estate investment more affordable. It enables multiple individuals to collectively acquire property, thereby reducing financial burdens and offering a pathway for young investors to enter the market without the need for substantial capital commitments (Swinkels, 2023). Additionally, shared ownership fosters collaboration by allowing co-owners to collectively manage and maintain the property. However, traditional real estate mechanisms often fall short in supporting shared ownership due to their limited flexibility, high costs, and lack of transparency. These limitations create inefficiencies and lead to disputes over ownership rights and responsibilities.

Blockchain technology has emerged as a transformative tool for shared ownership certification, ensuring transparency, immutability, and security in real estate transactions (Uchani Gutierrez and Xu, 2022; Chung et al., 2022). By eliminating intermediaries, blockchain reduces transaction costs and streamlines ownership verification processes, making property transactions more efficient and accessible. Blockchain tokenization has introduced new models of real estate ownership that facilitate fractional ownership through fractional NFTs. This allows properties to be divided into digital shares, enabling multiple parties to co-own and trade property fractions with verifiable proof of ownership.

In this chapter, we expand on the GREP framework by incorporating fractional NFTs to establish a structured and verifiable method for shared ownership certification, aligning with Objective 3. Our objective is to develop a reliable solution that effectively manages the creation, division, and transfer of a property's ownership record among multiple parties, ensuring a secure and efficient ownership certification process. Additionally, this chapter includes the validation and the evaluation of the shared ownership model, contributing to Objective 4.

This chapter proceeds as follows: Section 7.2 describes the proposed solution, beginning with an overview of fractional NFTs for shared real estate ownership certification, followed by an introduction to the improved ERC-721 standard for shared ownership, and concluding with a conceptual solution overview. Section 7.3 presents the scenarios and algorithms for shared ownership certification, outlining the key processes for owners with and without NFTs. Section 7.4 details the development tools and blockchain environment utilized, along with the implementation scenarios for shared ownership certification in GREP. Section 7.5 covers the evaluation and discussion, analyzing the system's performance in terms of transaction cost and time taken to issue ownership proof. Following this section, the comparative analysis presented in Table 7.8 serves as a critical assessment of GREP's effectiveness. Finally, Section 7.6 summarizes the chapter's findings.

A significant portion of the contents of this chapter has been published in the proceedings of the *2023 IEEE International Conference on e-Business Engineering (ICEBE)*. The full article can be accessed via the following link: `https://ieeexplore.ieee.org/abstract/document/10356171`.

7.2 Developing the Proposed Solution

In this chapter, our objective is to develop a reliable method for managing the creation, division, and transfer of a property's ownership record among multiple parties. To develop this method, we integrate fractional NFTs into GREP's shared ownership certification framework.

To lay the foundation for the proposed solution, we introduce fractional NFTs as a foundational mechanism for shared ownership certification in real estate. Furthermore, we present our enhanced ERC-721 standard, which has been improved to support fractional ownership. Finally, we provide an overview of the framework we propose.

7.2.1 Fractional NFTs for shared real estate ownership certification

The real estate industry presents several challenges that limit accessibility, flexibility, and transparency in property ownership. High costs, complex legal procedures, and the involvement of multiple intermediaries make it difficult for individuals to enter the market and participate in shared ownership models. These barriers highlight the need for a more efficient and verifiable approach to managing property co-ownership.

Blockchain tokenization provides a mechanism for representing real estate assets as digital tokens, ensuring that ownership rights are securely recorded and easily transferable. Fractional NFTs further extend this concept by allowing properties to be divided into tradable digital shares, enabling multiple participants to co-own and exchange property fractions with verifiable proof of ownership.

By leveraging fractional NFTs within GREP, our proposed solution introduces a structured and verifiable certification system for shared ownership. The benefits of this approach include:

- **Transparency and Security:** Blockchain ensures that ownership records remain tamper-proof, preventing fraud or unauthorized modifications.
- **Efficient Ownership Transfers:** Smart contracts ensure that all transactions, including the creation, division, and transfer of property shares, are executed according to predefined rules. This eliminates the need for intermediaries, reduces transaction costs, and enhances the efficiency of ownership transfers.
- **Increased Market Accessibility:** Fractionalization allows investors to own and trade property fractions, lowering financial barriers and expanding participation in real estate.

- **Liquidity and Tradability:** Fractional NFTs enable co-owners to trade ownership fractions, making shared property ownership more dynamic, efficient, and market-driven.

To fully support shared ownership certification, the ERC-721 standard requires enhancements for fractionalization, traceability, and secure transfers. The next subsection details the improved ERC-721 standard within the GREP framework.

7.2.2 Improved ERC-721 standard for shared ownership

The ERC-721 standard comes with several built-in events and functions, as shown in the original ERC-721 (Figure 6.2). While these functions offer a variety of tools for managing ownership and transferring tokens, they do not fully meet the specific needs of our solution for shared ownership in real estate. Consequently, we have improved the ERC-721 standard to include new functions and events that facilitate the effective management of the creation, division, and transfer of a property's ownership record to multiple parties. The newly introduced functions and events, designed to handle fractional ownership and streamline shared ownership transfers, are displayed in Figure 7.1.

Improved ERC-721 Standard for Shared Ownership

```
event OwnershipTransferred(uint256 indexed propertyId, address indexed fromOwner, address
      indexed toOwner, uint256 percentageTransferred);
event Transfer(address indexed _from, address indexed _to, uint256 indexed _tokenId);
event Approval(address indexed _owner, address indexed _approved, uint256 indexed _tokenId);
event ApprovalForAll(address indexed _owner, address indexed _operator, bool _approved);

function addOwner(uint256 propertyId, string memory ownerName, address ownerAddress);
function mintNFTForLastOwner(uint256 propertyId, string memory tokenURI);
function transferToGov(uint256 propertyId, address currentOwner);
function divideNFT(uint256 propertyId, address[] memory newOwners, uint256[] memory
         ownershipPercentages);
function transferOwnership(uint256 propertyId, address fromOwner, address toOwner, uint256
         percentageToTransfer);
function getFractionalOwners(uint256 propertyId)
function balanceOf(address _owner);
function ownerOf(uint256 _tokenId);
function safeTransferFrom(address _from, address _to, uint256 _tokenId, bytes data);
function safeTransferFrom(address _from, address _to, uint256 _tokenId);
function transferFrom(address _from, address _to, uint256 _tokenId);
function approve(address _approved, uint256 _tokenId);
function setApprovalForAll(address _operator, bool _approved);
function getApproved(uint256 _tokenId);
function isApprovedForAll(address _owner, address _operator);
```

Figure 7.1: Functions and events of the improved ERC-721 standard for shared ownership - improved (in green) and original (in blue)

The Improved ERC-721 Standard for Shared Ownership introduces several key events and functions designed to facilitate fractional ownership and streamline the management of shared real estate assets. The newly added event and functions are as follows:

OwnershipTransferred

This event tracks the transfer of ownership between two parties, specifying the Property ID, the previous owner, the new owner, and the percentage of ownership transferred. It ensures transparency and provides a clear record for each fractional ownership transfer.

addOwner

This function allows the super admin to add a new owner to a property, creating an ownership entry without immediately minting an NFT. It is critical for managing ownership records before NFTs are created, especially in cases where the owner does not yet have an NFT as proof of ownership. This allows their details to be recorded in the system until the NFT is minted.

mintNFTForLastOwner

This function mints an NFT for the most recent owner added to a property's history, which represents ownership and assigns the NFT to the owner's wallet. It is used when an owner has not yet received an NFT as proof of ownership, providing a way to generate the NFT at a later stage after the ownership details are finalized and confirmed.

transferToGov

This function transfers full ownership of a property to the government's address, ensuring centralized control when required. It provides an additional layer of authority for secure transfers.

divideNFT

This function divides an existing NFT into fractional ownership, assigning respective ownership percentages to new owners. It enables the crucial functionality of fractional ownership, making property investment more accessible.

transferOwnership

This function transfers a percentage of ownership from one owner to another and updates the fractional ownership records. It facilitates the seamless transfer of partial ownership, a key aspect of shared ownership scenarios.

getFractionalOwners

This function retrieves the current list of fractional owners and their respective ownership percentages, providing transparency into the ownership distribution of a property and enhancing trust among co-owners.

7.2.3 Conceptual solution overview

This subsection explores the system's structure and workflow through the conceptual model of GREP's shared ownership certification framework. To illustrate the concept of our system and its underlying structure, we utilize the widely recognized and popular software architecture pattern known as Model-View-Controller (MVC) (Freeman, 2015). The MVC architecture organizes the system into three main components: Model, View, and Controller (see Figure7.2).

The Model layer represents the core logic of the platform. It manages the creation, division, and transfer of property ownership through NFTs and fractional NFTs. The components of the Model layer are as follows:

Property Creation: This component manages the creation of property records on the platform. It ensures that all the property details, such as ownership and related documentation, are correctly recorded and linked to an NFT representing the property.

NFT Management: This component handles the creation, transfer, and management of NFTs. Each property is tokenized into an NFT, which serves as a unique digital representation of ownership. This token can be transferred between parties to facilitate real estate transactions.

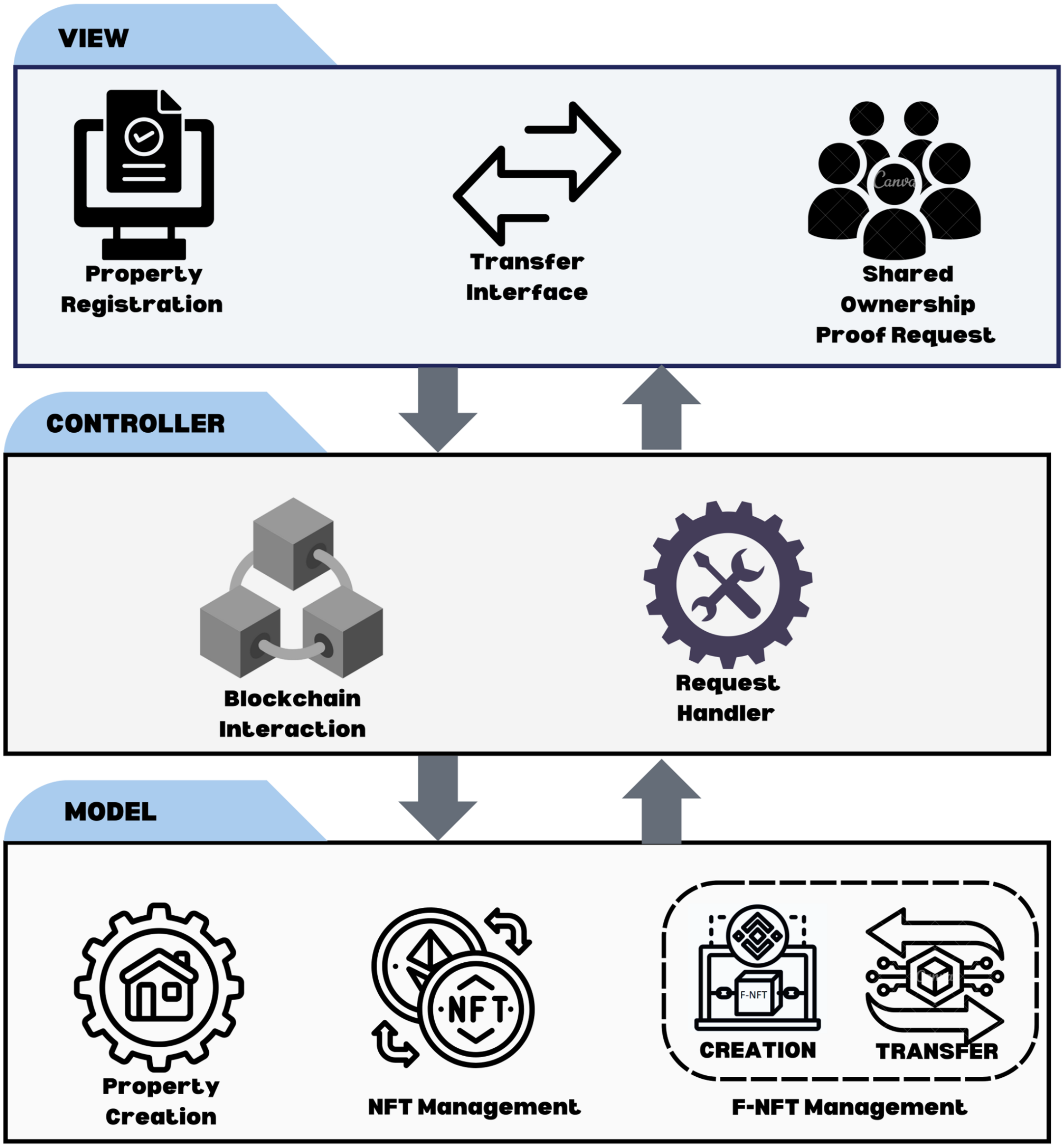

Figure 7.2: Model-View-Controller (MVC) architecture for the proposed solution

Fractional NFT Management (Creation and Transfer): This component divides an owner's NFT into fractional NFTs based on predefined ownership rules. These fractional NFTs represent fractional ownership and can be securely transferred and traded among investors on the platform.

The View layer in the MVC architecture serves as the front end of the system, emphasizing the visual presentation and user interface elements. It displays key functionalities, including Property Registration, Transfer Interface, and Shared Ownership Proof Request. Its primary role is to present information to users in a clear and organised manner while capturing their input efficiently in a user-friendly environment.

The controller layer acts as an intermediary between the view and the model. It handles user requests, processes input data, and interacts with the model layer to perform the necessary actions. The controller layer ensures smooth communication and coordination between the layers. It consists of the following two key components:

- **Request Handler**: This component is responsible for handling off-chain data. It serves as the gateway for user requests, receiving input from the view layer. It validates the user input, ensuring that all required information is provided and meets the necessary criteria. By coordinating with the model layer, the Request Handler performs the necessary actions to fulfill the user's request.
- **Blockchain Interaction**: This component is responsible for handling on-chain data and interactions with the blockchain network. It enables the platform to interact with the blockchain network, submit transactions, retrieve data, and monitor events. Once the Request Handler validates and processes the user request, it interacts with the Blockchain Interaction component to execute the necessary actions on the blockchain.

7.3 Scenarios and Algorithms for Shared Ownership Certification

Before developing our reliable solution for shared ownership in the form of fractional NFTs, it is important to consider how ownership is first created in the form of an NFT. Since shared ownership within GREP relies on fractional NFTs, establishing initial ownership through NFTs is a fundamental prerequisite. There are two possible scenarios: either the owner does not have an NFT, or the owner already holds an NFT. The subsequent discussion outlines both scenarios with their respective algorithms.

7.3.1 Scenario 1: The owner does not have an NFT

In this case, the property information needs to be registered first, after which the system issues an NFT to represent the ownership. Within GREP, this NFT serves as the foundation for shared ownership certification, which ensures that ownership rights are securely established before fractionalization. Once this NFT is created, the fractionalization process can begin. Algorithm 7.1 addresses this scenario by outlining the steps for adding a new owner to the property and minting an NFT to represent the ownership.

Algorithm 7.1: Add Owner and Mint NFT

Inputs:

- **propertyId:** The unique identifier for the property.
- **ownerName:** Name of the property owner.
- **providerName:** Name of the entity providing the property details.
- **ownerType:** Type of ownership (e.g., individual, corporate).
- **propertyLocation:** Location of the property.
- **CityandState:** City and state of the property.
- **associationDate:** Date when the ownership was associated.
- **basicKey:** A new basic key for accessing provenance information.
- **detailedKey:** A new detailed key for accessing full provenance information.
- **ownerAddress:** The blockchain address of the new owner.
- **tokenURI:** Metadata associated with the property/NFT.

Output:

- The owner is added to the property history with a unique token ID.
- The NFT is minted for the most recent owner and assigned to their wallet.

Procedure:

sequence ← propertyToNextTokenId[propertyId]++
tokenId ← propertyId * 1000 + sequence
newOwner ← create Owner structure with (ownerName, ownerAddress, 100%, tokenId)
_**safeMint**(lastOwner.ownerAddress, lastOwner.tokenId)
properties[propertyId] ← Property({propertyId: propertyId, nftTokenId: tokenId, govAddress: lastOwner.ownerAddress, totalOwnership: 100})

The procedure for adding an owner and minting an NFT involves several key steps, including:

Generate sequence ID for token:

The system increments the `propertyToNextTokenId[propertyId]` to create a unique sequence for the property. This ensures that each token associated with a property is uniquely identified.

Create unique token ID:

The token ID is generated by multiplying the `propertyId` by 1000 and adding the sequence number. This creates a distinct token ID for each new ownership entry.

Add new owner to property history:

A new owner structure is created, containing details such as `ownerName`, `ownerAddress`, and the `tokenId`. The ownership percentage is set to 100% as the initial owner fully owns the property.

Mint NFT for the owner:

The `_safeMint` function is called to mint an NFT for the last owner in the property history. This ensures that the ownership is represented as an NFT on the blockchain and assigned to the owner's wallet.

Update property ownership:

The property details are updated in the `properties` mapping to reflect the newly minted NFT, setting the NFT token ID and the owner's address as the government-controlled address with total ownership of 100%. This step links the property to its NFT and its ownership structure, ensuring the platform can track and manage the property correctly on the blockchain.

7.3.2 Scenario 2: The owner already has an NFT

If the owner already holds an NFT representing their property, GREP manages the process without requiring a new registration. This means that the initial ownership details are already recorded on the blockchain, which allows the property to move directly to the next step in the shared ownership certification process.

In both scenarios, the NFT must be transferred to the government account, where it undergoes verification and validation before further processing. There are several reasons for including this step. First, it is a data-driven decision based on our systematic literature review, where we observed that processes involving verification typically include government oversight, and no public blockchain is solely proposed. Another reason is the vast size and financial significance of the real estate market, which is valued in the trillions of dollars. Involving the government adds a protective layer that enhances accountability and trust among users. Another point to consider is the importance of real estate taxes as a major source of government revenue. It is highly unlikely that governments would allow this process to function without their oversight or involvement.

Following the transfer of the NFT to the government account for verification and validation, the next key step involves fractionalizing the NFT and distributing ownership to multiple parties. As shown in Algorithm 7.2, the process ensures that fractional ownership is created for the property, and the fractional NFTs are transferred to the new owners. Additionally, the data on fractional ownership is stored and made available for retrieval, which ensures transparency and traceability of ownership records on the system.

Algorithm 7.2: Fractionalize NFT and Transfer F-NFTs

Inputs:

- **propertyId:** The unique identifier for the property.
- **tokenId**: The ID of the NFT representing the property.
- **newOwners**: An array of addresses of the new fractional owners.
- **ownershipPercentages**: An array of percentages corresponding to each new owner's share.

Output:

- Fractional ownership is created for the property.
- F-NFTs are transferred to new owners.
- Data on fractional ownership is stored and available for retrieval.

Procedure:

```
totalPercentage ← sum(ownershipPercentages[])
 require ∑ Percentage == 100%
delete fractionalOwners[tokenId]
_safeTransfer(ownerOf(tokenId), newOwners[0], tokenId, "")
for i in newOwners:
  create FractionalOwner(ownerAddress: newOwners[i], ownershipPercentage: ownershipPercentages[i])
  if i > 0:
    _safeTransfer(newOwners[i-1], newOwners[i], tokenId, "")
require ownerOf(tokenId) == newOwners[lastIndex]
properties[propertyId] ← Property(propertyId: propertyId, nftTokenId: tokenId, govAddress: "",
totalOwnership: 100%)
```

The procedure for fractionalizing an NFT and transferring fractional NFTs involves several key steps, including:

Calculate and Validate Total Ownership Percentage:

```
totalPercentage ← sum(ownershipPercentages[])
require ∑ ownershipPercentages[] == 100%
```

In this step, the system first sums all the ownership percentages provided in the `ownershipPercentages[]` array to calculate the total percentage. Then, it validates that the total equals exactly 100%. This ensures that the fractional ownership distribution among all new owners is accurate and complete, preventing errors in the division of ownership.

Clear Previous Fractional Ownership Records:

```
delete fractionalOwners[tokenId]
```

This command removes all existing fractional ownership records associated with the specific token ID. It ensures that there is no residual data that could conflict with the new ownership structure.

Transfer the NFT to the First New Owner:

```
_safeTransfer(ownerOf(tokenId), newOwners[0], tokenId, "")
```

The NFT is transferred from its current owner to the first address listed in the `newOwners` array. This is the initial step in redistributing ownership.

Create Fractional Ownership Records:

```
for i in newOwners:
create FractionalOwner(ownerAddress:  newOwners[i],
ownershipPercentage:  ownershipPercentages[i])
```

For each address in the `newOwners` array, a new fractional ownership record is created, specifying the owner's address and their respective share of ownership.

Transfer Ownership Between New Owners:

```
if i > 0:
_safeTransfer(newOwners[i-1], newOwners[i], tokenId, "")
```

Sequential transfers are made from one new owner to the next, facilitating the distribution of ownership as specified by the percentages. This loop ensures that each transfer is secured and verifiable.

Verify Final Ownership Transfer:

```
require ownerOf(tokenId) == newOwners[lastIndex]
```

The procedure concludes with a verification step to ensure that the last person in the `newOwners` array is the final holder of the NFT. This confirms the completion of the transfer process.

Update Property Details:

`properties[propertyId] ← Property(propertyId: propertyId, nftTokenId: tokenId, govAddress: "", totalOwnership: 100%)`

The property record is updated to reflect the new ownership structure, incorporating the details of the fractionalized NFT and its distribution among the new owners.

The entire workflow, from verifying ownership to issuing and transferring fractional NFTs, is depicted in Figure 7.3, outlining the steps involved in managing shared ownership through blockchain technology.

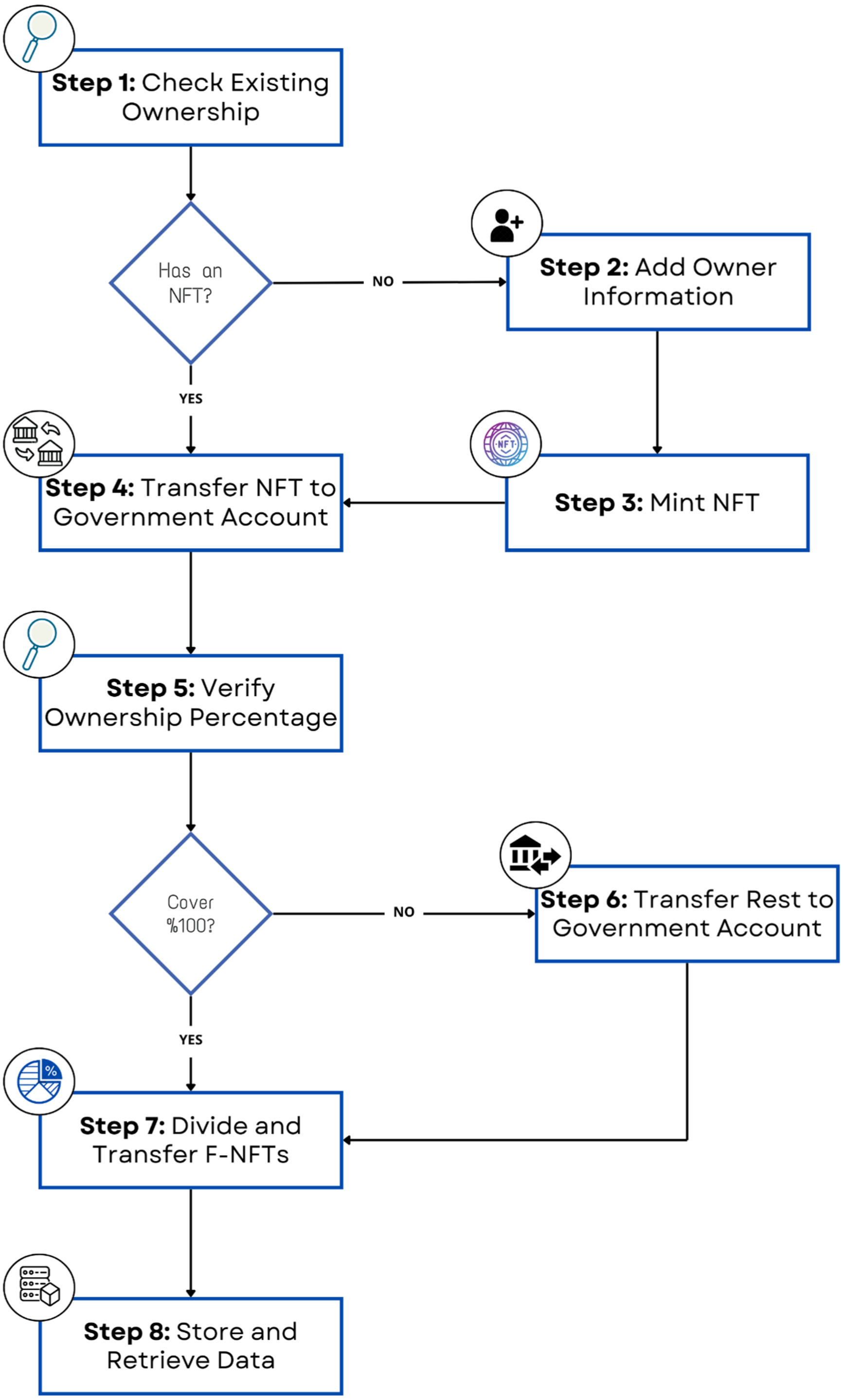

Figure 7.3: Shared ownership workflow using fractional NFTs and blockchain technology

7.4 Implementation

7.4.1 Development tools and blockchain environment

In the development of GREP's shared ownership certification framework, we utilized a system running a 64-bit version of the Windows operating system, powered by a 13th Generation Intel® Core™ i9-13900H CPU and supported by 32 gigabytes of RAM. A range of tools facilitated the development process. The primary environment for developing and testing smart contracts was the Remix - Ethereum IDE, specifically version v0.44.0. Remix allowed us to code, compile, and deploy smart contracts efficiently. The smart contract was written in Solidity, utilizing the enhanced ERC-721 standard to mint fractional NFTs, representing shared real estate ownership on the Ethereum blockchain.

To execute transactions, we integrated MetaMask as the injected provider. Several accounts were created within MetaMask, with one designated as the government account to control the system. This account was funded through Ethereum from the Sepolia faucet, ensuring it could carry out transactions. This setup provided a controlled environment for simulating real-world transaction processes and testing the functionality of the system.

For the experiments, we utilized the dataset from the Data World website (Data.world, 2016). We prepared the dataset by removing extra columns and organizing it to suit the needs of our system.

7.4.2 Scenarios for implementing shared ownership certification in GREP

As we aim to develop a reliable method that effectively manages the creation, division, and transfer of a property's ownership record to multiple parties, we present the implementation for three different scenarios: providing shared ownership proof for an owner who does not have an NFT, providing shared ownership proof for an owner who already has an NFT, and transferring existing fractional ownership (fractional NFTs) to new owners.

Scenario 1: Providing shared ownership proof for an owner who does not have an NFT

To begin, we have a real-world example from the dataset illustrating three property owners. The owners—Kevin Archer, Solanges Vivens, and Scott Taylor—are associated with a property at 901 First Street NW in Washington, DC. Each owner holds a different percentage of fractional ownership, as indicated in the dataset. We incorporated a MetaMask wallet address for each owner, as the original dataset did not include this information. These wallet addresses represent each owner's identity on the blockchain, enabling secure and transparent transactions on the platform. The table lists the ownership percentages for each individual: 10%, 85%, and 5%, respectively, as shown in Table 7.1.

Table 7.1: Fractional ownership breakdown and wallet addresses for property located at 901 First Street NW, Washington, DC

Property ID	**Owner Name**	**Ownership Percentage**	**Wallet Address**	**Property Location**	**City and State**
95036	ARCHER, KEVIN	10%	0x3453fd2e7028F0f4405d28B2dfEfb62FaF7200aC	901 FIRST STREET NW	WASHINGTON, DC
95036	VIVENS, SOLANGES	85%	0x82Fb81B1F62Dd432d3E20dbc79508fEc6c49bA5	901 FIRST STREET NW	WASHINGTON, DC
95036	TAYLOR, SCOTT	5%	0xDaa7538c758861c15452B4bD1d3b0c526e1f6D3B	901 FIRST STREET NW	WASHINGTON, DC

In this scenario, we assume that the owners of the property at 901 First Street NW, Washington, DC, do not possess an existing NFT and require a reliable fractional ownership proof that accurately represents their shared ownership. In this case, our proposed system offers a solution to their demand by providing proof of fractional ownership in the form of fractional NFTs. The entire process, from the creation of the smart contract to the division of the property's NFT into fractional NFTs, is detailed in Table 7.2. Each transaction is recorded with its respective timestamp, gas usage, and transaction hash, which ensures the transparency and traceability. The table explains how ownership proof was generated for the property, starting with the addition of the owner, followed by minting the NFT for the last owner, transferring the NFT to the government account, and finally dividing the NFT into fractional ownership portions, as listed in Table 7.1.

To validate the process of providing shared ownership proof for the property owners who already possess an NFT, we decoded the input, as illustrated in Figure 7.4, for Property ID: 95036. The wallet addresses of the new owners and their respective ownership percentages are displayed. This matches the data from Table 7.1, which includes the fractional distribution for the owners.


```
decoded input    {
                     "uint256 propertyId": "95036",
                     "address[] newOwners": [
                         "0x3453fd2e7028F0f4405d28B2dfEfb62FaF7200aC",
                         "0x82Fb81B1F62D4d32d3E20dbc79508fEc6c49b3A5",
                         "0xDaa7538c758861c15452B4bD1d3b0c526e1f6D3B"
                     ],
                     "uint256[] ownershipPercentages": [
                         "10",
                         "85",
                         "5"
                     ]
                 }
```


Figure 7.4: Decoded input for Property ID: 95036, illustrating the wallet addresses and ownership percentages of the new owners

Table 7.2: Record of transactions involved in creating and fractionalizing the NFT for property at 901 First Street NW, distributed as detailed in Table 7.1

Transaction	**Timestamp (Unix)**	**Gas Used**	**Transaction Hash**	**Details**
Contract Creation	1723744104	4,482,070	0x93666861a58fdca45bec31ff07e9abf44 71944806be561e2c4bf92c205962a64	Contract address: 0x6b244ce95444ee0fc813c5 c48ea6f546ea93028a
Add Owner	1723744200	166,876	0x3426677cba2c1c06824b6f25a03090e0 45b58a2521e18501a84d302e06b07edb	Owner Name: ARCHER, KEVIN; Owner Address: 0x3453fd2e7028F0f4405d 28B2dfEfb62FaF7200aC
Mint NFT for Last Owner	1723744236	198,869	0x49344a33e3b2cd48a7f6d82fb19db2b a4c6eaba00a8de3cb9a73b92e959edca	Property ID: 95036; Owner: 0x3453fd2e7028F0f4405d2 8B2dfEfb62FaF7200aC
Transfer NFT to Government	1723744272	44,606	0xdfccccd4a16fc9342d40492acdb78dc ffc9c43a3c3f9dd3a0f0aa65c9e52378c8	Transferred NFT from owner: 0x3453fd2e7028F0f4405d2 8B2dfEfb62FaF7200aC to: Government account
Divide NFT into F-NFTs	1723744368	323,962	0x9e470e9ca7adf70b50176cbb9cafb7c 2c3fd2b055424e298a1e7f68ff1379f0f	Divided NFT into F-NFTs: 10% (Owner: 0x3453fd2e7028F0f4405d2 8B2dfEfb62FaF7200aC), 85% (Owner: 0x82Fb81B1F62Dd432d3E 20dbc79508fEc6c49bA5), 5% (Owner: 0xDaa7538c758861c15452B 4bD1d3b0c526e1f6D3B)

After decoding the input information, the `getFractionalOwners` call was executed to verify the results of the NFT fractionalization process. The output of this function, as shown in Figure 7.5, returns the data in alignment with the expected results. This output confirms that the NFT for the property at 901 First Street NW has been successfully fractionalized, and the fractional owners have been recorded on the blockchain with the correct distribution of ownership percentages. The addresses and ownership percentages match those from the original dataset and decoded input, validating that the smart contract functions correctly and accurately represents shared ownership on the blockchain.

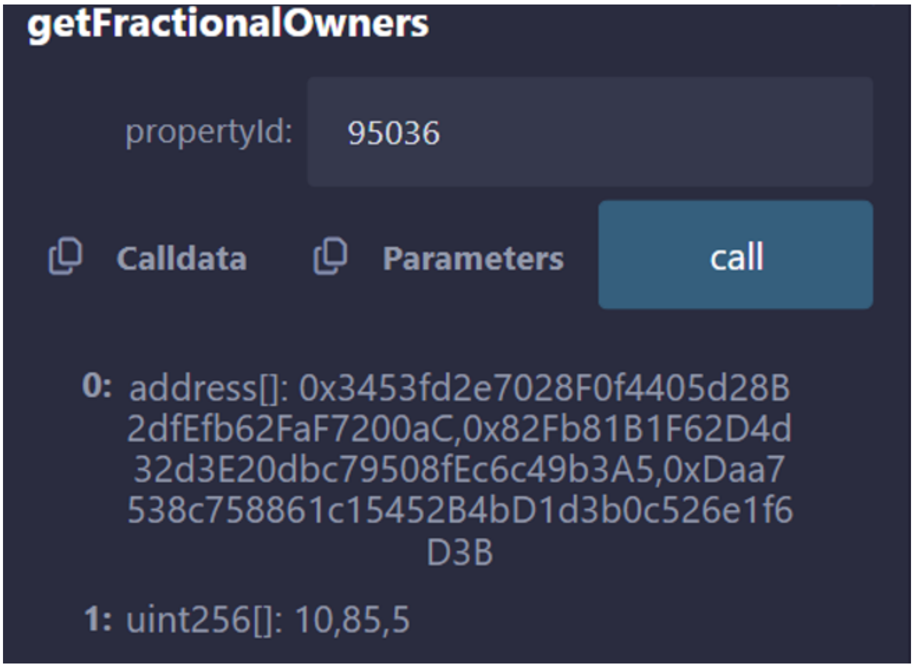

Figure 7.5: Output from the getFractionalOwners function, confirming the accurate fractionalization of the NFT and correct recording of ownership on the blockchain

Scenario 2: Providing shared ownership proof for an owner who already has an NFT

In this scenario, the implementation differs from the previous case because the owner already possesses an existing NFT. To start this scenario, we assume that the ownership of Property ID 105551 is represented by the NFT shown in Figure 7.6. This property currently has an existing owner, as indicated by the wallet address `0x42Bb382582dABd29502a28fb8413178f6957C46A`.

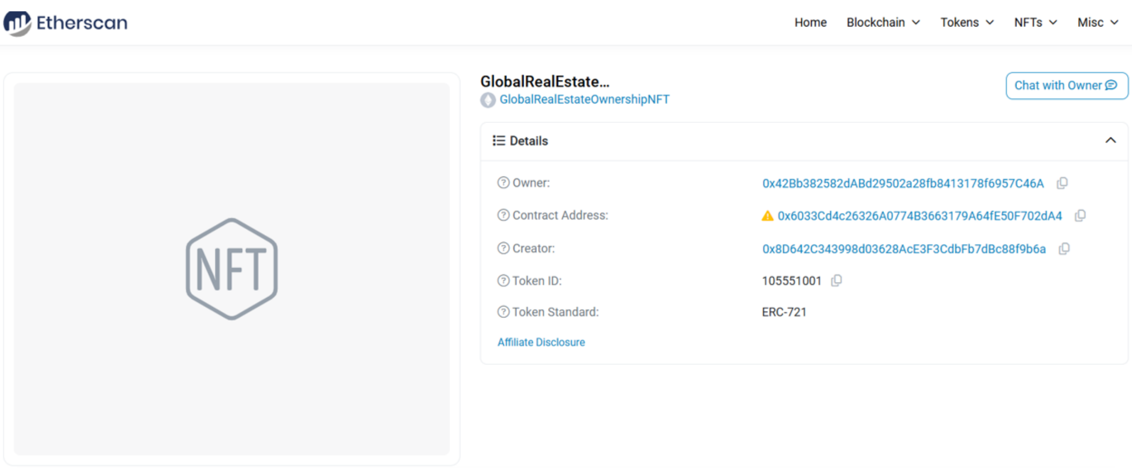

Figure 7.6: NFT representing the ownership of Property ID 105551 before fractionalization

However, the distribution of ownership needs to be updated according to the new fractional ownership arrangement. As shown in the original dataset, Table 7.3 reflects the new distribution of ownership, with four new owners having ownership percentages of 15%, 20%, 50%, and 15%, respectively. Each owner is assigned a MetaMask wallet address, representing their respective identities on the blockchain.

Table 7.3: The distribution of fractional ownership for Property ID 105551, as in the original dataset and wallet addresses

Property ID	**Owner Name**	**Ownership Percentage**	**Wallet Address**
105551	NEUMAN, MARK	15%	0x42Bb382582dABd29502a28fb8413178f6957C46A
105551	GOTTLIEB, SARAH	20%	0x75A8860e5ED2FEd5f0023cF9d813771e2b2c6A3B
105551	GOTTLIEB, STEVEN	50%	0x64DddB54fbC33a7fDBBC62F3d133Bb157fd68f4c
105551	JOZEF, HERBERT	15%	0xe9AD1cD13f1DF26586a34AA12f75cf1be8a976AF

Since the owner already has an NFT, the process begins by transferring the existing NFT to the government account for verification and division. As shown in Table 7.4, the first transaction involves transferring NFT ID 105551001 from the owner's wallet address `0x42Bb382582dABd29502a28fb8413178f6957C46A` to the government account. This step ensures that the current ownership details are accurately captured and stored before the fractionalization process takes place.

Once the NFT is transferred, the next step is dividing it into fractional NFTs according to the predetermined ownership percentages. Table 7.4 also provides details of the transaction that divided the NFT into fractional NFTs, distributing the ownership as 15%, 20%, 50%, and 15% among the four new owners. Each owner's MetaMask wallet address is recorded, ensuring transparency and traceability of the fractional ownership.

Table 7.4: Transaction details for the transfer and fractionalization of NFT for Property ID 105551

Transaction	Timestamp (Unix)	Gas Used	Transaction Hash	Details
Transfer NFT to Government	1723920060	65259	0x8ab4cc2da9f7cabd782b296324 24db6bca7d0e3ba690949a3f97db 61bf7aac8b	Transferred NFT ID 105551001 from owner 0x42Bb382582dABd29502a28fb 8413178f6957C46A to Government account
Divide NFT into F-NFTs	1723920228	374333	0xf9be09dd736137c1e193f7bc729 4b5791a95fcf9d943aeb7bcf0a473 a1ad8dfc	Divided NFT into F-NFTs: 15% (Owner: 0x42B...46A), 20% (Owner: 0x75A...A3B), 50% (Owner: 0x64D...f4c), 15% (Owner: 0xe9A...6AF)

To validate the process of providing shared ownership proof for the property owners who already possess an NFT, we decoded the input, as illustrated in Figure 7.7, for Property ID: 105551. The wallet addresses of the new owners and their respective ownership percentages are displayed. This matches the data from Table 7.3 in Scenario 2, which includes the fractional distribution for the owners.


```
decoded input                {
                                     "uint256 propertyId": "105551",
                                     "address[] newOwners": [
                                             "0x42Bb382582dABd29502a28fb8413178f6957C46A",
                                             "0x75A8860e5ED2FEd5f0023cF9d813771e2b2c6A3B",
                                             "0x64DddB54fbC33a7fDBBC62F3d133Bb157fd68f4c",
                                             "0xe9AD1cD13f1DF26586a34AA12f75cf1be8a976AF"
                                     ],
                                     "uint256[] ownershipPercentages": [
                                             "15",
                                             "20",
                                             "50",
                                             "15"
                                     ]
                             }
```


Figure 7.7: Decoded input for Property ID 105551, displaying the wallet addresses and ownership percentages

After decoding the input information, the `getFractionalOwners` call was executed to verify the results of the NFT fractionalization process. The output of this function, as shown in Figure 7.8, returns the data as expected. This output confirms that the NFT for the property at 105551 has been successfully fractionalized, and the fractional owners have been recorded on the blockchain with the correct distribution of ownership percentages. The addresses and ownership percentages match those from the original dataset and decoded input, validating that the smart contract functions correctly and accurately represents shared ownership on the blockchain.

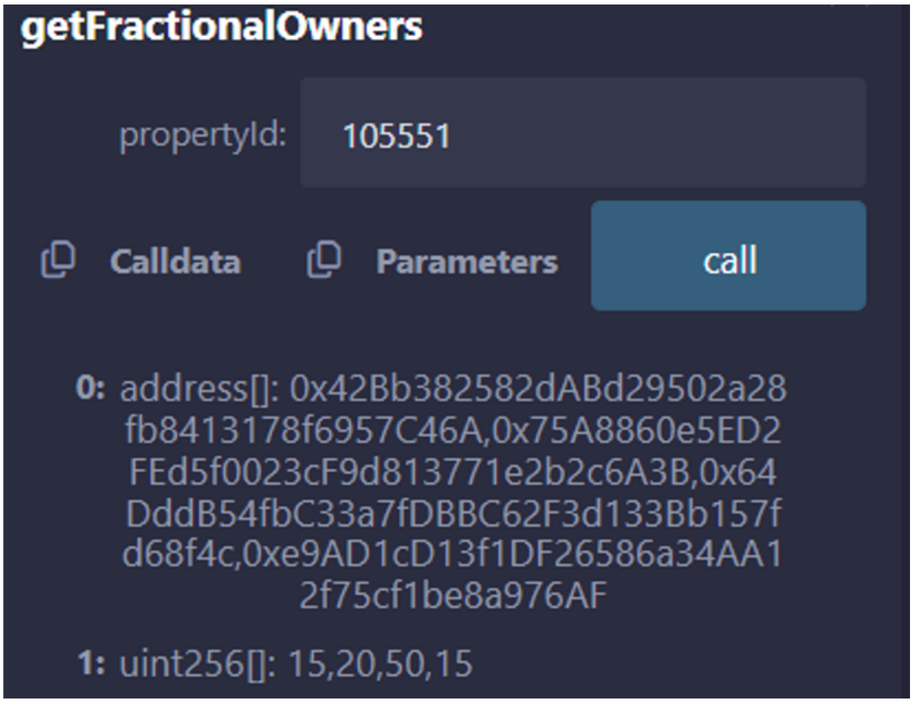

Figure 7.8: Output from the `getFractionalOwners` function, verifying the correct fractionalization of NFT and ownership distribution

Scenario 3: Transferring existing fractional ownership (fractional NFTs) to new owners

In this scenario, the focus is on transferring the existing fractional ownership (fractional NFTs) to a new owner. We begin by assuming that the Property ID 35072 is co-owned, with each of the two owners holding an equal 50% share, as shown in Table 7.5. Their respective shares are tied to the wallet addresses:
`0xC13ec36b7a178C510360B047B2E484351bd33E71` and
`0x82Fb81B1F62D4d32d3E20dbc79508fEc6c49b3A5`.

Table 7.5: Initial ownership distribution for Property ID 35072

Property ID	Owner Name	Ownership Percentage	Association Date	Wallet Address
35072	ADAMS, BRENDA	50%	01/01/1991	0xC13ec36b7a178C510360B047B2E484351bd33E71
35072	ADAMS, DOUGLAS	50%	01/01/1991	0x82Fb81B1F62D4d32d3E20dbc79508fEc6c49b3A5

Figure 7.9 illustrates the current state of fractional ownership before the transfer, showing that the two owners hold an equal 50% share, as shown in Table 7.5.

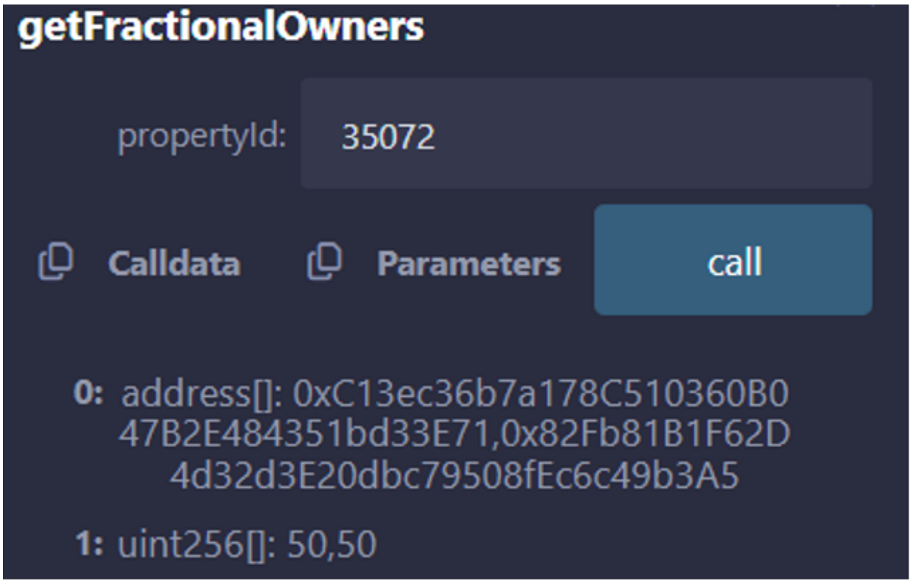

Figure 7.9: Current state of fractional ownership before the transfer, with two owners each holding a 50% share

The goal of this scenario is to transfer full ownership of Property ID 35072 to a new owner. Table 7.6 illustrates the desired outcome, where Tatum Holding Company Inc. holds 100% ownership of the property. This new ownership is linked to the wallet address `0xA96066A9FcAa33F79aB6412C7F096f3b386a8Dc9`.

Table 7.6: Targeted ownership distribution for Property ID 35072 after Transfer

Property ID	**Owner Name**	**Ownership Percentage**	**Association Date**	**Wallet Address**
35072	TATUM HOLDING COMPANY INC	100%	01/01/2012	0xA96066A9FcAa33F79aB6412C7F096f3b386a8Dc9

The next step is to process the transfer of ownership. As illustrated in Table 7.7, two separate transactions were performed to transfer 50% ownership from each of the original owners to the new owner, Tatum Holding Company Inc.

The first transaction in the table details the transfer of 50% ownership from the wallet address `0xC13ec36b7a178C510360B047B2E484351bd33E71` to the new owner's address `0xA96066A9FcAa33F79aB6412C7F096f3b386a8Dc9`. The second transaction shows the transfer of the remaining 50% ownership from the wallet address `0x82Fb81B1F62D4d32d3E20dbc79508fEc6c49b3A5` to the same wallet address of the new owner, completing the transfer of full ownership of the property.

Table 7.7: Ownership transfer transactions for Property ID 35072

Transaction	**Timestamp (Unix)**	**Gas Used**	**Transaction Hash**	**Details**
Transfer Ownership (1)	1724009064	111888	0x8f1a94637192054f055a02702628ebb75916bc339bbb4581ad284436a3f4427a	For Property ID: 35072; Transfer 50% ownership from `0xC13ec36b7a178C510360B047B2E484351bd33E71` to `0xA96066A9FcAa33F79aB6412C7F096f3b386a8Dc9`
Transfer Ownership (2)	1724009112	47939	0x78bdc86334e02561e8fa06b12575745c7df695cac92a87e6ace54dbc9d83aa6	For Property ID: 35072; Transfer 50% ownership from `0x82Fb81B1F62D4d32d3E20dbc79508fEc6c49b3A5` to `0xA96066A9FcAa33F79aB6412C7F096f3b386a8Dc9`

Figure 7.10 illustrates the successful completion of the ownership transfer for Property ID 35072. The getFractionalOwners call was executed to verify the updated ownership status. The output displays the wallet addresses associated with the property, confirming that both of the previous owners (holding 50% each) have transferred their shares, now displaying 0% ownership, which reflects GREP's capability in tracking real estate provenance within shared ownership. The new owner, represented by the wallet address 0xA96066A9FcAa33F79aB6412C7F096f3b386a8Dc9, is shown to hold 100% ownership of the property. This confirms that the smart contract has correctly handled the transfer of fractional ownership (fractional NFT), ensuring transparency and accuracy in recording the updated ownership information on the blockchain.

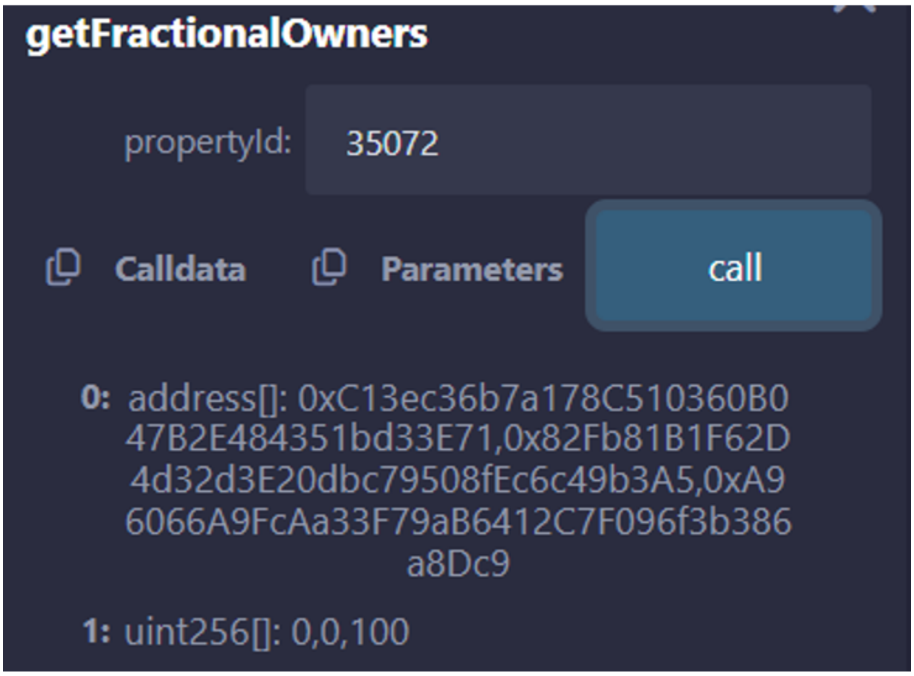

Figure 7.10: Successful completion of ownership transfer for Property ID 35072, with the new owner holding 100% ownership

To conclude, the implementation across all three scenarios demonstrates GREP's effectiveness in shared ownership certification. Collectively, these scenarios showcase the robustness of our approach, successfully achieving the creation, division, and transfer of ownership with full transparency and traceability on the blockchain, as designed for the fulfillment of Objective 3.

7.5 Evaluation and Discussion

This section evaluates and discusses the effectiveness of GREP's shared ownership certification framework by analyzing transaction costs and time efficiency in issuing fractional ownership in the form of fractional NFTs. Through these metrics, we assess the efficiency and practicality of the blockchain-based system for managing shared real estate ownership.

7.5.1 Transaction cost

Transaction cost is a fundamental metric in the business world, especially in industries such as real estate, where managing expenses can directly impact overall success. To calculate the transaction cost associated with each operation in our system, we utilize the gas used for each operation, as shown in Table 7.2. This allows us to calculate the cost in ETH using Equation 6.2, and then convert it to USD using Equation 6.3.

Figure 7.11 illustrates the cost of transactions in USD for various stages of the fractional NFT issuance and management process. We calculated these values based on the historical average gas price of 23.89 Gwei, derived from Etherscan data between 1 September 2023 and 1 September 2024, and the average ETH to USD exchange rate of $2690.73 for the same period. The chart covers four key transactions involved in the management of fractional NFTs:

- **Add Owner**: This transaction incurs a cost of $10.72 USD. It represents the initial step where an owner is added to the system, establishing their ownership record on the blockchain.

- **Mint NFT for Last Owner**: This transaction costs $12.77 USD. It reflects the process of minting an NFT that represents the property for the last owner, creating the digital representation of ownership.

- **Transfer NFT to Government**: The transaction of transferring the NFT to the government account for verification costs only $2.86 USD, a relatively low cost for this crucial step in the ownership validation process.

- **Divide NFT into fractional NFTs**: The most expensive transaction, at $20.81 USD, is the division of the NFT into fractional NFTs. This reflects the complexity of splitting ownership into fractional shares and updating the blockchain accordingly.

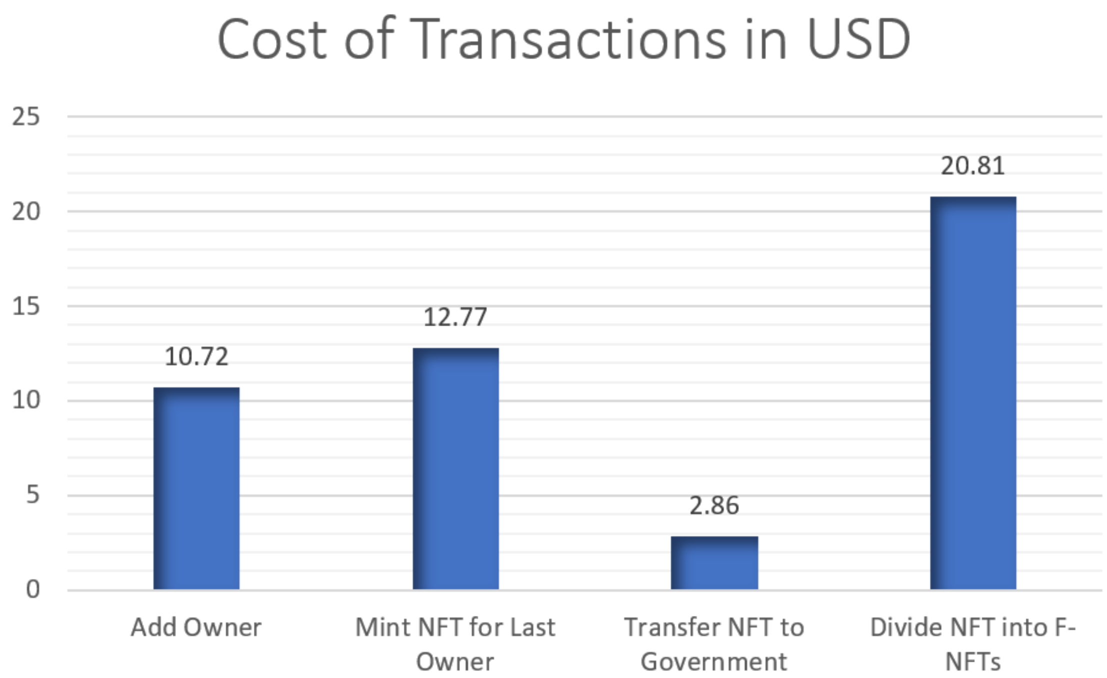

Figure 7.11: Transaction costs in USD for various stages of the fractional NFT issuance and management process

In comparison, the traditional real estate system involves significant costs for dividing a property, which can vary depending on location and value, with property deed transfer alone ranging from \$500 to \$5,000 on average (Pow, 2024). On the other hand, in our blockchain-based system, the total cost for completing all four blockchain transactions—'Add Owner,' 'Mint NFT for Last Owner,' 'Transfer NFT to Government,' and 'Divide NFT into F-NFTs'—amounts to approximately \$47.16 USD. This demonstrates the financial efficiency of our system in managing shared ownership.

7.5.2 Time taken to issue ownership proof

Another key metric in evaluating such a system is time efficiency, where delays in ownership transaction processing can impact the user experience, cause financial setbacks, lead to legal issues, and slow down property transfers. In our system, the time taken to issue proof of ownership is calculated for various operations, as shown in Figure 7.12.

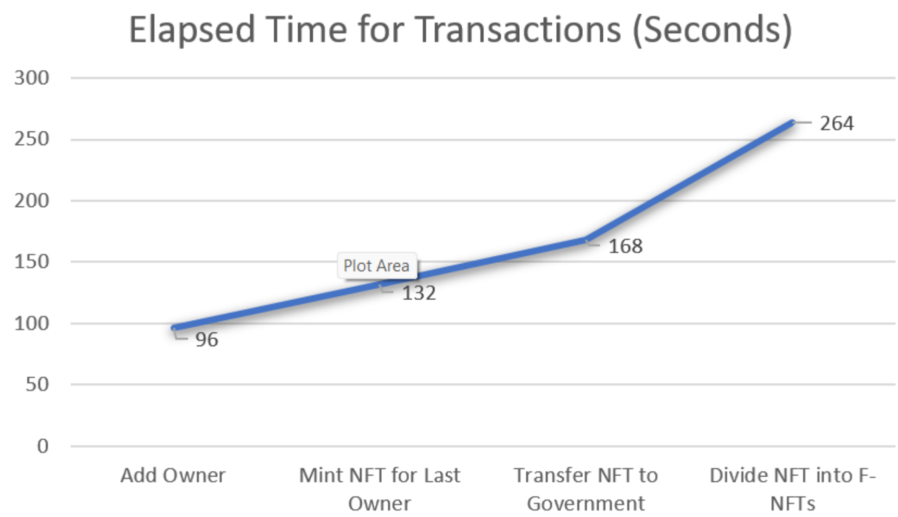

Figure 7.12: Time taken for various operations in the fractional NFT issuance and management process

This line chart illustrates the elapsed time for transactions, measured in seconds, across various stages of the fractional NFT issuance and management process. We recorded the transaction times based on the actual processing time required for each operation, using the following formula:

$$\text{Elapsed Time}_i = \text{Cumulative Time}_i - \text{Cumulative Time}_{i-1} \quad (7.1)$$

Elapsed Time_i refers to the time taken for a specific transaction step. Cumulative Time_i represents the total time recorded for all transactions up to and including step i, while Cumulative $\text{Time}_{(i-1)}$ indicates the total time recorded for all transactions up to the previous step.

The four key transactions include:

- **Add Owner**: The system takes approximately 96 seconds to add an owner to the blockchain. This step involves establishing an ownership record and ensuring that the blockchain has the necessary details to assign ownership rights.
- **Mint NFT for Last Owner**: The minting process for the last owner adds an additional 36 seconds, during which the NFT representing the property is created, marking the digital representation of ownership on the blockchain.
- **Transfer NFT to Government**: Transferring the NFT to the government for verification adds another 36 seconds. The relatively short time required for this step highlights the system's efficiency in quickly transferring ownership within the system.
- **Divide NFT into fractional NFTs**: The final transaction adds an additional 96 seconds. This operation is more complex as it involves carefully updating the ownership records to reflect the fractional shares on the blockchain.

The entire process in the traditional real estate system often involves unpredictable processing times. The involvement of multiple parties further complicates the process, often leading to extended delays. These factors can stretch transaction times from weeks to months, adding uncertainty and inefficiency to the overall system.

In contrast, GREP's shared ownership certification framework offers a highly efficient alternative. The time required to complete all four key transactions ('Add Owner,' 'Mint NFT for Last Owner,' 'Transfer NFT to Government,' and 'Divide NFT into F-NFTs') amounts to approximately 264 seconds.

Table 7.8 compares several aspects of the traditional real estate system and GREP's blockchain-based system. The data for the traditional system was taken from a recent report, published on 21 February 2024, on the Pricer website (Pow, 2024), based on real estate practices in the United States. Notably, the United States is a highly developed, first-world country, and these costs and delays may be even higher in other regions, particularly in developing economies.

The table demonstrates that our blockchain-based system significantly reduces both transaction costs and processing time by eliminating expensive legal fees, third-party dependencies, and unpredictable delays. Unlike traditional systems, our approach does not require attorney or title search fees, as all transactions are securely recorded on the blockchain and can be retrieved for free using call functions. This comparison highlights how our blockchain-based solution outperforms the traditional real estate system by reducing costs, improving efficiency, and enhancing both accessibility and predictability.

Table 7.8: Comparison between traditional real estate system and our blockchain-based system

Category	Traditional Real Estate	Our Blockchain-Based System
Attorney Fees	\$200 - \$2000 USD	No need for attorneys; ownership added directly to the blockchain
Deed Preparation	\$150 - \$300 USD	N/A (Standardized deed provided through NFT issuance)
Title Search Fees	\$200 - \$500 USD	Free (users can explore property records via call function)
Total Cost for Legal Services	\$50 - \$200 USD (additional legal service fees may apply)	\$30.15 USD $\pm$ \$3.64 USD
Cost Efficiency and Predictability	Costs vary based on property location and value	Standardized process reduces variability
Time Efficiency and Predictability	1-2 weeks for county recorder; 2 weeks to 2 months for legal preparation	After information is verified, it takes approximately 24 seconds to issue proof of ownership
Shared Ownership Cost	Unpredictable; deed transfer alone may range between \$300 and \$5000 USD	Around \$47.16 USD (Total for 'Add Owner,' 'Mint NFT,' 'Transfer NFT,' 'Divide NFT into F-NFTs')
Shared Ownership Time	Unpredictable; could take weeks or months	Approximately 264 seconds (for dividing NFT into F-NFTs and completing the process)

7.6 Conclusion

In this chapter, we introduced GREP's shared ownership certification framework, addressing Objective 3: developing a reliable method to prove shared ownership of real estate property through fractional NFTs. We conceptually explained our proposed solution, which includes an improved ERC-721 standard for shared ownership, alongside the development of supporting algorithms. This solution was implemented through two key scenarios: one where the owner already possesses an NFT and one where they do not.

Furthermore, as part of the evaluation process under Objective 4, we evaluated the system based on transaction costs, which amounted to approximately $47.16 for all transactions, from the creation of the smart contract to submitting the proof of ownership. Additionally, the total transaction time was approximately 264 seconds. We then compared our results to traditional real estate systems, demonstrating GREP's effectiveness in shared ownership certification, with significant improvements in both transaction speed and cost.

In the next chapter, we introduce the development of the GREP prototype, which contributes to Objective 4 by demonstrating its feasibility and real-world applicability. The chapter features technical tools, screenshots, and in-depth explanations to illustrate the prototype's creation and functionality.

CHAPTER 8

Prototype Development and Testing

8.1 Introduction

During the systematic literature review, we observed a significant lack of blockchain-based implementations for real estate within the existing literature, despite the availability of advanced technologies with the potential to revolutionize the industry. This gap underscores the need for practical implementations, given the dominance of theoretical contributions, as identified in Chapter 2

Recognizing this gap, in this chapter, we present the implementation of the GREP prototype to demonstrate its functionality in managing real estate provenance, ownership verification, and shared ownership. We explore the various technologies and tools used in the development of both the backend and frontend components of the platform. The backend, primarily based on Solidity smart contracts, manages property provenance and ownership, while the frontend, developed using React.js, provides a dynamic and responsive user interface. This prototype contributes to Objective 4 by demonstrating the feasibility of all developed solutions within a unified system, demonstrating the real-world applicability of the integrated solutions.

This chapter is organised as follows: Section 8.2 outlines the setup and implementation tools used for the development of the GREP prototype, detailing both backend and frontend components. Section 8.3 focuses on the implementation of real estate provenance management (Objective 1), explaining how property data is entered, stored, and retrieved through the platform. Section 8.4 covers the implementation of ownership proof (Objective 2), demonstrating how NFTs are issued to verify single ownership of real estate properties. Section 8.5 details the implementation of shared ownership proof (Objective 3), describing how fractional NFTs are used to manage co-ownership, including the creation, division, and transfer of ownership shares. Finally, Section 8.6 summarizes the key points of this chapter and introduces the final chapter of this thesis.

8.2 Setup and Implementation Tools

To implement the GREP prototype, several technologies and tools were used. The following subsections describe the tools used in the backend and frontend setup for the prototype implementation.

8.2.1 Backend setup

The backend of the GREP platform is centered around Solidity smart contracts, which form the core logic of the system by managing property provenance and ownership on the Ethereum blockchain. These smart contracts were developed and tested using Remix IDE (V0.54.1), an online development environment accessible directly from a web browser without the need to install any additional software.

Remix allows for the easy compilation and deployment of contracts on both local environments and Ethereum testnets. The local environment in Remix includes several simulated environments and 15 pre-configured accounts (an increase from the previous 10), each pre-funded with 100 Ether, as shown in Figure 8.1.

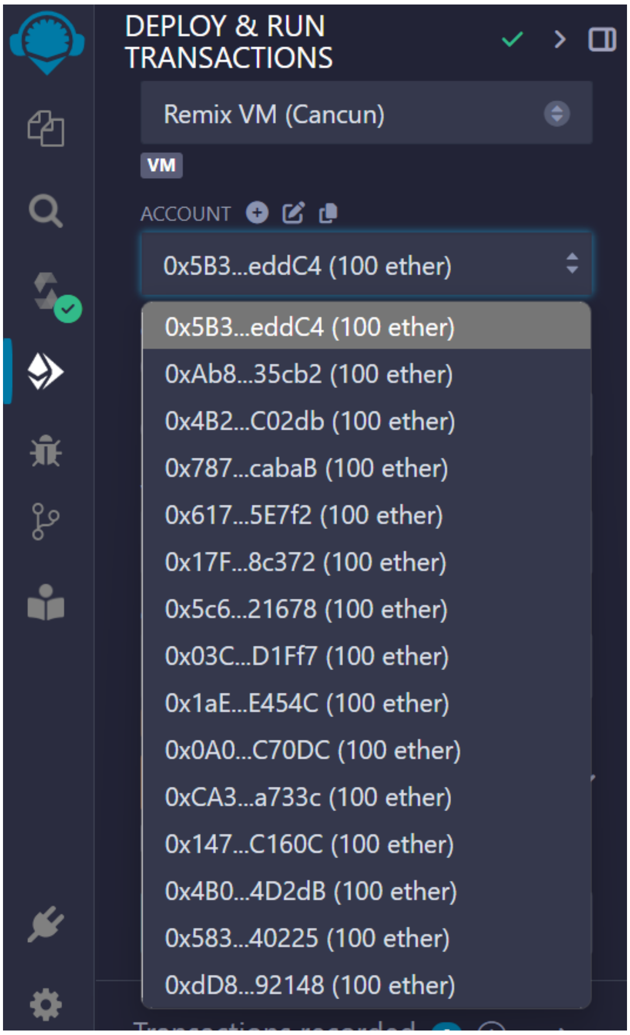

Figure 8.1: Screenshot showing Remix IDE with the default environment (Remix VM - Cancun) and the 15 pre-configured accounts

We also used MetaMask (V11.16.14), a browser extension wallet, to manage Ethereum accounts and sign transactions within the GREP platform. For our experiment, we created 10 accounts: one super admin, one admin, one user (which could be a prospective buyer, insurance company, or any relevant stakeholder), and multiple owners, as shown in Figure 8.2. The super admin account was funded with Ether using the Sepolia Faucet, a free service for acquiring test Ether for development purposes. The Sepolia testnet imposes a limit of 0.5 Ether per request every 24 hours, as shown in Figure 8.3, which required multiple visits to accumulate a sufficient amount of test Ether for the experiment.

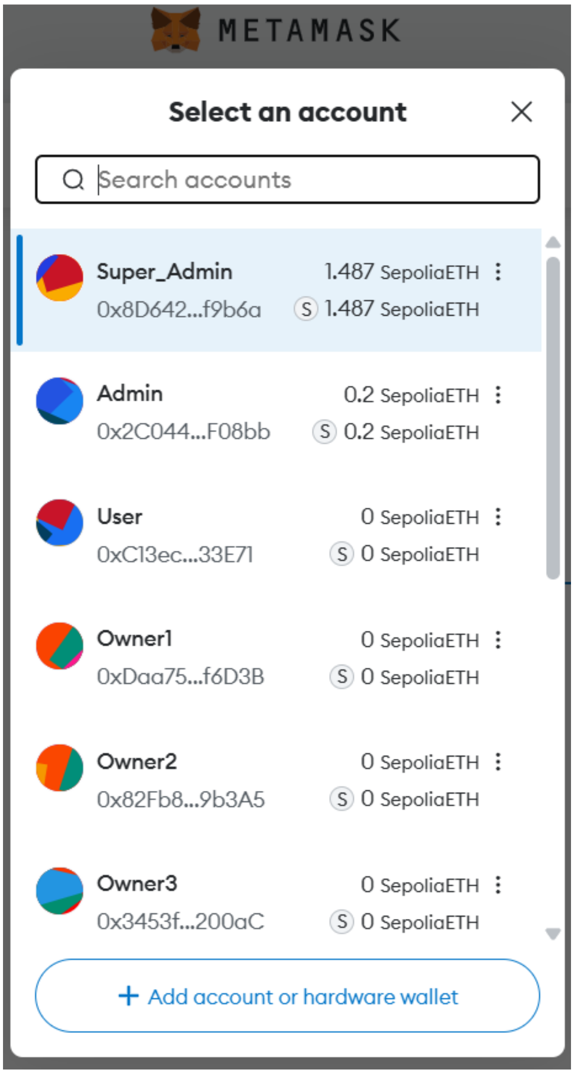

Figure 8.2: Screenshot showing the accounts created in MetaMask, including the super admin, one admin, one user (which could represent any stakeholder), and multiple owners.

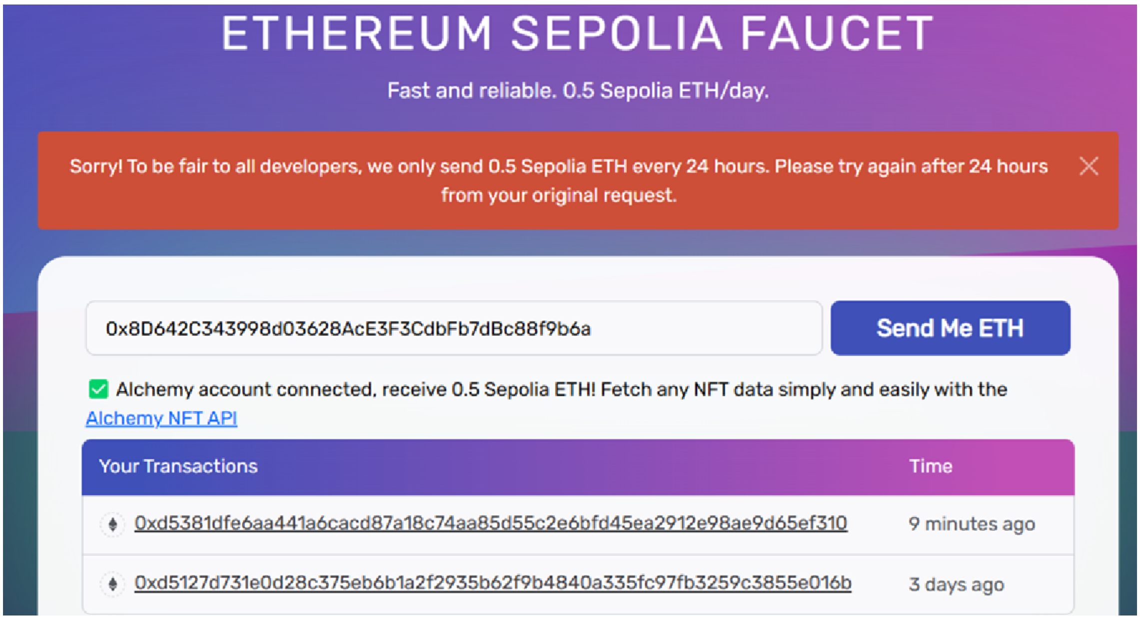

Figure 8.3: Screenshot showing the 0.5 Ether limit imposed by the Sepolia Faucet

8.2.2 Frontend setup

The frontend of the GREP platform was developed using React.js, a JavaScript library widely used for building user interfaces. React.js enabled the development of dynamic and responsive user interfaces. To begin the development process, we used the command npx create-react-app my-react-app, which sets up a new React project with all the necessary dependencies pre-installed, as illustrated in Figure 8.4.

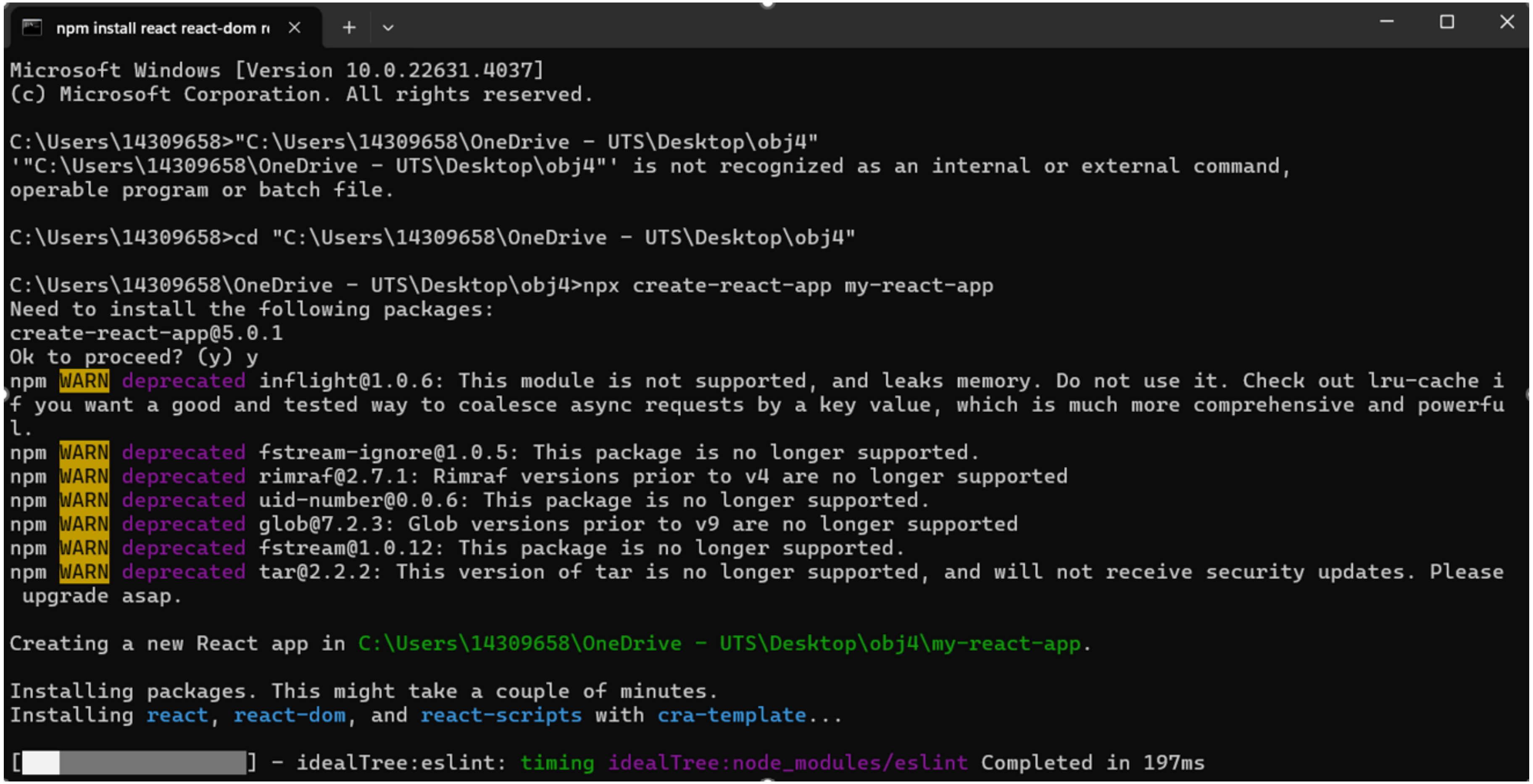

Figure 8.4: Screenshot of the React application setup using the `npx create-react-app` command

For blockchain interaction, we utilized Web3.js, a JavaScript library that enables communication between the frontend and the Ethereum blockchain. Web3.js was integrated into the React app, allowing users to connect their MetaMask accounts, submit transactions, and interact with the smart contracts deployed on the Ethereum network. This connection ensured that users could perform actions such as submitting property ownership proof and provenance inquiries directly from the interface.

The development environment was powered by Node.js, which provided the runtime necessary to run the development server and compile the React application. Node Package Manager (npm) was used to manage project dependencies and ensure that all the required libraries, such as React and Web3.js, were installed and updated as needed. In addition, Visual Studio Code (VS Code) served as the primary code editor, facilitating the creation and debugging of React components and Web3.js integration. The overall file structure of the React application is illustrated in Figure 8.5.

The implementation design of the GREP prototype is summarized in Figure 8.6. The frontend development primarily utilized React.js to create the user interface, while Web3.js and MetaMask served as the bridge to facilitate communication between the frontend and backend. On the backend, Remix IDE was used to develop and deploy Solidity smart contracts, which serve as the backbone of the system.

```
    Directory: C:\Users\14309658\OneDrive - UTS\Desktop\obj4\my-react-app-MainObjectives\src


Mode                 LastWriteTime         Length Name
----                 -------------         ------ ----
da---l        29/08/2024  12:22 PM                contracts
-a---l        21/08/2024   7:05 PM           3564 AddProvenance.js
-a---l        29/08/2024  10:26 AM           1703 AdminPortal.js
-a---l        28/08/2024   4:26 PM              0 AdminPortalReviewRequests.js
-a---l        21/08/2024   1:26 PM            564 App.css
-a---l         1/09/2024   3:26 AM           2204 App.js
-a---l        21/08/2024   1:26 PM            246 App.test.js
-a---l         1/09/2024   2:06 AM           3651 FractionalOwnershipTransfer.js
-a---l        21/08/2024   1:26 PM            366 index.css
-a---l        21/08/2024   1:26 PM            535 index.js
-a---l         2/09/2024   5:40 AM           5081 IssueNFTSingleOwnership.js
-a---l        21/08/2024   1:26 PM           2632 logo.svg
-a---l        28/08/2024   4:49 PM           4836 ManageProvenanceEntry.js
-a---l         1/09/2024   3:54 AM           5723 OwnershipPercentages.js
-a---l         2/09/2024   5:14 AM           2003 PaymentPage.js
-a---l        27/08/2024  11:57 PM           3042 PropertyProvenanceInquiries.js
-a---l        21/08/2024   1:15 PM            564 RealEstateContract.js
-a---l        21/08/2024   1:26 PM            362 reportWebVitals.js
-a---l        21/08/2024   1:39 PM           1484 RetrieveProvenance.js
-a---l         2/09/2024   5:47 AM           2474 ReviewRequests.js
-a---l        21/08/2024   1:26 PM            241 setupTests.js
-a---l        30/08/2024   2:12 AM           5429 SharedOwnershipProofRequest.js
-a---l        29/08/2024  12:01 PM            574 UserPortal.js
-a---l        29/08/2024  12:14 PM           2699 VerifiedNFTownership.js
-a---l        21/08/2024   1:10 PM            992 web3.js
-a---l        29/08/2024  12:44 PM           2864 WelcomePage.js
```

Figure 8.5: Screenshot of the React application file structure, showing key folders for the application

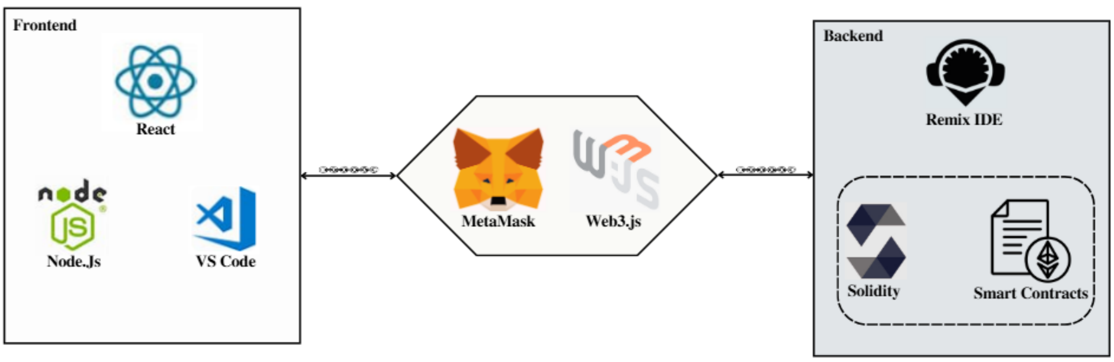

Figure 8.6: Overview of the tools used in the GREP prototype

8.3 Implementation of Real Estate Provenance Management in GREP (Objective 1)

This section demonstrates the functionality of the GREP prototype for Objective 1, which focuses on managing real estate provenance. The validation and the evaluation for Objective 1 were conducted in Chapter 5. The GREP platform serves as a unified system designed to manage property provenance, ownership verification, and shared ownership.

Figure 8.7 shows the GREP platform interface, which integrates the tools presented in the previous section. The homepage provides three main functionalities: Property Provenance Inquiries, Single-ownership Proof Requests, and Shared-ownership Proof Requests, along with options to access the Admin Portal, Sign Up, and Log In features.

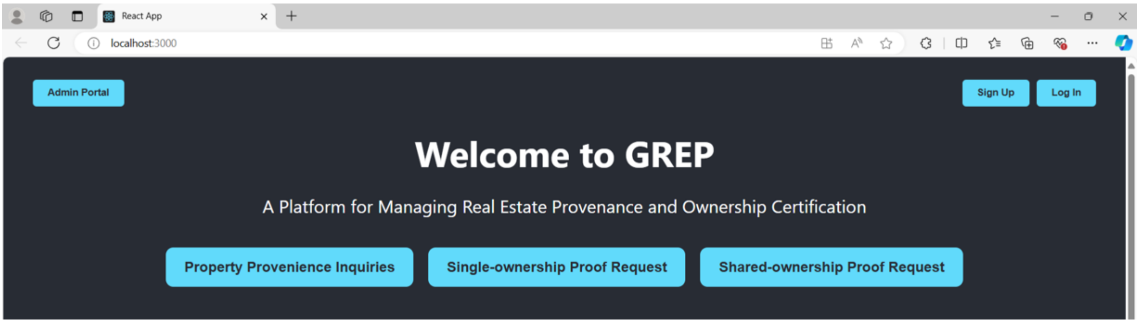

Figure 8.7: The GREP platform interface

Figure 8.8 displays the Admin Portal for property provenance data entry, which is only accessible by authorized entities, such as the super admin. This portal ensures that only verified personnel can input and manage provenance data.

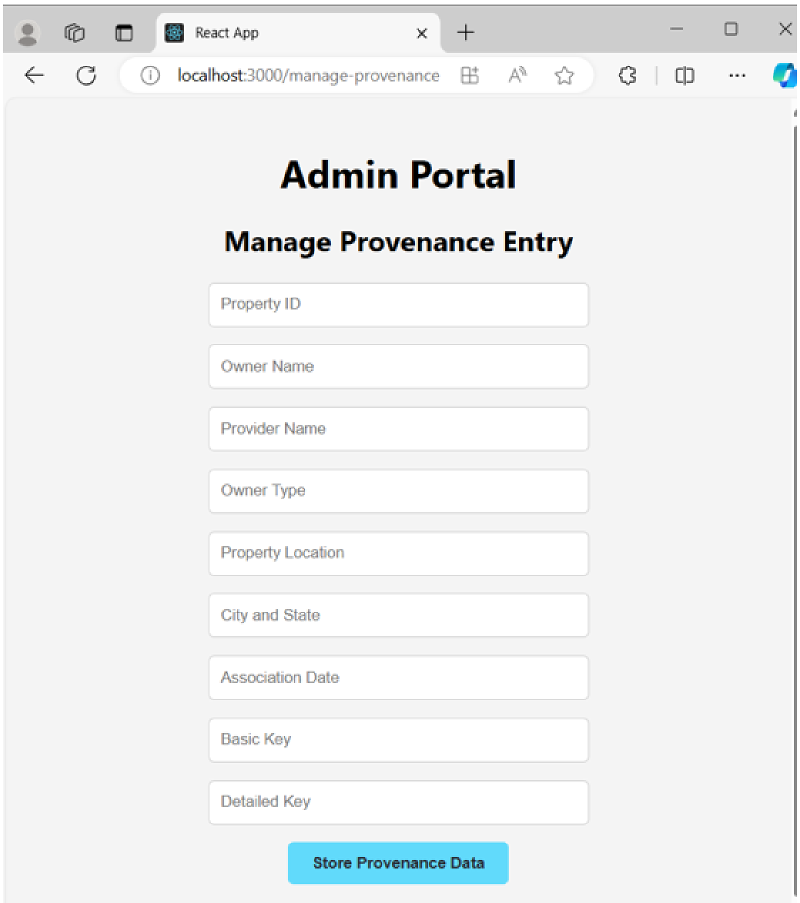

Figure 8.8: Admin portal for provenance data entry

As an example of property provenance data, Table 8.1 provides an example of provenance records. The authorized entity is expected to enter this data, which the system stores and makes available for future retrieval.

Table 8.1: Example of provenance data input

propertyId	ownerName	providerName	ownerType	propertyLocation	City and State	associationDate	basicKey	detailedKey
265711	GROSSBERG, GABE	DELMAR GARDENS OF MERAMEC VALLEY	Individual	#1 ARBOR TERRACE	FENTON, MO	since 04/08/2005	666	777
265711	NON-GST FAMILY TRUST ESTABLISHED	DELMAR GARDENS OF MERAMEC VALLEY	Organization	#1 ARBOR TERRACE	FENTON, MO	since 04/10/2013	666	777
265711	PHILLIPS, YVETTE	DELMAR GARDENS OF MERAMEC VALLEY	Individual	#1 ARBOR TERRACE	FENTON, MO	since 10/01/2014	666	777

Figure 8.9 demonstrates the successful entry of provenance data by the super admin. After completing the form with all the relevant details, the system confirms that the data has been stored successfully, ensuring the accuracy and trustworthiness of the property records.

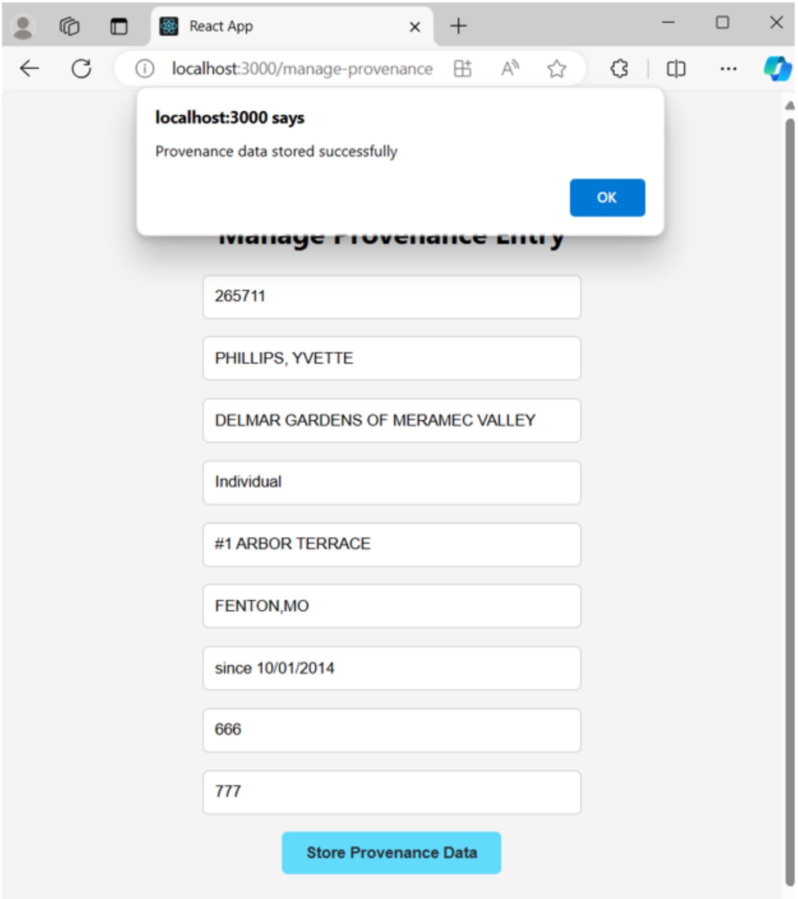

Figure 8.9: Successful provenance data entry

After the super admin enters the provenance data and the system stores it, the provenance data becomes available for stakeholders. By entering the Property ID and either the basic key or detailed key, they can retrieve the data. Figure 8.10 shows the interface for Property Provenance Inquiries, where users can input the necessary information to access the stored provenance details.

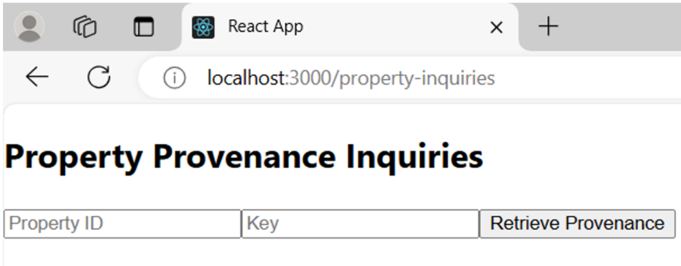

Figure 8.10: Interface for property provenance inquiries

Figure 8.11 illustrates the retrieval of provenance data for Property ID 265711 using the basic key (666), which provides basic ownership information. Alternatively, Figure 8.12 demonstrates the retrieval of more detailed provenance information for Property ID 265711 using the detailed key (777), derived from the information in Table 8.1.

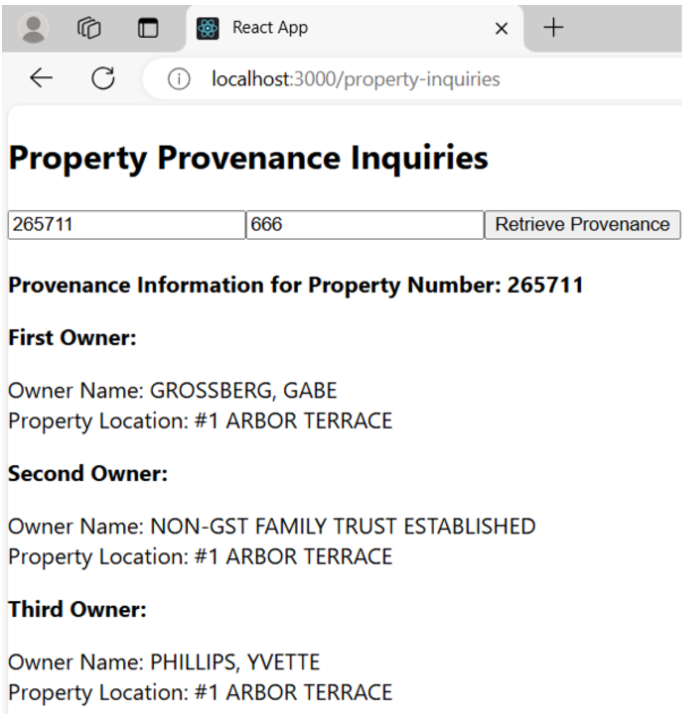

Figure 8.11: Retrieval of provenance data for Property ID 265711 using the basic key

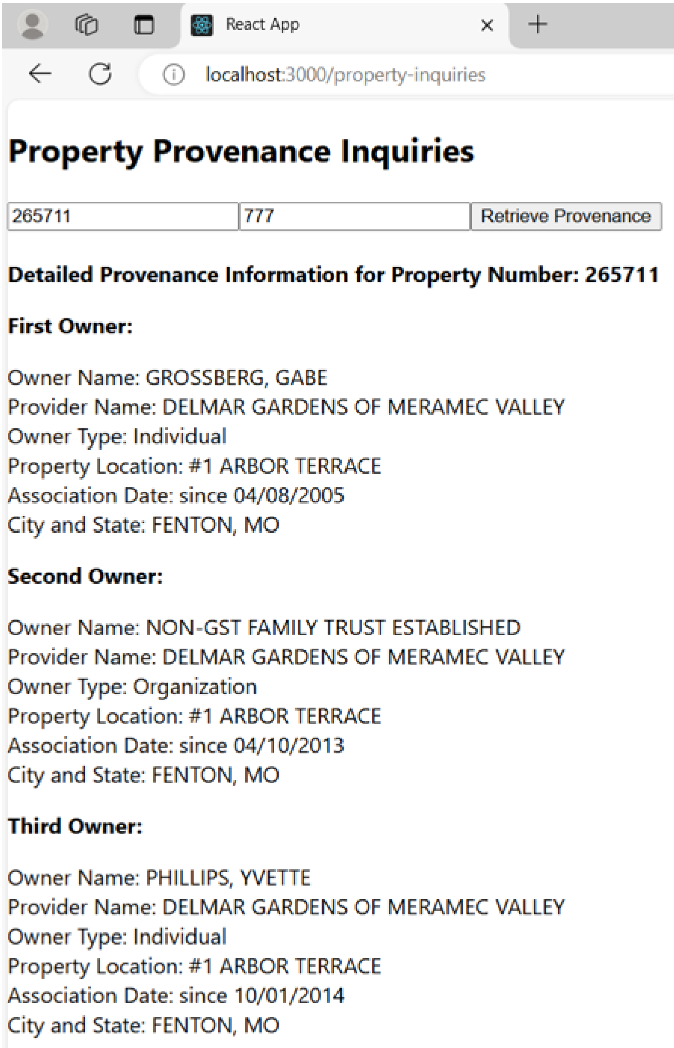

Figure 8.12: Retrieval of detailed provenance data for Property ID 265711 using the detailed key

8.4 Implementation of Ownership Proof of a Real Estate Property in GREP (Objective 2)

In this section, we demonstrate how the GREP prototype implements Objective 2, which focuses on providing a reliable method to prove ownership by issuing an NFT for the property owner. The validation and the evaluation of this solution were conducted in Chapter 6, where its effectiveness was assessed using predefined test cases and performance metrics.

The process begins with the owner fulfilling the requirements set by the government authority. These include, first, submitting a request on the GREP platform to issue an NFT for a single owner, as illustrated in Figure 8.13. The owner provides several details such as Property ID, Owner Name, Owner Type, and Property Location, and uploads any relevant documents.

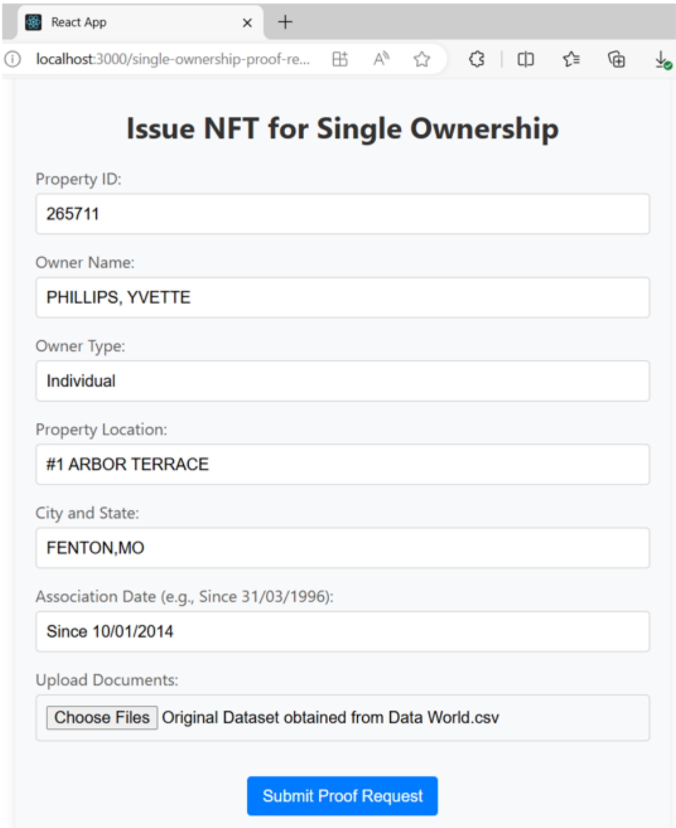

Figure 8.13: Submission of an NFT issuance request for a single owner on the GREP platform

Second, the owner is required to pay any necessary fees for the transaction, which covers the blockchain gas fees for executing the smart contract, as illustrated in Figure 8.14. The required amount in ETH (Ethereum) is calculated and displayed for the owner, along with the equivalent amount in USD.

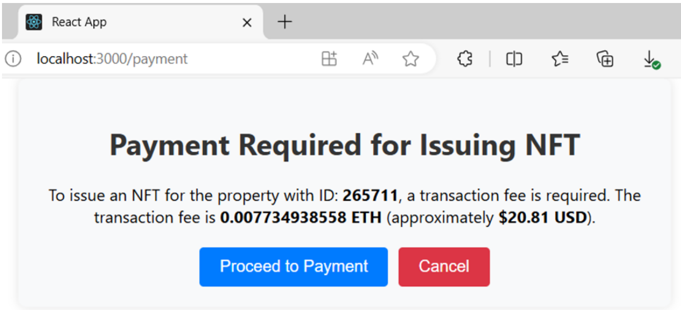

Figure 8.14: Payment interface for the NFT issuance transaction

Once the owner fulfills the requirements, the government authority receives the owner's request in the Admin Portal. The admin can review the request, verify the provided information, and then either accept or reject it based on that verification, as demonstrated in Figure 8.15.

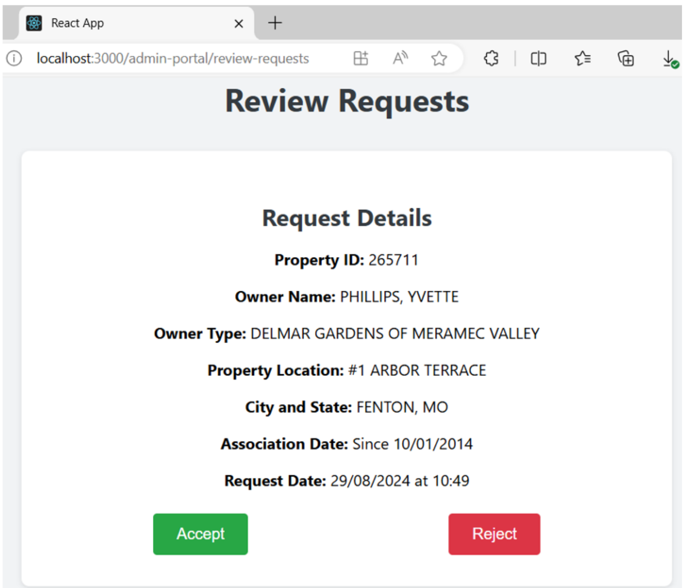

Figure 8.15: The Admin Portal where the government authority reviews the owner's NFT issuance request.

Upon the authority's approval of the owner's request, the owner receives an NFT as a certificate of ownership, which is stored in their wallet. The owner can also access the platform through the User Portal to review the verified NFT certifications. The certificate includes the ownership details, along with the basic Key and detailed Key, which can be used for ownership verification on the platform (see Figure 8.16).

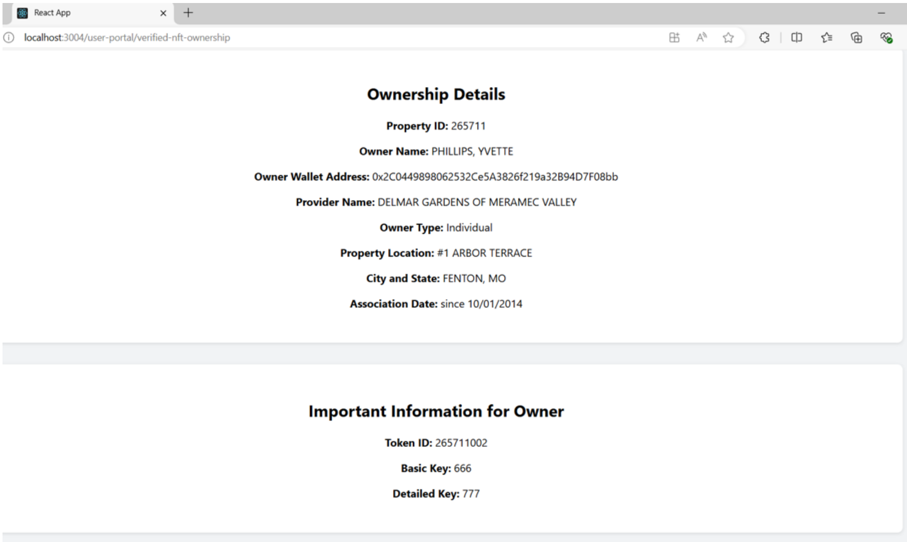

Figure 8.16: The user portal displaying the verified NFT certificate of ownership

8.5 Implementation of Shared Ownership Proof in GREP (Objective 3)

This subsection extends the prototype's implementation to manage the creation, division, and transfer of shared ownership using fractional NFTs, which aligns with Objective 3. The validation and the evaluation of this solution were conducted in Chapter 7, where multiple use cases and evaluation metrics were applied to assess its effectiveness and reliability.

To fractionalize the property NFT, the owner must fulfill the authority's requirements, which include the following steps:

First, the owner submits a request on the platform, as shown in Figure 8.17, assuming the owner already possesses an NFT certificate for the property. The owner must input the Property ID along with the Current Owner's Wallet Address. The owner can then add the new owners' wallet addresses, specifying the ownership percentages for each, which must total 100%. For example, the current owner can retain 10% ownership, while two new owners can be allocated 85% and 5%, respectively. If the owner does not have an NFT yet, they must first submit a request for Single Ownership Proof to obtain the NFT.

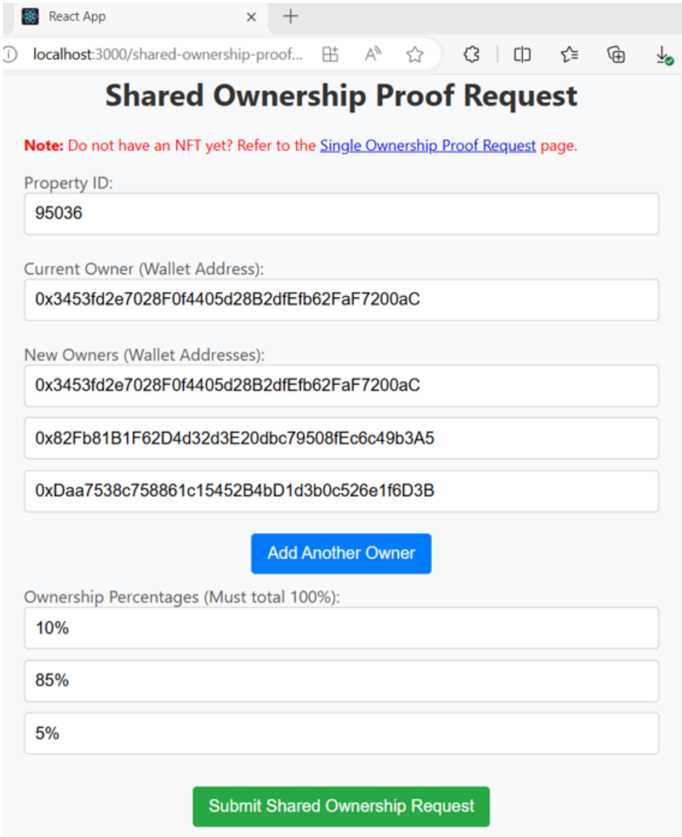

Figure 8.17: Submission of a request for fractionalizing the property NFT using fractional NFTs on the platform. The owner must already possess an NFT certificate for the property

Second, the owner is required to pay the necessary fees related to the transaction, as shown in Figure 8.18, to cover the blockchain gas fees for executing the smart contract to fractionalize the property.

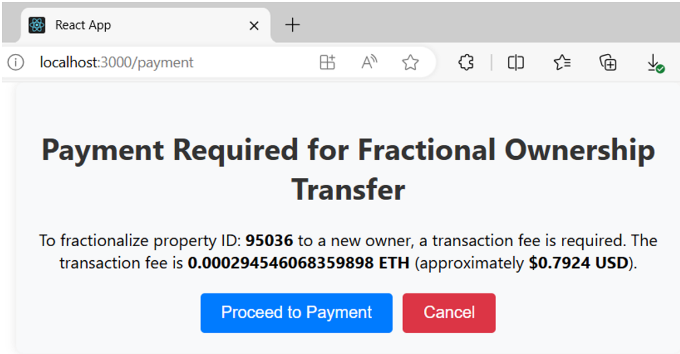

Figure 8.18: Payment interface for the fractionalization of the property NFT using fractional NFTs

Upon the authority's approval of the shared ownership request, the system records the fractional ownership details on the blockchain and sends the fractional NFTs to the respective owners' wallets. Moreover, the owners can access the platform to view their verified ownership shares through the User Portal, which displays the percentage of ownership held by each wallet address, as shown in Figure 8.19. In this case, the Property ID is 95036, and the ownership percentages are divided as follows:

10% is held by the wallet address `0x3453fd2e7028F0f4405d28B2dEfb62FaF7200aC`, 85% by `0x82Fb81B1F62D4d32d3E20dbc79508fEc6c49b3A5`, and 5% by `0xDaa7538c758861c15452B4bD1d3b0c526e1f6D3B`, as suggested by Figure 8.17. The graphical pie chart in Figure 8.19 further illustrates the ownership distribution among the three wallet addresses for Property ID 95036.

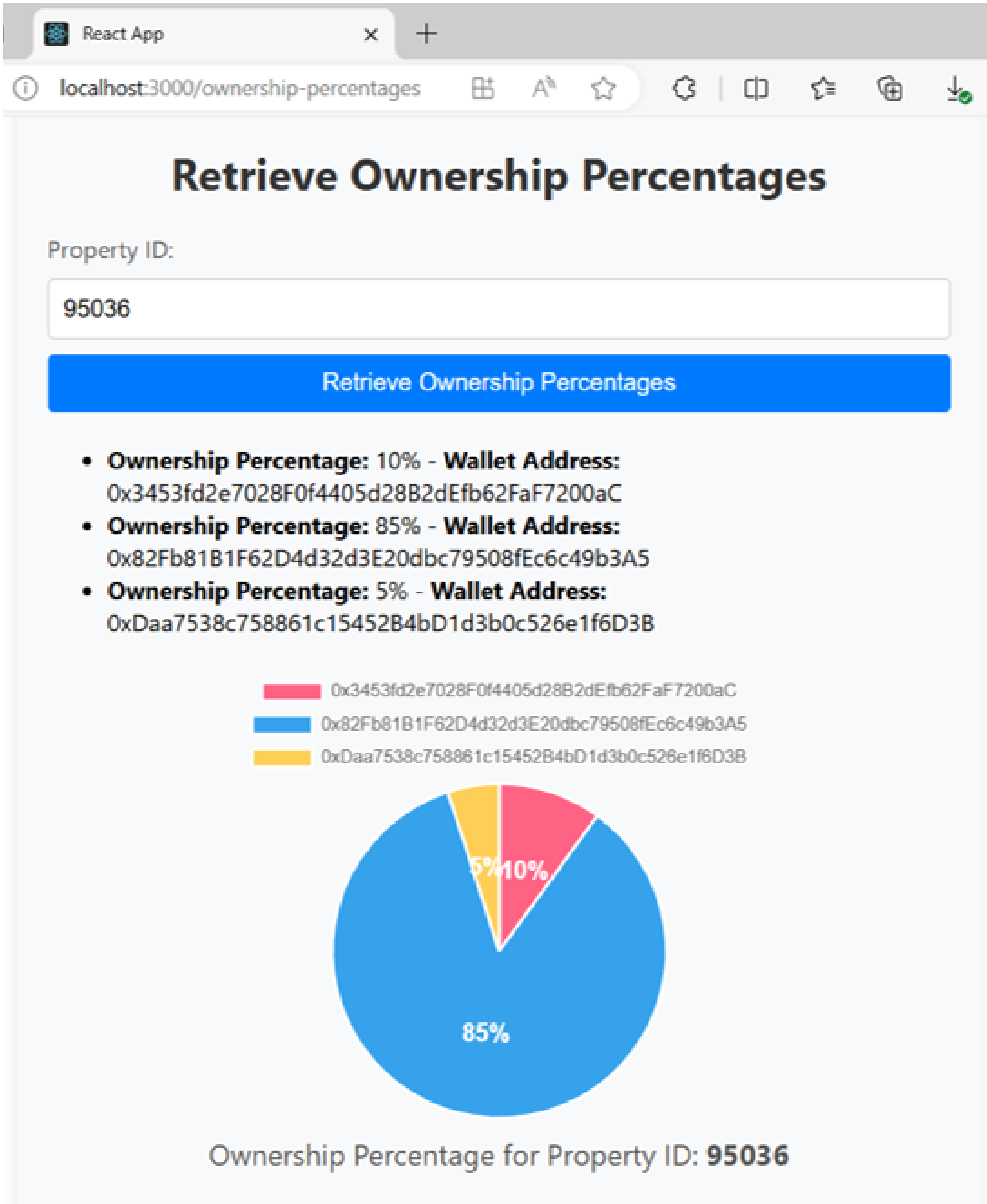

Figure 8.19: Displaying the fractional ownership distribution of the property, with ownership percentages linked to each wallet address after issuing fractional NFTs

The GREP platform also enables fractional NFTs to be transferred between users. Once the owner meets the required conditions, they can initiate the transfer of ownership shares. As shown in Figure 8.20, the owner enters the necessary details, including the Property ID, their wallet address, the recipient's wallet address, and the percentage of ownership to be transferred. After completing the form, the owner can submit the transfer request to redistribute the fractional ownership.

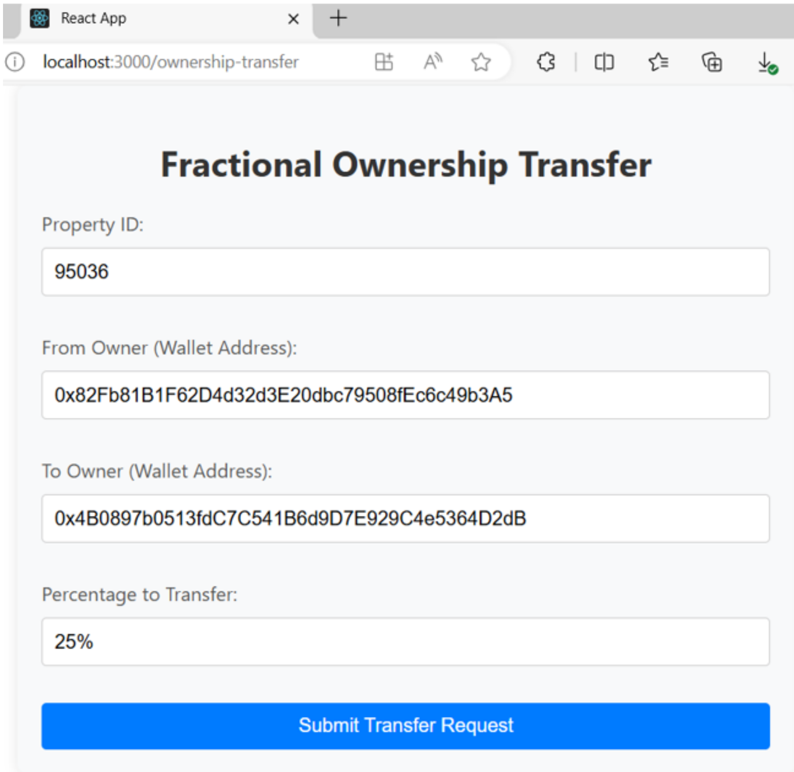

Figure 8.20: Transfer of fractional NFTs on the GREP platform

After the approval of the fractional ownership transfer request, the updated ownership percentages are stored on the blockchain and the fractional NFTs are sent to the respective owners. As shown in Figure 8.21, the updated distribution of ownership percentages for Property ID 95036 now reflects the changes after the transfer. The ownership percentages are displayed for each wallet address, and the corresponding chart visually represents the distribution. The ownership percentages have been updated to 10%, 60%, 5%, and 25%, accurately reflecting the current ownership shares after the transfer.

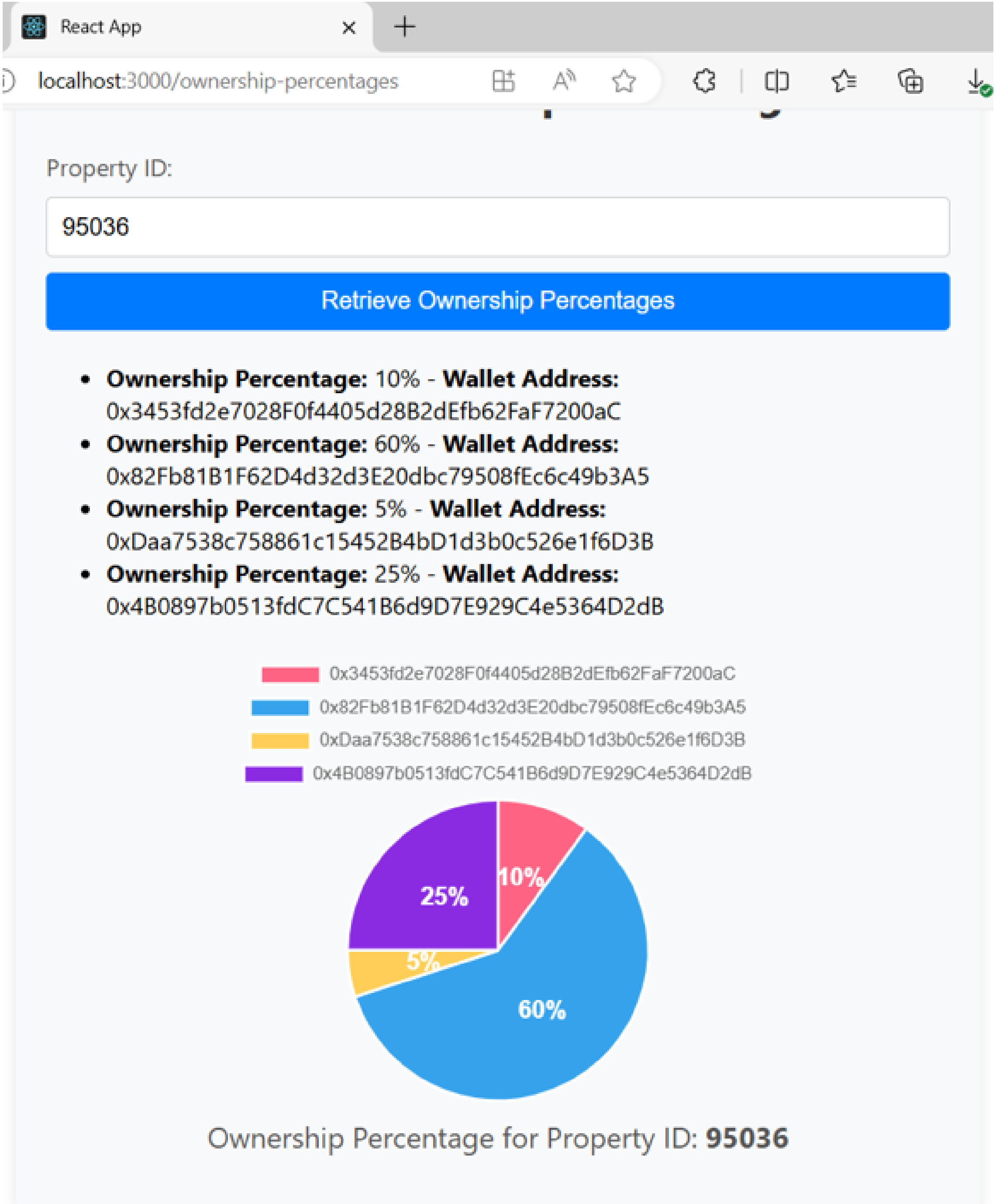

Figure 8.21: Updated ownership distribution for Property ID 95036 after the transfer

8.6 Conclusion

In this chapter, the setup and implementation of the GREP prototype were presented, outlining the tools and technologies used for both the backend and frontend development. The GREP prototype successfully demonstrates the management of real estate provenance, ownership verification, and shared ownership. The prototype also highlights the platform's ability to handle ownership transfers, securely record ownership information, and provide transparent, verifiable records on the blockchain. Collectively, the prototype implementation demonstrates the feasibility and real-world applicability of the proposed solutions within a unified system. This feasibility demonstration represents the final component of Objective 4, complementing the developments conducted in Chapter 5, Chapter 6, and Chapter 7, where the developed solutions were validated and evaluated.

In the next chapter, we summarize the key findings, highlight the thesis's contributions to the existing literature, and discuss its limitations and future research directions for enhancing and expanding the developed solutions.

CHAPTER 9

Conclusion and Future Work

9.1 Introduction

This chapter reviews the thesis's findings, discusses its contributions to the literature, and explores limitations and future research opportunities. Section 9.2 revisits the main issues addressed in the study, followed by Section 9.3, which highlights the research contributions to the existing literature. Finally, Section 9.4 concludes the thesis by discussing the study's limitations and highlighting areas for future research and improvements.

9.2 Key Issues Addressed in the Thesis

In this thesis, we conducted a comprehensive nine-step systematic literature review to explore the integration of blockchain technologies in managing real estate transactions and ownership certification. During this process, several gaps were identified, which were detailed earlier in the thesis. The key gaps addressed in this thesis are as follows:

1. The lack of a global platform for managing and tracing real estate provenance, along with a lack of studies specifically on real estate provenance within the existing literature.
2. The lack of a reliable method to prove ownership of real estate property, as traditional methods remain burdened by inefficiencies and vulnerabilities.
3. The lack of a reliable method to prove shared ownership of real estate property, as existing literature focuses on ordinary scenarios and does not address cases like creating, dividing, and transferring shared ownership of real estate property.
4. The lack of a validated and evaluated real estate platform for managing real estate provenance and ownership certification, as well as a lack of empirical studies in this field to build upon.

9.3 Research Contributions to the Literature

Corresponding to the key issues mentioned in the previous section, this research introduces GREP, a unified platform for managing real estate provenance and ownership certification. The following sub-sections outline the overall contributions of this thesis to the existing literature.

9.3.1 A detailed systematic literature review

This research provides a detailed review of the literature including a rigorous nine-step methodology and a comprehensive GSA keyword strategy to effectively categorize and retrieve all relevant studies. The process began with 505 studies, and through successive filtration stages, 19 studies were identified and selected for further analysis. All literature is assessed based on specific analytical standards. Based on these standards, further observations, implications, and recommendations are provided for each analytical standard. Beyond offering valuable insights into blockchain applications for managing real estate provenance and ownership certification, this study's systematic approach provides a robust framework that is applicable to other systematic literature review studies. A journal paper is currently under preparation to publish the content of this contribution.

9.3.2 The creation of GREP: A platform for managing real estate provenance and ownership certification

This thesis introduces GREP, a hybrid blockchain-based platform that incorporates real estate provenance, NFTs, and fractional NFTs to manage real estate provenance and ownership certification. GREP provides a unified and secure solution that addresses the gaps in both current real estate systems and the existing literature. The system is designed for managing the processes of provenance entry, retrieval, and updating, all of which are described in detail with a dedicated algorithm. GREP defines three distinct user roles, each with varying levels of authority and system access: super admin, admin, and regular user. A journal paper covering the contributions of this solution has been published in *Springer* and can be accessed at `https://link.springer.com/article/10.1007/s11761-024-00403-0`.

9.3.3 Developing a reliable method to prove ownership of real estate property

This research develops a secure and reliable method for proving ownership of real estate property, overcoming the limitations of traditional and web-based methods that are vulnerable to manipulation and unauthorized alterations. By leveraging blockchain technology and NFTs, this method ensures that property ownership is verifiable, traceable, and resistant to manipulation. The system is designed based on an improved ERC-721 standard, specialized for adding owners and minting NFTs for them. It creates a special token ID formula that facilitates the tracking of owners and their respective NFTs. A journal paper has been submitted to *Blockchain: Research and Applications* and is currently under review for the publication of this contribution.

9.3.4 Developing a reliable method to prove shared ownership of real estate property

In addition to proving individual ownership, this research introduces a method for proving the shared ownership of real estate property using fractional NFTs. This method allows for the creation, division, and transfer of shared ownership in a secure and transparent manner, addressing a critical gap in the existing literature. The system is built on an enhanced ERC-721 standard, which is designed to mint NFTs for owners who do not yet possess them and fractionalize the NFTs for multiple owners. It also enables the transfer of fractionalized NFTs, further proving the reliability of the system. This contribution is partly published in the proceedings of the *2023 IEEE International Conference on e-Business Engineering (ICEBE)* and can be accessed at `https://ieeexplore.ieee.org/abstract/document/10356171`.

9.3.5 Implementing, validating, and evaluating the developed solutions

This thesis implements, validates, and evaluates GREP, addressing a significant gap in the existing literature. The implementation of the proposed solution is described in detail for each objective, ensuring that the system is reliable and functional for its intended purpose. Furthermore, several scenarios are explored to demonstrate the system's effectiveness and validate the proposed solutions. Each objective is evaluated using relevant metrics to assess performance and reliability.

In addition, the prototype demonstrates the feasibility of integrating all developed solutions into a unified system. Details of the implementation, validation, and evaluation of GREP have been partially published within the previously introduced articles, contributing to the existing literature.

9.4 Limitations and Future Work

While this research provides a robust framework for real estate provenance and ownership certification using blockchain technology, there are still certain limitations that need to be addressed. These limitations also present opportunities for future research and system enhancements, including:

- **Enhancing System Usability Through a More Comprehensive Dataset:** The dataset used in this study covers only a limited scope of real estate provenance and ownership aspects. A more comprehensive dataset with richer information could improve system usability. Possible enhancements include:
  - Utilizing owners' provenance as an indicator of credibility and trustworthiness.
  - Expanding the system to integrate a wider range of property-related information, such as data on average utility bills (e.g., electricity and water) and landlords' payment reputations.
- **Smart Contract Optimization:** As the evaluation is part of the objectives in this study, multiple functions and events were implemented to assess system performance. However, these additional functions led to higher transaction costs and unnecessary computational overhead. Future work could focus on developing optimized smart contracts that prioritize core functionalities while

eliminating non-essential functions and events, which would lower transaction processing time and cost.

- **Gas Price Management:** One limitation of the current system is the variability of gas fees. Fluctuations in gas fees directly impact transaction costs, making it challenging to estimate expenses in advance. Hybrid blockchains provide a more controlled environment that allows for better gas fee management. Further research is needed to utilize this feature to stabilize gas prices at the lowest possible level, enhancing overall system predictability and cost-efficiency of transactions within the platform.

- **Advancing Towards a Market-Ready Product:** While this study focused on the development, validation, and implementation of a proof-of-concept system, it did not aim to advance the system into a fully market-ready product. Further enhancements to the framework are required to align it more effectively with practical applications and market demands, including incorporating additional functionalities and conducting broader testing to transition the system into a fully operational product.

Such advancements can open up new possibilities, including using the system as a secondary identifier and assisting international owners with no prior data to engage in the market, addressing the cold-start problem commonly found in recommender systems. Future work should also explore broader challenges such as incorporating the system into the real estate market, overcoming user adoption barriers, mitigating widespread security threats, and evaluating the economic implications of the system.

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