

Article

Practicality of Blockchain Technology for Land Registration: A Namibian Case Study

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Abstract

In the context of the information age, a land administration system must be technologically driven to manage land information and data transparently. This ensures the registration and protection of land rights for people. In this study, we present a Blockchain Land Registration system designed as a tool for enhancing land administration in South Saharan Africa (SSA). Drawing inspiration from Namibia, we have developed a user interface comprising a homepage/landing page, a users' registration form, a login form that incorporates MetaMask authentication prompts, and an authenticated dashboard for landowners and purchasers. Design Science was employed as the methodology for this proposal. Being technical design research for solving a land administration problem (that of inefficient land registration), the technical solution identified involves system design, the development of blockchain integration and testing, and development aspects. Based on this approach, blockchain was conceptualised as an "artefact" that could be investigated as a technical solution to address the challenges posed by inefficient land registration. This study provides a comprehensive roadmap for the conceptualisation, development, validation, and deployment of a blockchain-based land titles registry suitable for SSA countries. It also explores a discussion on the practical and policy implications of blockchain in land administration in SSA countries.



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Keywords: blockchain; land; land administration; land registration; land registry; smart contract; transparency

1. Introduction

Land is critical in developing all African economies, especially in sub-Saharan Africa (SSA). A sovereign role of the governments of countries in this region is "the development of their land administration system (LAS) to deliver sustainable development [1]. Land governance is the environment within which land administration systems exist [2]. Land governance is "the decision-making and activity-based practice that hinges on how land and other land-based resources improve people's living conditions and their environment" [3]. Hence, for a land governance system to be effective, it is mandatory to have a locally practicable land administration.

Many definitions of land administration exist [2,4,5]. However, the most acceptable definition identifies land administration as "the processes of determining, recording and disseminating information about the ownership, value, and use of land when implementing

land management policies” [6]. This study aligns with this definition because it recognises that land administration is a spatial data infrastructure for land governance. It hinges on the need for formal registration of land ownership and rights. A practicable land administration system is mandatory for appropriate governance of land because it will lead to “efficient and effective flow, and accessibility to reliable information on land and landed property, between, and amongst land sector agencies, as well as between these agencies and the public” [7]. To achieve such a system, reliance on technology that involves automated processes is mandatory. Such a system remains a missing link in land governance in SSA. Land administration systems that are practicable and capable of integrating land information and spatial data (particularly on land ownership, use, and rights) and allowing transparent data access and use for land sector service delivery are still challenging in SSA [8].

A land administration system cannot be effective, at least in the context of the information age, without being technologically driven in handling land information and data transparently for the registration and protection of land rights of people [9,10]. In this regard, many development organisations (such as the World Bank, United Nations agencies, and some researchers) have proposed the adoption of computer-aided and digital technology systems in support of land sector agencies in addressing the land information, data management and governance challenges in [11]. Over the past decades, digital land administration has been piloted and installed in land administration systems across SSA. Scholars have championed adopting blockchain technology in recent years [9,12,13]. Blockchain technology is a distributed digital ledger that securely records transactional data across a distributed network of computers in a consistent and linear mechanism [7]. Blockchain ensures data transparency through its immutable nature, based on cryptography techniques. This means that once land information is recorded, it cannot be altered retroactively [14]. The call to integrate blockchain technology in national land administration systems has been made for South Africa [9], Nigeria [12], Kenya [13], Ethiopia [15], Ghana [16], and in other countries [17].

While there have been several calls for adopting blockchain technology in SSA, there is a gap in the practicality of this technology. A lot has been published on blockchain, but most of these publications have focused on its relevance, need, and potential for SSA [9,10,12–17]. Not much has been researched or written about the technical practicality of its implementation.

For the reasons mentioned above, this research presents the development of a blockchain-based solution for land registration that can be used as a part of land administration in SSA. The focus of this paper is to describe technical aspects of the blockchain solution from a practical point of view.

By using this type of solution, some of the land administration challenges in SSA can be addressed. Also, an improvement of the overall effectiveness of land administration can be a byproduct.

This work was guided by the following research questions:

- What system design can be used for blockchain-based land registration?
- How can the blockchain be developed and integrated?
- How can the designed system for blockchain be tested and deployed for land registration?
- What are the practical and policy implications of using blockchain in land Administration in SSA Countries?

The study is structured sixfold. The next part (Section 2) presents the land administration challenge that necessitates the adoption of blockchain in SSA. Section 3 presented the methodology of the study. Section 4 is the output of the study. This part presents

the practical solution of blockchain for land administration in SSA countries. Section 5 presents an overall discussion on the emerging policy implications of blockchain in land administration in SSA countries. Section 6 is the conclusions.

2. Land Administration Challenge and Potential for Blockchain in SSA: An Overview

2.1. *The Land Administration Challenge in SSA*

To better grasp the context of land administration challenges in SSA, it is crucial to view land administration from an African perspective. This African lens of land administration has been captured by the African Union in [18], which defined land administration as “the structure and processes for the determination, archiving and delivery of land rights, and the systems through which general oversight on the performance of the land sector is managed.” From the context, land administration is a veritable tool for securing the land and real estate of citizens because its core function is to define, record, and store information and data on the relationships between people and land to protect citizens by asserting the provability of land ownership and rights. Without land administration, it will be impossible for citizens (especially the poor) to enjoy land tenure security (i.e., the rights individuals and groups have to effective protection by the state against forced eviction) to improve their living conditions [1].

The traditional land registration process in most SSA countries is vulnerable to inefficiencies (including lack of transparency, corruption, repetitiveness, time-wasting, high cost, and all forms of manipulation) that make it unreliable for ordinary citizens to rely on it for the security of their land and property [10,12,13]. In most SSA countries, “data stored in LASs are mostly found to be inconsistent, inaccurate, and tampered data” [14]. Some of the challenges in land information are due to honest mistakes made in the process of registration. Some are due to the manipulation of data by dishonest staff in the land agencies (e.g., land registration offices). In jurisdictions where the governance systems are weak, the LAS databases are exposed to corruption [1]. In all cases, the rates of land conflicts are high (and difficult to resolve) due to the lack of land data or inaccurate data. The generality of the land administration problems in SSA, according to the African Union [18], indicates that the land sector is still dependent on colonial structures, and that it is lagging behind in the use of technology in securing land records.

In the former British colonies such as Kenya, Zimbabwe, and South Africa, the failure to resolve historical claims arising from colonial expropriations compounded by unequal re-distribution of land after independence, remains a primary source of conflict. In other parts of Africa, such as the mineral-rich countries of Angola, the DRC, Southern Sudan, Sierra Leone, and Liberia, conflicts over land spurred by global commercial interests have been intense. In yet others, such as Uganda, Rwanda, Burundi, Somalia, the Central African Republic, the Republic of Congo (Brazzaville), and the Ivory Coast, persistent conflicts over the last two decades have led to large numbers of internally displaced persons (IDPs), raising complex issues about access to land, resettlement, and rehabilitation. Moreover, these conflicts have, in many countries, led to forced evictions and horrific atrocities (including genocide) against non-combatants, mainly women and children. Thus, apart from dealing with issues relating to the redress of historical injustices and the attainment of social equity, land policy development and reform must address the problem of conflict prevention and the restoration of peace and security in Africa.

Various scholars have confirmed these concerns [19–22]. Land administration’s effectiveness in supporting economic growth and sustainable development is well documented [23]. However, most of the land in SSA countries is undocumented or unregistered, owing to an inadequacy of the prevailing formal land administration systems to cover the

urban and rural areas [1,5,7]. This has posed a challenge in delivering land titles and coordinating the title management systems for land tenure security [15]. Furthermore, the high fees and lengthy procedures associated with property registration have resulted in numerous violations of title administration (Simon J., personal communication, 7 September 2022). Dealing with these problems requires effective land governance, which is impossible without reliable land administration systems (LASs) in these countries. Hence, LAS represents a public repository of land data to ensure correctness, equitable and affordable access, appropriate use, and tenure security. LAS functions are based on land registration, documentation, and storage of land information and data. Unfortunately, the reliance on manual LASs means that land transactions in SSA are still slow, insecure, and non-transparent. This is why most land parcels in most SSA countries are still undocumented or unregistered. This implies that it is still a challenge to identify who owns what land, where, and for what the land is used in SSA. It is also why this study argues for the practical adoption of blockchain in SSA countries.

2.2. Blockchain and Its Potential in Land Administration in SSA

Blockchain technology works based on the concept of blocks. Tiana [24] credits Satoshi Nakamoto¹ with inventing the concept of “blocks” and “chains” to organise and secure records [25], which led to the introduction of blockchain technology. The decentralised time-stamp server, which operates on a peer-to-peer network, ensures that the integrity and authenticity of entries can be confirmed and validated using mathematical verification. Müller and Markus [26] defined blockchain as an ever-expanding network of interconnected records secured by encrypted data exchange. Each block contains transaction data, a timestamp, and a reference to the previous block (Figure 1). This ensures secure transactions even in unreliable environments because the blockchain uses a consensus algorithm agreed upon by all parties validating new transactions. This has resulted in widespread adoption across countless industries, including land administration [27].

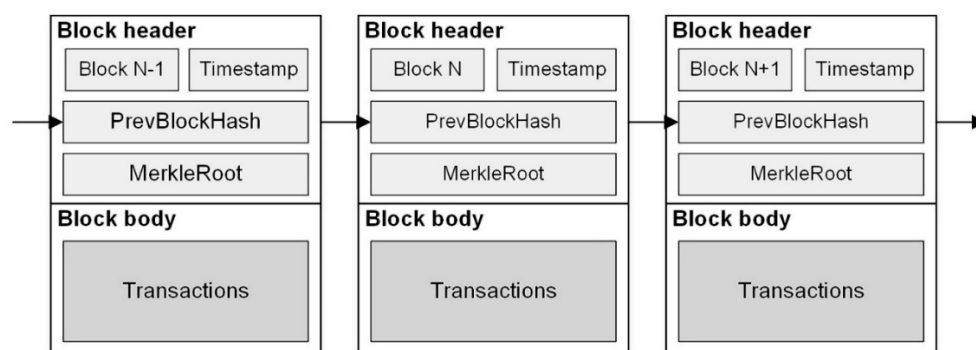


Figure 1. A schematic representation of a blockchain.

Considering its several land administration challenges, blockchain has high potential in SSA. Being a distributed ledger, blockchain technology (when compared to other transaction records management ledgers) offers a possibility for a more reliable and viable database for land administration [9,10]. The novelty of blockchain is that it can give immutability and authenticity to land records, a core necessity in land administration [13,16]. It is also based on peer validation of records, which enables fast execution of land transaction processes and decreases transaction costs [12,17]. It can reduce human error and the opportunity for corruption in land transactions and provides greater transparency and accountability between government agencies and citizens [14,15]. Despite blockchain’s advantages, scholars within land governance (including land management, land policy, and land administration) have focused on researching the relevance and potential of blockchain

use in the land sector. Ameyaw and de Vries [7] identified the main potential for blockchain in SSA to be that:

“Against other transaction records management ledgers, some uniqueness of blockchain technology center on; the traceability of records which are linked to each other in a linear chain system, the immutability of records, and the decentralised nature of the technology’s operation that requires consensus building among connected actors to a transaction before it can be completed.”

These features that make blockchain technology appropriate for SSA have the potential to contribute to the registration aspect of land sector challenges in the region. A core concern is that while most studies on the blockchain discourse hinge around its viability in SSA, fewer investigations have been conducted on its feasibility. This current study focuses on the technical practicalities involved in setting up a blockchain for land registration in operation.

2.3. Blockchain Land Registration for Effective Registration in Land Administration in SSA

The critical roles land tenure security plays in any nation are enabled through well-documented property ownership and rights. Without secure land and property rights, land conflicts may increase. These land conflicts, common in SSA countries, negatively affect development activities (including infrastructure, real estate development projects, and other economic activities). For instance, “when a dispute arises over a plot of land where a development project is to be carried out, the development cannot proceed until the land dispute is effectively settled, and this constitutes a source of major risks to investors” [28]. This leads to prolonged litigation and violence, which stifles the potential for land-based economic activities.

Land registration is one of the factors that ensures that people’s land ownership and rights are secured against unlawful evictions. Land registration is a land administration process involving formally recording land characteristics (including use, location, possession, interests and rights in land) to establish legal ownership [28]. This is usually evidenced by a land title [29]. It can facilitate transactions and protect owners and users against unlawful disposal. A land registration system usually contains official land and property records (including the deeds, mortgages, and titles). When land is registered, a unique identifying (title) number is assigned to it, and its up-to-date information is recorded to establish legal ownership and other relevant characteristics. When a parcel of land or property is recorded in the land register, the various changes made to that land (e.g., ownership changes, leases, and mortgages) are recorded. A title or certificate of occupancy plan is created to show the boundaries of that parcel of land or property. In a typical SSA country, land registration is usually carried out in a land registry—a government agency or department responsible for maintaining the register of land and property ownership. “The land registry is at the core of the governance processes within the land and real estate sector” [9]. Institutional arrangements can differ from one SSA country to another. However, in all cases, the land registry carries out the function of land registration. The current state of land registration in SSA countries is problematic. They are mostly paper-based and require much time, resources, and effort to ensure transparency in the registration process and the durability of registered data. Even where they are digital (computer-based), the recordation process remains time-consuming (due to the layers of bureaucratic procedures involved). It lacks transparency as not all stakeholders are involved or engaged in the registration process. The blockchain may provide a more transparent and efficient option for land registration.

There is some evidence of the application of blockchain in some SSA countries. However, these applications were experimental pilots designed and funded by private sector organisations. For instance, in Ghana, a blockchain piloted by Bitland ² helped to reduce

fraud in customary land registration. Still, it was met with a low adoption rate due to distrust in digital systems [30]. A UNDP-backed blockchain pilot programme in Kenya enabled transparency in informal settlements' land administration but faced legal challenges over land information and data ownership [13]. Another pilot programme in Rwanda (by Medici Land Governance) ³ helped to digitise more than 10 million land parcels to produce blockchain-backed land titles. Still, it was met with very high costs of nationwide rollout [31].

Blockchain's applicability to land is unique among other land registration approaches because it is a decentralised, distributed, and immutable ledger. It is decentralised because it processes data on several "nodes" or computers connected to the blockchain network, ensuring no single deciding authority validates transactions [16,17]. This makes its transactions to be peer-validated (on public blockchains) or validated by multiple authorised users (on private blockchains), thereby reducing the opportunity for corruption or rent-seeking behaviour by a single actor or entity [12,14]. Its decentralised nature also means that it decreases transaction costs and time on public blockchains where peer-validation takes over functions of third-party intermediaries [10,13]. Hence, the need, in this study, is to propose a design—steps for a technical solution for practical blockchain applications in SSA countries.

3. Materials and Methods

Land administration is a broad field. The focus of the practicality of blockchain technology presented in this study is from the perspective of its application as a technical solution to some land registration challenges. Therefore, the problem under focus is delays and non-transparency in land registration. The study is based on a design thinking framework for developing a practical blockchain for enhancing land registration in SSA. This study employed design science as its methodology.

Design science is the study and creation of artefacts to solve practical problems of public interest [32]. It can also be viewed as the scientific study and creation of solutions (either as artefactual objects or concepts) developed to be used by people to solve practical problems of public interest [33]. By adopting a design science approach, the authors consider blockchain as an "artefact" capable of being investigated as a technical solution [34] for problems posed by inefficient land registration in SSA. Hence, the researchers have taken an intentional stance that blockchain is an "artefact" that can support stakeholders (landowners, land users, governments, and land governance practitioners, to mention a few) in their effort to enjoy quick, transparent or traceable, and trustworthy land transactions through registrations.

Together with design science research, Personal Extreme Programming (PXP) agile methodology was used to develop the software artefacts that support the answers to the research questions. This software development methodology is well-known and suitable for developments that involve single developers or small teams, and requires the delivery of small, regular new features, instead of delivering the software only when it is completely implemented. This approach contributes to identifying potential design mistakes early, which makes them easy to correct.

4. Results

Being technical design research for solving a land administration problem (that of inefficient land registration), the technical solution identified involves three key components—system design, the development of blockchain integration and testing, and development aspects (Figure 2).

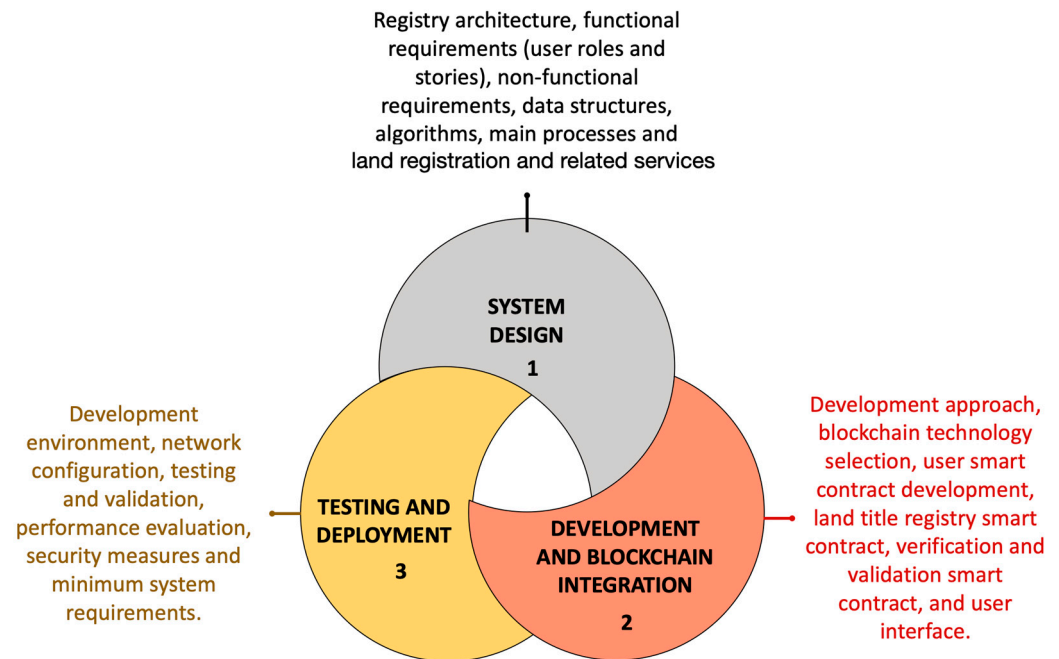


Figure 2. Aspects of the design science for a technical solution for a blockchain-based land registration.

The first step of any solutions-driven activity in land administration should be the identification of a problem [35]. This study, as earlier stated, recognises that to be inefficient land registration (in terms of speed and transparency) and the need for blockchain application in SSA. To respond to the research questions, the authors adopted steps for developing and implementing a blockchain-based land title registry tailored to SSA countries. It frames a practical application of the architectural design and functionality of the decentralised land registry by identifying and outlining the essential elements that shaped the system's design, performance, and usability. Choosing Ethereum as its primary platform (alongside Ganache and MetaMask), with Solidity as the primary language, the study addressed the testing, deployment, performance, security, and system requirements for blockchain in SSA. It also addressed deployment complexities and smart contract migration by providing tips for overcoming them. The following sections address the four questions for the study.

4.1. System Design

System design is critical in the development of complex software and hardware systems, as it ensures scalability, reliability, and performance [36]. In this solution, a structured and participatory approach was used to thoroughly understand the architecture and functionality of the blockchain-based land registry, outlining the critical elements that shape the system's design, performance, and usability. To ensure that the system met real-world needs, consultations were held with Namibian state officials: a Senior Land Administrator at the Ministry of Agriculture, Water and Land Reform, as well as a practising lawyer with expertise in land administration. The design was then revisited and refined iteratively to meet the specified system requirements, resulting in a system that is both technically sound and aligned with key stakeholders' expectations. Figure 3 depicts the registry's overall structure and components.

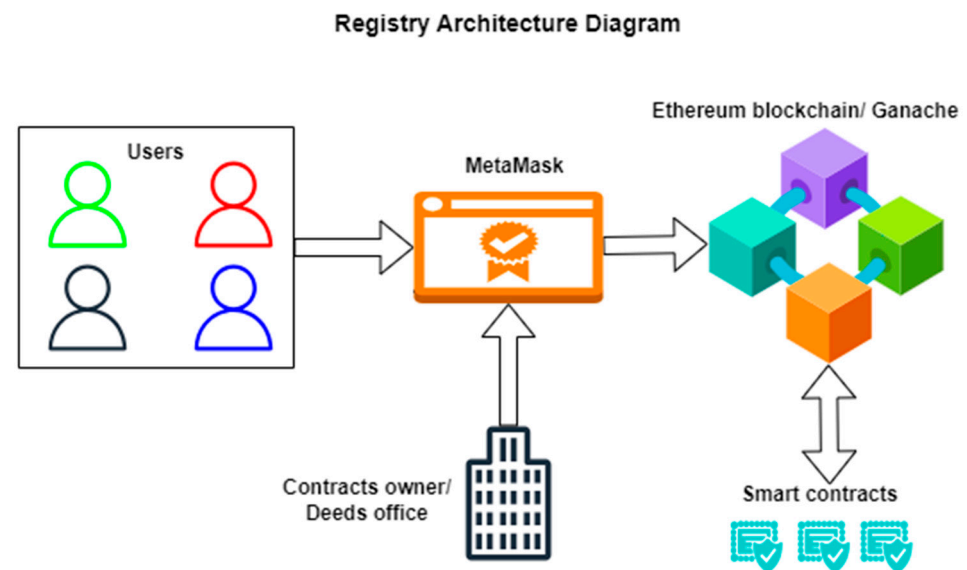


Figure 3. The developed registry architecture diagram.

4.1.1. Functional Requirements

There will be diverse potential users of blockchain technology for land registration. Depending on how land is held, they would be individuals (natural persons), governments, and corporate entities (businesses and organisations).

User Roles

- Landowners should be able to register their land in the blockchain and add a sales transaction to the blockchain.
- Purchasers should be able to initiate a purchase request for any land listed for sale, complete the transaction, and become the owner.
- Conveyancers should be able to participate in the verification of the legal and financial requirements of land sales initiated by landowners.
- Government entities, such as the Deeds Office and the Municipality, should have the authority to validate and verify land and user registrations.

Table 1 below provides a precise outline of the roles and responsibilities of the registry users.

Table 1. Registry users' roles and responsibilities.

Users/Roles	Verify Users	Add Land	Purchase Land	Verify Land	Validate Land
Landowners	✗	✓	✓	✗	✗
Purchasers	✗	✗	✓	✗	✗
Deeds Office	✓	✗	✗	✓	✓
Municipality	✗	✗	✗	✓	✗
Conveyancers (e.g., lawyers, land administrators/managers, etc.)	✗	✗	✗	✓	✗

User Stories

The primary user stories listed below describe various interactions between users and the developed land registry system. Each user story includes a brief description and a priority rating.

User Story 1

Priority: High

Description: Users should be able to register in the land registry. During registration, they will be required to enter their personal information, such as their name and contact information, as well as their user type (for example, landowner, municipality, lawyer, etc.).

User Story 2

Priority: High

Description: Landowners should be able to initiate the process of registering their land on the land registry. This process involves submitting information such as the precise location, land area, and Erf (parcel) Number, which ensures complete land records. Adequate capacity building would be necessary to ensure that this is carried out correctly.

User Story 3

Priority: Medium

Description: Access to specific processes for verifying and validating land records should be limited to government entities and authorised conveyancers. These privileged users will have the authority to review land ownership, legality, and other requirements.

User Story 4

Priority: High

Description: The land registry system should allow users to initiate land sales. This feature will simplify the process of transferring land ownership and facilitate secure land sales. It is crucial to note that this aspect would be subject to the accepted interpretations of the legal processes of property transfer within SSA jurisdictions.

4.1.2. Non-Functional Requirements

- Security: measures should be implemented to ensure users' data and land records are securely stored on the blockchain, with tamper-proof attributes and access control mechanisms to restrict unauthorised access to data.
- Performance: The registry should possess the capability to efficiently process a high volume of transactions while maintaining low latency, and user interaction response times should be within acceptable bounds.
- Scalability: Scalability is crucial to handling a growing user base. The registry should be designed to be scalable, and both land records and smart contracts should be optimised for gas efficiency.
- Usability: To ensure a positive user experience, user interfaces should be intuitive and user-friendly, and error messages should be clear and informative throughout the registry.

4.1.3. Data Structures

User Profile Data Structure:

Attributes: first name, last name, email, user type, password, registration date, terms agreed, ID, gender, ID document, ownership history.

Relationships: Users can own multiple lands, but lands cannot have multiple owners at the same time.

Land Record Data Structure:

Attributes: location, area, Erf (parcel) Number, current owner, owner's history, purchase price, purchase date, for sale status, verification status, validation status, legal clearance status.

Relationships: while a single owner can own a piece of land, it can have multiple verification or validation records.

4.1.4. Algorithms

A set of validation rules is used in the user registration and land registration processes to ensure the accuracy and integrity of the data entered. During the user login phase, the

system uses the Elliptic Curve Digital Signature Algorithm (ECDSA), a key component of the Ethereum protocol. This algorithm is used for signature verification, which confirms a user's identity by comparing the signed message to the public key associated with their Ethereum account. The ECDSA offers an elevated level of security, making it extremely difficult to forge digital signatures, ensuring that only authenticated users have access to their accounts.

The LandTitleRegistry smart contract uses a set of rules to transfer ownership of land. This rule is divided into several steps: it first verifies the ownership of the land, then checks for any legal or governmental restrictions, and finally executes the transfer of ownership only if all conditions are met. This process is protected by Solidity's smart contract capabilities, which include transactional integrity and atomicity (a core property in database management systems), ensuring that the transfer either completes fully or returns if any step fails. This secure strategy is critical in preventing unauthorised or fraudulent land transfers and maintaining the integrity of the land registry.

4.1.5. Main Processes Flowcharts

User Registration

Inputs: Personal information, user type selection, email, password, terms of agreement.

Outputs: User registration confirmation.

Figure 4 depicts the user registration process, in which user inputs such as personal information, user type, email, password, and terms of agreement lead to a user registration confirmation.

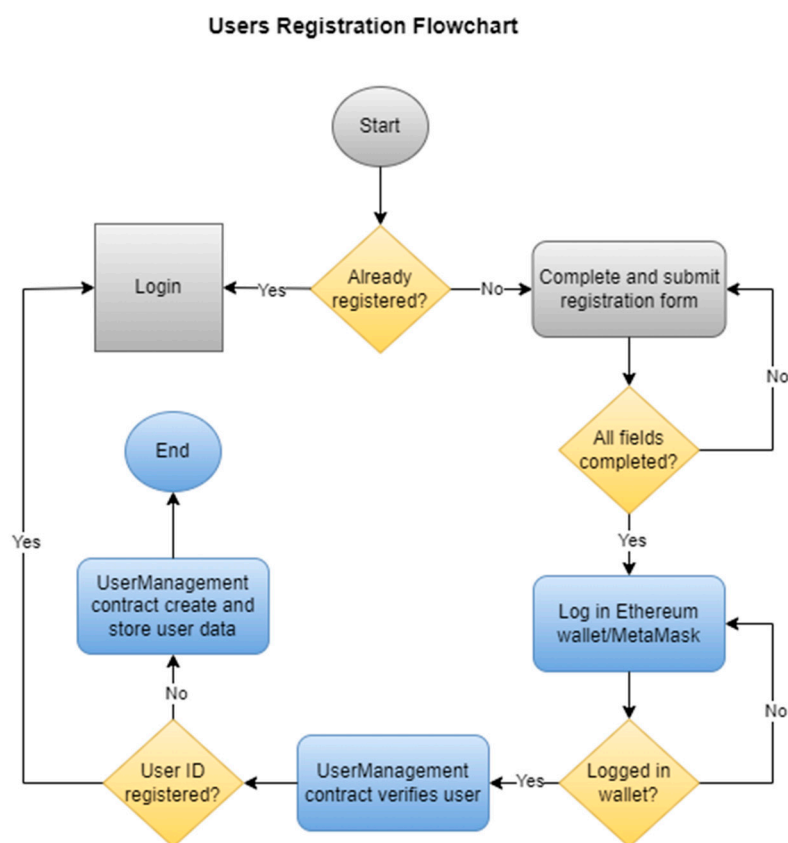


Figure 4. Users registration flowchart.

Land Registration/Purchase

Inputs: Land details (location, area, Erf (parcel) Number, or offer), owner/purchaser authentication.

Outputs: Land registration confirmation.

Figure 5 illustrates the Land Registration/Purchase process, which involves inputs such as land details and owner authentication and produces a land registration confirmation as an output.

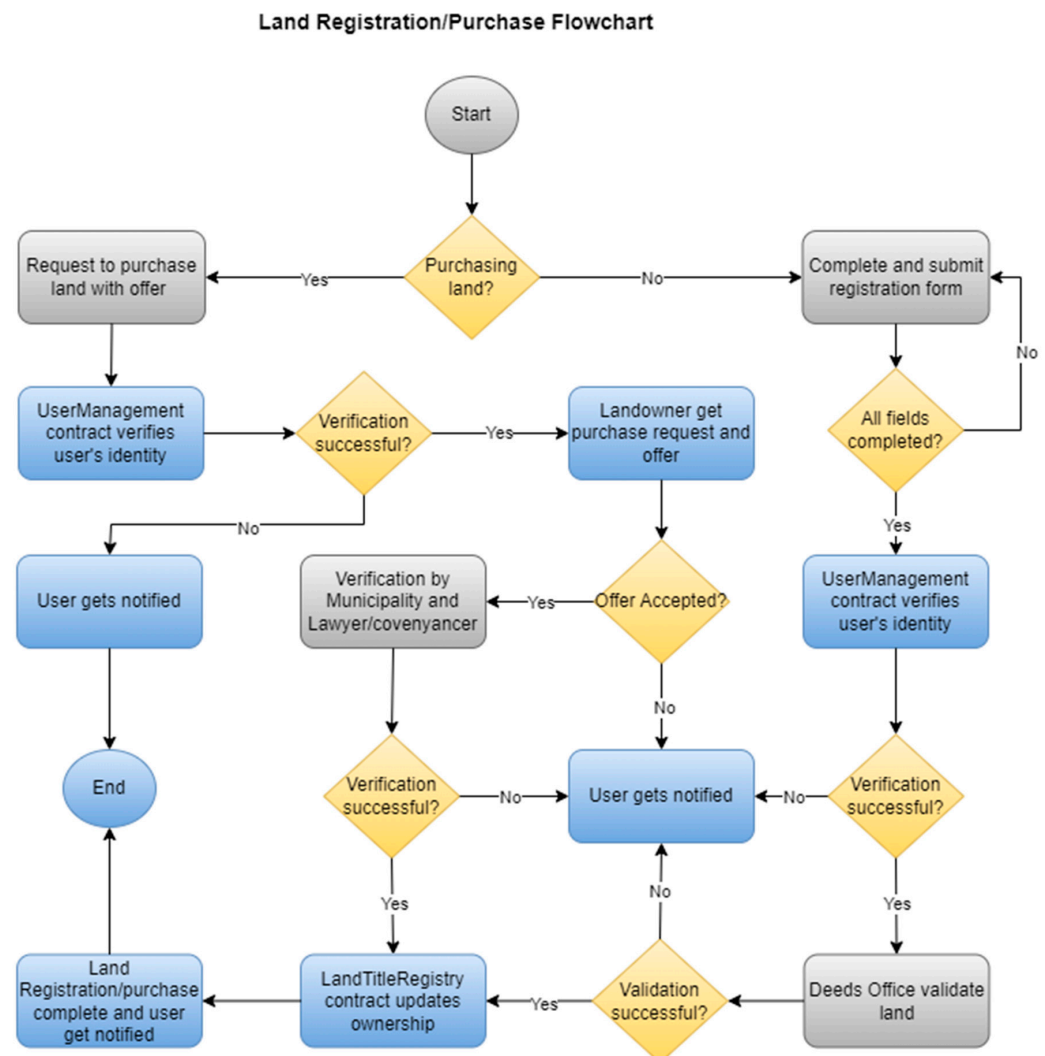


Figure 5. Land registration/purchase flowchart.

4.2. Development and Blockchain Integration

This section examines the process of development and integration of blockchain technology into the land registry. It thoroughly evaluates the development strategy, blockchain technology selection, smart contract development, and user interface design.

4.2.1. Development Approach

The development approach for the blockchain-based land registry incorporated the principles of transparency, security, and user-friendliness. The aspects that were taken into consideration are described as follows:

- **Decentralised Approach:** Initially, the project was designed as a decentralised land registry that aimed to transform ownership verification by leveraging blockchain technology. The primary objective is to establish transparency, minimise the time and financial resources required for land registration, and reduce land administration contraventions in SSA countries.

- **Agile Development:** The project utilised iterative releases, a key advantage of the agile development methodology, to enhance efficiency by allowing the researcher to accommodate changes, find and fix flaws, and align expectations early on [37]. This approach, specifically PXP, allowed the developed registry to evolve incrementally, improving functionality and usability as it progressed. The extreme programming method utilised to develop the land registry is depicted in Figure 6.

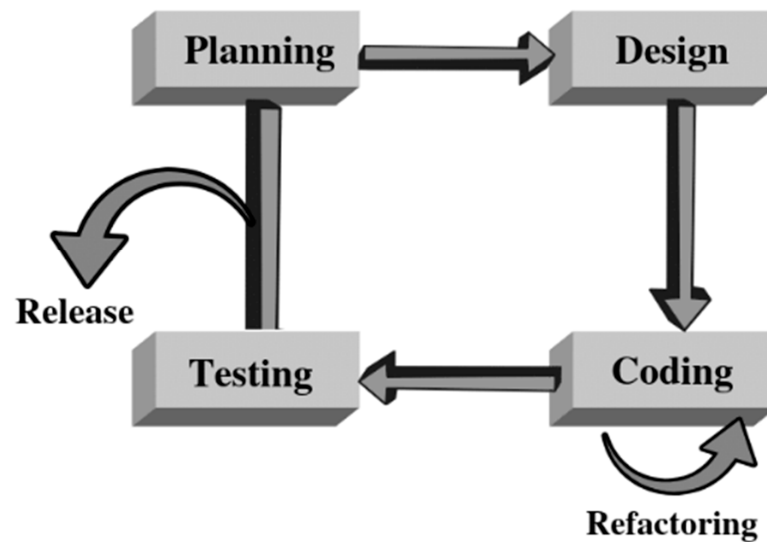


Figure 6. Extreme Programming (XP) method depicted in diagram form [37].

- **Version Control:** GitLab was utilised as a version control system to effectively handle code modifications and support potential collaborative development in the future. Due to the lack of comprehensive documentation, the descriptions of smart contracts and the rationale behind UI design were kept straightforward and easily manageable.

4.2.2. Blockchain Technology Selection

Choosing the right blockchain technology was a critical decision in the project. To begin, various blockchain types, such as private and public, were assessed to determine the best fit for the SSA context. Table 2 below compares the key differences between the public and private blockchains considered for the developed registry.

Table 2. Private blockchain vs. public blockchain attributes.

Private Blockchain	Public Blockchain
Users must be invited to use the blockchain (permissioned blockchain).	Anyone can use the blockchain (permissionless blockchain).
Owned and controlled by a centralised authority.	Owned by no one.
Tend to be centralised.	Fully decentralised.
Blockchain owners can reverse or delete transactions.	Data is immutable and cannot be changed once added to the blockchain.
Transaction verification and validation.	Transaction verification and validation.
The entire ledger can be modified by the owner.	Data cannot be altered.
The rules for using the blockchain can be changed at any time.	The rules on how the blockchain works are defined in the Bitcoin white paper.
Potentially less secure, as fewer nodes could be more easily compromised.	Potentially more secure, as many nodes make it hard for malicious actors to gain network control.

While both private and public blockchains have their upsides, a hybrid blockchain was deemed more appropriate because it combines the most important qualities that align with the project objectives, providing flexibility, transparency, and privacy advantages.

The next step was to choose a suitable blockchain platform, which was accomplished through careful comparisons of available options. Due to several compelling factors, Ethereum emerged as the most favourable option.

Ethereum has a well-established and recognised presence in the blockchain ecosystem, demonstrating its dependability and resilience. Its vibrant developer community, comprising over forty thousand members worldwide, signifies a robust and constantly evolving ecosystem. According to its official website [38], Ethereum is fundamentally a global network of interconnected computers that follow a predefined set of rules known as the Ethereum protocol. This network serves as a foundational infrastructure supporting diverse communities, applications, organisations, and digital assets, all of which anyone can create and use.

The exceptional ability of Ethereum to execute smart contracts seamlessly aligns with the requirements of the land title registry. These smart contracts make it possible to execute contractual agreements automatically, reliably, and transparently. Moreover, Ethereum's infrastructure is open source, ensuring transparency and accessibility for all. Interactions with Ethereum can be facilitated using established programming languages such as JavaScript, simplifying development for a wider audience. Additionally, Ethereum's open-source nature allows developers to fork existing codebases and reuse functionalities, promoting efficiency and collaboration within the Ethereum ecosystem.

4.2.3. Smart Contract Development

Solidity was the natural choice for smart contract development after choosing Ethereum as the platform for the developed land registry. Solidity is a statically typed curly-braces programming language for developing smart contracts that are compatible with the Ethereum blockchain [39].

The foundation of the developed blockchain-based registry is built on three smart contracts: UserManagement, LandTitleRegistry, and VerificationAndValidation, which are designed with a modular system architecture to streamline code organisation and accommodate future improvements while ensuring efficient interaction among contract components. Furthermore, the smart contracts were developed in strict accordance with industry best practices recommended by reputable sources such as Ethereum. These practices included implementing measures to prevent common vulnerabilities like re-entrancy attacks, integer overflow/underflow, and gas exhaustion attacks. To mitigate re-entrancy vulnerabilities, the 'checks-effects-interactions' pattern was used, which ensured that external calls were the last step in contract functions, preventing re-entrancy. In addition, the smart contracts underwent rigorous code audits and security assessments to reinforce their security measures.

User Management Smart Contract

The "User Management" contract is in charge of managing user registration, login, and user details in a blockchain-based system. It allows users of diverse types (Landowners, including purchasers; Government—the Deeds Office; Municipality; Lawyers/Conveyancers) to register, store their information, and verify their identity using MetaMask signatures. The following are the primary responsibilities of this contract:

- **User Registration:** The contract allows diverse types of users to register by providing personal information such as first and last name, email, password, ID, gender, and ID document. The contract requires that each ID be unique for each type of user, and the terms and conditions must be accepted by the user.

- **User Login:** Registered users can log in using their email address as their username, password, and a MetaMask signature. The contract compares the provided information to the stored data and validates the MetaMask signature.
- **Ownership:** The Deeds Office owns all contracts and has special privileges such as the ability to add new user types and verify specific users (Municipality and Lawyers).
- **Events:** To track user actions and state changes, the contract emits events such as `UserRegistered`, `UserLoggedIn`, `UserDetailsSentToDeedsOffice`, and `UserVerified`.

In its entirety, the contract manages various categories of users within the title land registry, facilitates user registration and login, and safeguards the confidentiality and integrity of user information.

LandTitleRegistry Smart Contract:

The contract “LandTitleRegistry” is in charge of managing land records and their ownership within the land title registry. For user-related functionality, it interacts with the “UserManagement” contract. The following are the primary responsibilities of this contract:

- **Land Registration:** Users can register lands by providing the location, area, Erf (parcel) Number and ID in the contract. Each piece of land has a unique owner.
- **Ownership History:** The contract uses IDs to track each land’s ownership history.
- **Land Details Retrieval:** By entering their unique ID, users can retrieve information about specific lands for sale. This information includes things like location, area, owner, purchase price, and various status flags (for sale, verified by the government, validation status, and legal clearance status).
- **User Ownership Information:** Users can retrieve their ownership information, which includes their first and last names, as well as the total number of lands they own.
- **Listing Land for Sale:** Landowners can list their lands for sale by entering the land ID and the purchase price.
- **Requesting to Purchase Land:** Users can request to purchase land that is listed for sale by submitting an offer.
- **Transfer of Land Ownership:** Land ownership can be transferred from one user to another by specifying the land’s unique ID and the new owner’s address. Following contract owner verification, the contract updates ownership information and ownership lists accordingly.

In its entirety, the “LandTitleRegistry” contract functions as a land registry, facilitating land registration, sale, and status updates, and preserving ownership records. It works in conjunction with the “UserManagement” contract to oversee user data and authenticate ownership.

Verification And Validation Smart Contract

The contract “VerificationAndValidation” is in charge of verifying and validating land records within a land title registry system. It communicates with both the “LandTitleRegistry” and “UserManagement” contracts to access land parcel details and verify users. The following are the primary responsibilities of this contract:

- **Verify Municipality or Lawyer:** Using the “UserManagement” contract, the Deeds Office can confirm the legitimacy of a user as a government entity (Municipality) or a Lawyer/Conveyancer.
- **Verify Land:** Only verified users can mark a land as verified. This function determines whether the land exists, has not yet been verified, and is owned by a legitimate user. If all of the conditions are met, the land is verified in the “LandTitleRegistry.”
- **Validate Land:** Only the Deeds Office can mark land as validated. This function determines whether the land exists and can then be validated as belonging to the landowner.

- **Clear Land:** For contractual purposes, verified lawyers/conveyancers can mark (verify) land as cleared. This function determines whether the land exists, has been validated by the Deeds Office, verified by the Municipality, and is available for purchase. If all of the requirements are met, the land is designated as cleared for contractual purposes in the “LandTitleRegistry.”

In its entirety, the “VerificationAndValidation” contract functions as a regulatory overlay upon the land title registry, enabling clearance, validation, and verification operations to be executed on land parcels by verified users. Additionally, it offers a means by which the contract proprietor can authenticate the credentials of specific users.

4.2.4. User Interface Design

The UI design’s primary goal was to create a welcoming and friendly user experience. The registry interface integrated Hypertext Markup Language (HTML) for content structuring, Cascaded Style Sheet (CSS) with the Font Awesome library for styling elements, and JavaScript for interactive features. It also used user-friendly language and clear instructions to guide users throughout the registry, reducing confusion and improving overall usability. This combination produced a dynamic interface, effectively presenting blockchain data and functionalities in an accessible manner.

The registry’s user interface included registration forms, login screens, land registration forms, and interactive dashboards for users and land verification. All of these components are carefully designed to optimise user interaction.

JavaScript was crucial in creating interactive UI components that allowed users to perform tasks such as user registration, land registration, verification, and validation requests. It is also worth noting that Web3.js enabled the seamless integration of HTML, CSS, and JavaScript with blockchain technology. According to its official documentation [40], Web3.js is a collection of libraries that enable HTTP, IPC, and WebSocket communication with a local or remote Ethereum node. This integration enabled users to interact securely with smart contracts and the Ethereum network, including seamless integration with Ethereum wallets such as MetaMask, which was a key component of this development, ensuring secure interaction while safeguarding private keys.

Although the diversity of devices used to access the land registry was not initially considered, usability testing sessions were held in a controlled environment to validate UI design choices. Iterative refinements, informed by valuable feedback from three potential registry users, including landowners and a lawyer/conveyancer, improved the UI’s usability and user satisfaction, which were assessed primarily on the default device, which is the desktop version, as most users navigate important systems like these on desktops. Users expressed high satisfaction, which will translate to positive user experiences and overall system usability.

Furthermore, colour selection was critical in the registry’s UI design. The SSA government agencies or ministries are responsible for ensuring equitable and efficient allocation, management, administration, and sustainable use of the country’s land resources; the colour theme was considered to evoke trust, professionalism, and a sense of familiarity, thereby promoting user engagement and confidence.

4.3. Testing and Deployment

This section offers an inclusive examination of the deployment, testing, and validation procedures of the land registry. The components that have been configured in the development environment to facilitate these tasks are detailed in Table 3, along with their corresponding versions. Each element is further elaborated upon in its respective section.

Table 3. Components and their versions in the development environment.

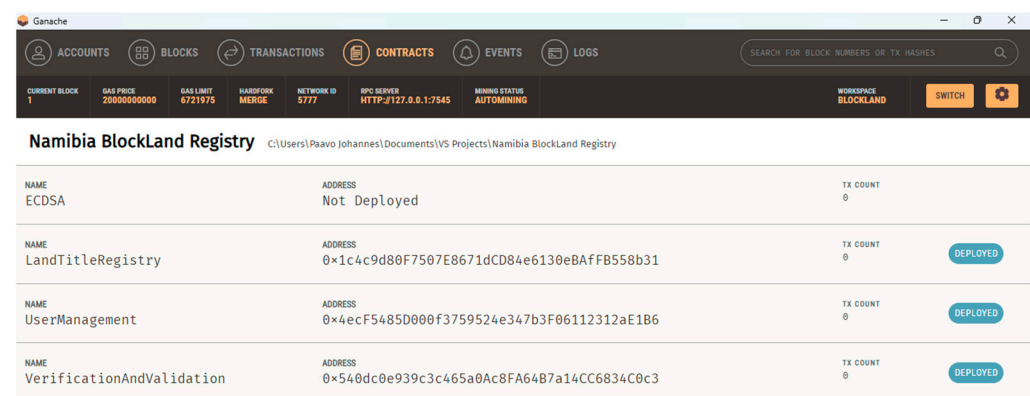
Software	Version
Truffle	5.11.5
Ganache	7.9.1
MetaMask	11.7.3

4.3.1. Deployment and Network Setup

Development Environment

A local Ethereum-based development environment was established for the development and deployment of the land registry. The main tools and components of this environment were as follows:

- Truffle: A world-class open-source development environment, testing framework, and asset pipeline for blockchains using the Ethereum Virtual Machine [41].
- Ganache: A personal blockchain emulator that enables the deployment and testing of smart contracts in a secure and deterministic environment [41]. It also includes a set of pre-funded accounts for development and testing. Figure 7 depicts the three deployed smart contracts of the registry on Ganache UI.

**Figure 7.** The land registry deployed (initial) smart contracts on Ganache.

- MetaMask: MetaMask is a browser extension wallet that provides the simplest yet most secure way to connect to blockchain-based applications [42]. It provides users of the land registry with the key vault, secure login, token wallet, and token exchange required to manage land, as well as acting as a bridge between the browser and the Ethereum network. Figure 8 depicts a user's MetaMask wallet linked to a pre-funded Ganache account.

Network Configuration

The Truffle configuration file specifies the configuration for the developed registry network. This configuration is intended to connect to the Ganache blockchain emulator via MetaMask, which is accessible locally at 127.0.0.1 (localhost) on port 7545 as shown in Figure 9. To make the configuration more versatile, the network ID is set to "*", allowing Truffle to connect to any network. This file also specifies the Solidity compiler version (0.8.11) that is needed for contract compilation. This ensures the compatibility and maintainability of smart contracts throughout their development and deployment to the land registry network.

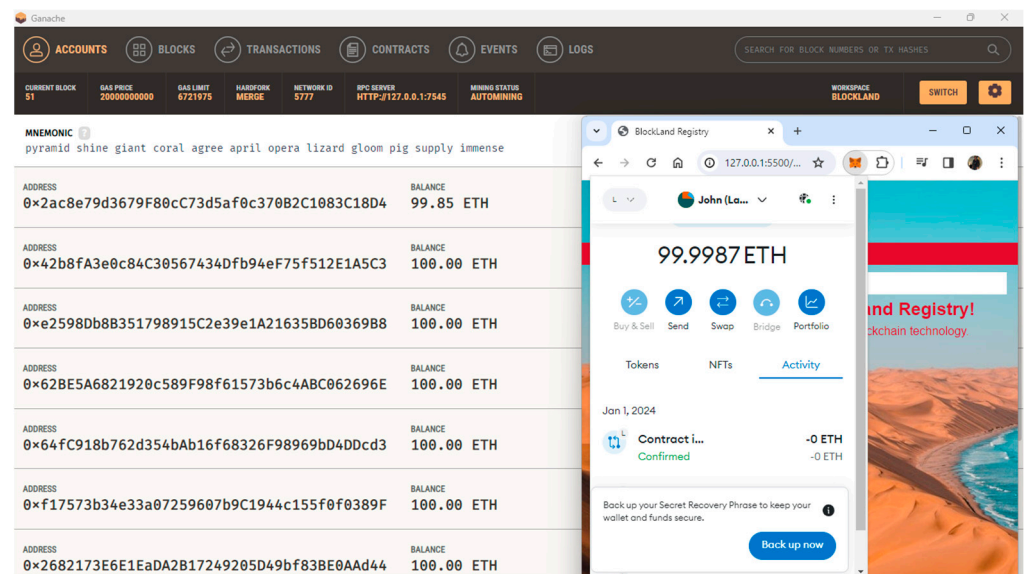


Figure 8. MetaMask wallet next to pre-funded Ganache accounts.

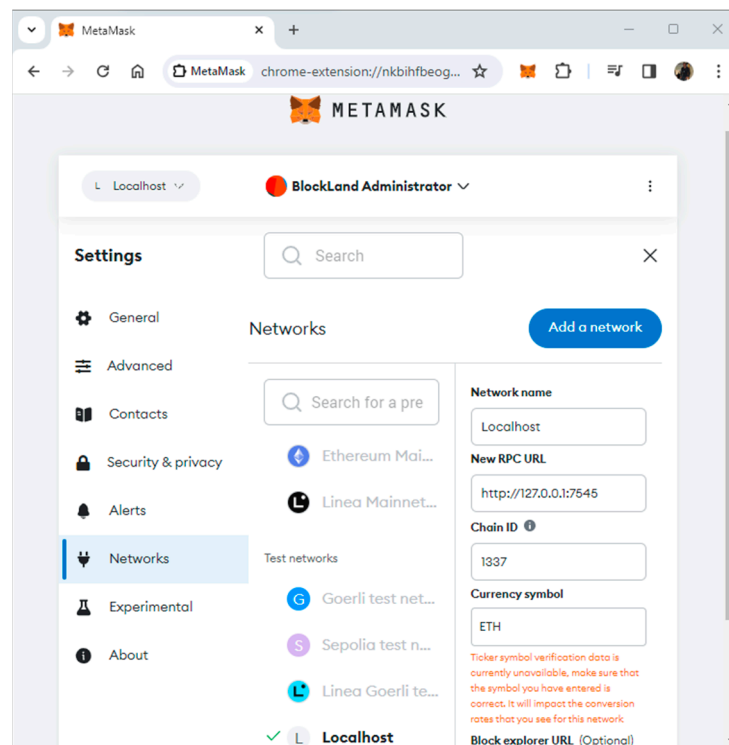


Figure 9. MetaMask network configuration to access Ganache.

4.3.2. Testing and Validation

To thoroughly evaluate the developed land registry's internal structures and functionalities, a two-tiered testing approach was used: white-box and black-box testing. White-box testing, also known as code-based testing, was used to investigate the inner workings and functionalities of the land registry's smart contracts. During this stage, a suite of unit tests was created using the Truffle testing framework. These tests were created to evaluate the behaviour of individual functions and methods within smart contracts and ensure that they functioned as expected. For instance, the UserManagement contract transaction example is depicted in Figure 10.

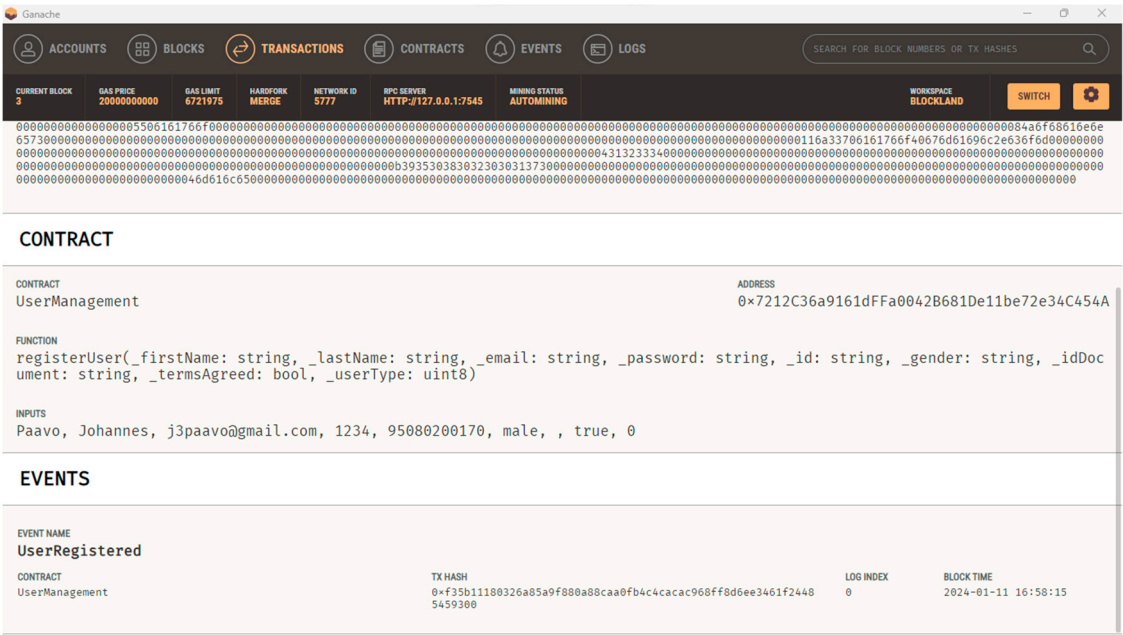


Figure 10. UserManagement contract transaction example when a new user registers on the land registry.

Several scenarios were thoroughly examined, including input validation and contract state changes. After ensuring that the internal code was error-free, functioning as expected, and reliable, the testing focus shifted to black-box testing. This phase was dedicated to assessing the interactions and functional requirements of the land registry as outlined during the system design phase. To ensure seamless functionality, the black box testing phase included user interface evaluation. This included inspecting the registry’s front-end to ensure that it was functioning properly. The test scenarios included user registration, land registration, verification processes, and transaction workflows. By simulating real-world user interactions with the land registry, end-to-end testing was used to adopt a holistic perspective. These tests validated the entire system flow by simulating typical user journeys, beginning with registration and ending with changes in land ownership. The frontend user interface and backend smart contracts were also tested for seamless integration. This phase of testing confirmed that user actions triggered the necessary smart contract functions. With the combination of white-box and black box testing approaches, the researcher was able to ensure both code quality and a user-friendly experience, resulting in a robust blockchain-based land title registry that meets its requirements.

4.3.3. Performance Evaluation

The performance of the developed land registry was evaluated based on its efficiency and extensibility. Significant performance indicators and factors considered included a deliberate design for smart contract extensibility, as well as a proactive approach to ensuring the system could easily integrate new functionalities and adapt to changes from the start, rather than relying on post-development adjustments. The goal of this strategy was to build a foundation for the seamless integration of new features and updates as the system’s user base and number of registered lands grow. To ensure that extensibility features were effectively integrated, the development process involved regular code reviews and design validations. The advantage of this proactive approach is that addressing extensibility concerns early in the development process lays a solid foundation for the developed registry’s future evolution and adaptability. While specific numerical data on extensibility may not be available, design decisions that prioritise extensibility have helped to improve the system’s overall efficiency and operational robustness. In addition, gas costs associated

with contract interactions were monitored to determine the registry's economic efficiency. This observation helped the researcher to understand the financial implications of using the registry.

Gas costs are the fees associated with the execution of a smart contract on the blockchain. It is the price of the computations required to record a transaction. This fee is important because it supports the security of the network, fairness, and helps to manage network congestion, among others.

4.3.4. Security Measures

Secure coding practices were used to prioritise transaction correctness and transparency to ensure transparent transactions. These practices included several key components.

First, event logging was implemented, making use of Solidity's event-logging mechanism to record important transaction events. Additionally, critical data related to land and ownership history was immutably stored on the blockchain. Once recorded, this data cannot be modified or deleted, resulting in a transparent and tamper-resistant transaction history. Furthermore, access control mechanisms were critical in maintaining transaction security and transparency. To assign specific roles and permissions to users, Role-Based Access Control (RBAC) was implemented. This approach enabled the system to grant various levels of access and authority to government entities and lawyers/conveyancers. This ensured that sensitive actions like verification and validation could only be performed by authorised users. In addition to user security, user authentication and authorisation procedures were created to validate transaction security and transparency. Users were required to verify their identities during registration and login. Finally, the smart contracts that govern the land registry were implemented in an immutable manner. This immutability ensured the contract logic and rules' transparency and resistance to tampering.

4.3.5. Minimum System Requirements

The land registry was designed with user convenience in mind. Users can interact with the platform with just three simple requirements. A Web3-enabled browser is required, which includes popular browsers such as Google Chrome, Mozilla Firefox, and Microsoft Edge. Users can interact with the platform directly from their browser by incorporating MetaMask or similar browser extensions to ensure a seamless and secure connection to the blockchain. Secondly, a stable internet connection will ensure that users can access the platform's features without interruption, allowing them to register their land, verify and validate lands, and conduct secure transactions from anywhere. Finally, to actively participate in the ecosystem, users must have an Ethereum account. Creating an Ethereum account is simple, and it allows users to manage land records and conduct transparent transactions on the platform. With these minimal requirements in place, the land registry provides a user-friendly and inclusive environment that allows people from all walks of life to navigate land management efficiently and securely.

5. Discussion

Despite all the possible benefits, there are two key limitations that future research should address. First, the legal frameworks governing land registries are often complex, and ensuring compliance with regulatory requirements across different jurisdictions can be particularly challenging. Second, the integration of blockchain in land registries raises important concerns about data confidentiality and protection.

Judging from this study, two main foreseeable implications exist for the technical solution to land administration through blockchain. There are implications related to the practical use of the solution and policy consequences for its adoption by SSA countries.

5.1. Practical Implications

5.1.1. Technical Practical Implications

Dealing with the deployment and potential migration of smart contracts on the Ethereum blockchain was one of the major challenges encountered while implementing the land registry. Once deployed, Ethereum smart contracts are unchangeable, emphasising the importance of planning for future updates and alterations. To address this issue, a comprehensive contract deployment and migration strategy was developed, including careful versioning of smart contracts to allow for future improvements. Each contract was designed with modularity and with essential functionalities separated from auxiliary features.

Another significant challenge was ensuring a seamless integration between the front-end user interface and the back-end smart contracts to ensure real-time data synchronisation and a consistent user experience. To overcome this barrier, the Web3.js libraries were used to interact with Ethereum smart contracts directly from the front end, allowing for real-time contract functions and data retrieval. Furthermore, an event-driven architecture was implemented, allowing the front-end to listen to contract events and react immediately to changes in the blockchain state. As land registration involves multiple stakeholders, smart contracts can notify stakeholders of any changes in land transactions. “For example, once a change of ownership is registered, the land registry and other interested parties, such as state tax agencies and insurance companies, are notified” [14].

5.1.2. User Interface Implications

A major practical implication of the technical solution is that, if successfully implemented, the system will provide a one-stop solution to land registration and land information or data access for the national land registry. This means a user interface for human–machine interaction is necessary for effective operations in each SSA country. Using Namibia—a country in the Southern African region—as an example, the authors developed a user interface (website) with a homepage/landing page (Figure 10), a user’s registration form (Figure 11), a login form with MetaMask authentication prompt and an authenticated landowners and purchasers’ dashboard.

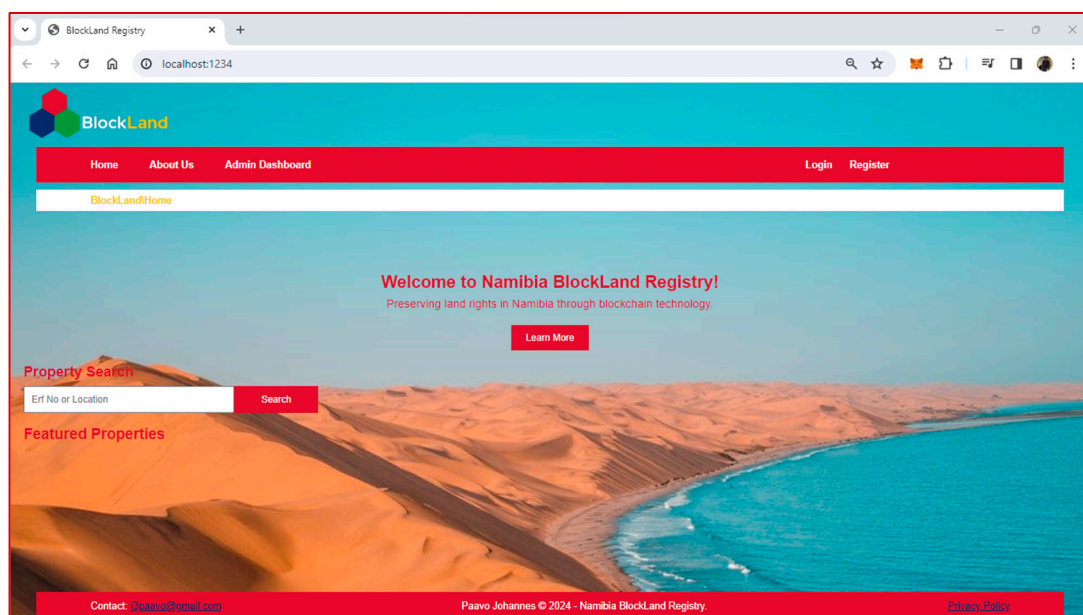


Figure 11. Homepage/landing page.

Figures 11 and 12 show two of the user interfaces (using Namibia as an example) developed. Effective error handling and recovery mechanisms are required for any robust

system to be stable. The challenge was efficiently identifying, managing, and recovering from unexpected errors. An error logging mechanism was implemented to record and categorise errors that occurred during user interactions and contract executions. An expected user interface concern remains the “garbage in, garbage out” practice. These sorts of errors persist and would lead to inaccurate data if not checked. Experience elsewhere has shown that blockchain networks can become slow with high land transaction volumes.

Figure 12. Users’ registration form.

5.1.3. Infrastructure, Funding, Awareness and Capacity Development Implications

Another practical implication of blockchain application in land registration in SSA relates to infrastructural availability. Despite the expected low-cost application of blockchain, the infrastructural challenges related to access to electricity and reliable internet must be solved before the implementation of the technical solution becomes a locally realistic solution in SSA countries. Electricity and the internet are often lacking in most SSA rural areas. These are where most of its unregistered customary and communal land is located [43].

There is a need for citizens to be digitally literate to develop the required awareness for blockchain usage. Implementing blockchain in the SSA land sector may require an upfront investment by SSA governments. The current low level of digital literacy in SSA could mean that the specific demography of the citizenry (such as the elderly and the poor) may not be able to take advantage of the technological adoption of blockchain. This may lead to financial challenges on the government’s side in supporting its development and awareness, and training/capacity development for its usage.

It is also possible that resistance to blockchain rollouts may come from the elites (especially the traditional authorities and land registration officers), who are key players in the manual land registration system. Where corruption is prevalent, these stakeholders (especially corrupt individuals who take advantage of the current system) may oppose blockchain’s transparency. It is also possible that women’s land rights could be overlooked if the blockchains are not operationalised inclusively.

5.2. Policy Implications: Legal/Regulatory Challenges and Privacy Concerns

Since most SSA countries already have established land policies that were formulated without recourse to the possibility of implementing blockchains, there are bound to be legal (and regulatory) and privacy concerns for their implementation.

The non-existence of laws on the use and regulation of blockchain technology means that many SSA countries lack blockchain-friendly land laws or the digital identification frameworks needed for their operationalisation. It would be illogical to expect the blockchain's smart contract to enable legal protection for land transactions securely for users if the laws on the use of blockchain are unclear. This means that a legal system that recognises the use of blockchain may be necessary (depending on jurisdictions within SSA) to establish the basis of its legal and institutional legitimacy. Creating a regulatory environment for blockchain (where none exists) will require creating rules and procedures (which may include sociopolitical and legal policies) to guide its usage. Frizzo-Barker et al. [44] have warned that if blockchain-based land administration is deployed without a satisfactory legal and governance framework, it can potentially exacerbate the existing problems in the land sector.

Since the land registration is situated within a public-led sector, using public ledgers means that transparency is a key part of its usage. This means transparent, sensitive ownership of data could be exposed when improperly managed. In such a situation, a contradiction may exist between the existing regulatory framework and the newly introduced blockchain technology application. Some laws that may be affected by the introduction of blockchain technology may include laws related to commodities, transactions, banking, privacy, cybersecurity, and conveyancing, among many others.

6. Conclusions

This research shows that a blockchain-based land registration solution can be part of land administration in SSA. The study doesn't imply that blockchain will solve all land administration problems. It focuses on the practical aspects of the blockchain solution. It presents the potential of blockchain in SSA. By focusing on a technological solution, we don't ignore the human aspects of land challenges. Technologies are created by humans for human use. Jurisdictions determine how to apply blockchain to benefit their societies.

A methodical approach was used to achieve this. The solution, a decentralised land registry, had iterative releases for developing smart contracts and user interfaces. Ethereum, Ganache, and MetaMask were the preferred platforms, with Solidity as the primary development language.

This study also detailed the testing and deployment phases, including setup, testing, performance assessments, security enhancements, and minimum system requirements. It also addressed deployment complexities and smart contract migration challenges, offering insights into overcoming them throughout the project lifecycle. In summary, it provides a comprehensive roadmap for conceptualising, developing, validating, and deploying a blockchain-based land titles registry suitable for SSA countries.

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Conflicts of Interest: The authors declare no conflicts of interest.

Notes

- ¹ The name, Satoshi Nakamoto, is believed to have been used by the pseudonymous person or persons who developed Bitcoin, who authored the Bitcoin white paper, and created and deployed Bitcoin's original reference implementation.
- ² A consortium blockchain technology from Ghana, Denmark, and the USA.
- ³ A provider of user-friendly, low-cost land titling and administration systems.

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