UNIVERSITY OF PIRAEUS - DEPARTMENT OF INFORMATICS

MSc "Cybersecurity and Data Science"

MSc Thesis

Thesis Title:	***An architecture for ERP interoperability based on blockchain*** *Αρχιτεκτονική διασύνδεσης συστημάτων ERP με χρήση της τεχνολογίας αλυσίδων μπλοκ*
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Περίληψη

Στο σύγχρονο τοπίο της διαχείρισης της εφοδιαστικής αλυσίδας, η επίτευξη απρόσκοπτης διαλειτουργικότητας μεταξύ διαφορετικών συστημάτων ERP (Enterprise Resource Planning) αποτελεί σημαντική πρόκληση. Η παρούσα μεταπτυχιακή διατριβή προτείνει μια καινοτόμο αρχιτεκτονική που αξιοποιεί την τεχνολογία blockchain για τη διευκόλυνση της διαλειτουργικότητας του ERP μεταξύ πολλαπλών ενδιαφερομένων σε μια εφοδιαστική αλυσίδα. Η βασική λύση περιλαμβάνει την ανάπτυξη ενός στρώματος υπηρεσιών blockchain, το οποίο ενσωματώνεται πάνω σε υπάρχοντα συστήματα ERP, εξασφαλίζοντας ασφαλή, διαφανή και αμετάβλητη ανταλλαγή δεδομένων μεταξύ όλων των συμμετεχόντων φορέων.

Η παρούσα διατριβή περιγράφει τον ολοκληρωμένο σχεδιασμό της προτεινόμενης αρχιτεκτονικής, περιγράφοντας λεπτομερώς τα στοιχεία της, τις αλληλεπιδράσεις και το υποκείμενο δίκτυο blockchain, όπου κάθε ενδιαφερόμενος της εφοδιαστικής αλυσίδας λειτουργεί έναν κόμβο. Με τον τρόπο αυτό, επιτρέπει τον συγχρονισμό και την επικύρωση των συναλλαγών σε πραγματικό χρόνο σε διαφορετικές πλατφόρμες ERP, αμβλύνοντας έτσι τα ζητήματα που σχετίζονται με την ασυνέπεια των δεδομένων και ενισχύοντας τη συνολική επιχειρησιακή αποτελεσματικότητα.

Για την τεκμηρίωση της σκοπιμότητας και της αποτελεσματικότητας αυτής της αρχιτεκτονικής, η διατριβή περιλαμβάνει επίσης την ανάπτυξη και ανάλυση μιας προσομοιωμένης περίπτωσης χρήσης εντός της αλυσίδας εφοδιασμού σιταριού. Αυτή η προσομοίωση καταδεικνύει την πρακτική εφαρμογή του στρώματος υπηρεσιών blockchain, παρουσιάζοντας τον τρόπο με τον οποίο εξασφαλίζει την ακριβή και αξιόπιστη ανταλλαγή δεδομένων μεταξύ προμηθευτών, κατασκευαστών, διανομέων και λιανοπωλητών.

Τα ευρήματα της παρούσας έρευνας υπογραμμίζουν τις δυνατότητες της τεχνολογίας blockchain να φέρει επανάσταση στη διαλειτουργικότητα της εφοδιαστικής αλυσίδας, προσφέροντας μια κλιμακούμενη και ισχυρή λύση που μπορεί να προσαρμοστεί σε διάφορους κλάδους. Αυτή η αρχιτεκτονική όχι μόνο αντιμετωπίζει τις τρέχουσες προκλήσεις διαλειτουργικότητας, αλλά θέτει επίσης τις βάσεις για μελλοντικές εξελίξεις στην ενσωμάτωση συστημάτων ERP.

Abstract

In the contemporary supply chain management landscape, achieving seamless interoperability between disparate ERP (Enterprise Resource Planning) systems poses significant challenges. This master thesis proposes an innovative architecture that leverages blockchain technology to facilitate ERP interoperability across multiple stakeholders within a supply chain. The core solution involves the development of a blockchain service layer, which is integrated atop existing ERP systems, ensuring secure, transparent, and immutable data exchange among all participating entities.

This thesis delineates the comprehensive design of the proposed architecture, detailing its components, interactions, and the underlying blockchain network where each supply chain stakeholder operates a node. Doing so enables real-time synchronization and validation of transactions across different ERP platforms, thus mitigating issues related to data inconsistency and enhancing overall operational efficiency.

To substantiate the feasibility and efficacy of this architecture, the thesis also includes the development and analysis of a simulated use case within the mock bread supply chain. This simulation demonstrates the practical application of the blockchain service layer, showcasing how it ensures accurate and reliable data sharing among suppliers, manufacturers, distributors, and retailers.

The findings of this research underscore the potential of blockchain technology to revolutionize supply chain interoperability, offering a scalable and robust solution that can be adapted across various industries. This architecture addresses current interoperability challenges and lays the groundwork for future advancements in ERP systems integration.

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1. Introduction

In today's globalized economy, supply chains have become increasingly complex, involving numerous stakeholders with distinct roles, responsibilities, and systems. ERP systems are critical tools for organizations, enabling the seamless integration and management of core business processes. Despite their extensive functionalities, ERPs often face significant interoperability challenges when integrated across different enterprises or supply chains. Effective interoperability is vital for the real-time exchange of information, which is essential for optimizing supply chain operations, reducing costs, and enhancing overall efficiency. This fragmentation becomes particularly pronounced in complex supply chains, such as those in the food industry, where multiple stakeholders need to collaborate efficiently. The Mock Bread Supply Chain is a quintessential example, involving various entities like suppliers, manufacturers, distributors, and retailers. Each entity typically employs distinct ERP systems, leading to data silos, inefficiencies, and trust issues.

In recent years, blockchain technology has emerged as a promising solution for enhancing transparency, security, and interoperability across different systems. Blockchain's decentralized nature can ensure that data is tamper-proof and verifiable by all participants in a supply chain. However, despite its potential, the application of blockchain for ERP interoperability remains underexplored, particularly in practical implementations within real-world supply chains.

Defining a universally approved and accepted blockchain-enabled architecture for the interconnection of ERP-based systems and interoperability is still considered a difficult topic that is still open to research. Although many functions of such a system alongside supporting technologies such as IoT, Smart Contract, Digital Wallet, Cloud Computing, and Building Information Model are clarified, for business use, this is a relatively new technology. This master thesis addresses the pressing issue of ERP interoperability by proposing an innovative solution based on blockchain technology. The proposed architecture involves developing a blockchain service layer that sits atop existing ERP systems, creating a unified platform where all supply chain participants maintain a node in the blockchain network.

The primary objective of this research is to design and implement a blockchain-based architecture that ensures reliable and real-time data exchange between disparate ERP systems. This architecture aims to overcome the limitations of current interoperability methods, which often rely on complex and costly middleware solutions or suffer from data synchronization issues. By leveraging blockchain's capabilities, the proposed solution ensures data integrity, security, and transparency, thereby enhancing trust and collaboration among supply chain participants.

1.1 Motivation and Contribution

Our motivation for this research is to address the pressing need for an interoperable ERP architecture that leverages blockchain technology to enhance the coordination and trust among various stakeholders in the Mock Bread Supply Chain. By integrating multiple ERP systems through a blockchain-based architecture, we aim to overcome the limitations of traditional ERP systems, ensuring data consistency, process transparency, and improved overall efficiency.

This thesis makes several significant contributions to the fields of ERP systems, blockchain technology, and supply chain management. The contributions can be categorized into three main areas: theoretical framework, architectural design, and practical implementation. Specifically:

We provide a comprehensive analysis of the current interoperability issues faced by ERP systems within supply chains. This includes a detailed examination of the challenges related to data consistency, process synchronization, and trust among disparate ERP systems. Our research delves into the potential of blockchain technology to address these issues, presenting a thorough literature review on Blockchain's application in supply chain management and ERP integration. This theoretical groundwork sets the stage for the development of our novel architecture.

The core contribution of this thesis is the design of a novel architecture that integrates multiple ERP systems with a blockchain layer. This architecture is meticulously crafted to ensure that data flows seamlessly across different ERP systems, with the blockchain layer providing a secure, transparent, and immutable record of all transactions. The architecture includes smart contracts to automate processes and enforce business rules across the supply chain. These smart contracts are designed to facilitate real-time data sharing, reducing delays and discrepancies in supply chain operations.

A detailed model of the architecture is presented, highlighting the interaction between the ERP systems and the blockchain layer. This model serves as a blueprint for future implementations and adaptations in other supply chains.

To validate the proposed architecture, we implement it in the context of the Mock Bread Supply Chain. This implementation serves as a case study, demonstrating the practical feasibility and benefits of our approach.

We detail the integration process, showcasing how various ERP systems used by different stakeholders in the supply chain are connected through the blockchain layer. This includes the setup of nodes, deployment of smart contracts, and data migration procedures. Our implementation is evaluated against key performance metrics such as data consistency, transaction speed, and system scalability. The results indicate significant improvements in these areas, corroborating the theoretical benefits of our architecture.

By applying our architecture to the Mock Bread Supply Chain, we provide empirical evidence of how blockchain can enhance supply chain transparency and trust. This has broader implications for supply chain management, suggesting that similar architectures could be applied to other sectors facing interoperability challenges. The case study reveals insights into the practical challenges and solutions in implementing blockchain-based ERP interoperability, offering valuable lessons for practitioners and researchers in the field.

1.2 Paper Structure

By proposing a novel architecture for ERP interoperability based on blockchain, this thesis aims to contribute to the advancement of supply chain management practices, offering a scalable and robust solution that can be adapted to various industries and contexts.

The thesis consists of five chapters. Specifically:

- Chapter 1, is the introduction, which refers to the motivation and the existing needs that led to the writing of this thesis.
- Chapter 2, studies Blockchain technology and an analytical approach to ERP systems. The expected benefits of the integration and interoperability of both technologies are listed. The chapter closes with a literature review, focused on the studies and research about the interoperability of both technologies.
- Chapter 3, presents the operational and implementation challenges. The chosen supply chain is described, along with the stakeholders and their needs. A high-level description of the design of the proposed system is described here and each layer of the system is analyzed.

- Chapter 4, gives a detailed description of the proposed architecture of the implemented system. All of the components the system consists of are described in detail. The technology used to implement the system and various security controls used to showcase various features are listed. Features of the produced web app are analyzed as the main demo is described in detail. The chapter closes with the validation of the produced system.
- Chapter 5 consists of the conclusion drawn from the implemented system and the proposed architecture. The chapter closes with a few words about future work and thoughts about directions that should explored or technologies that should be experimented with to improve or test potentials.

2. Background and Literature Review

In this chapter, a historical review will be done academically, examining the development of ERP systems and Blockchain technology through academic papers. The evolution of ERP systems and Blockchain technology will be studied up to the present day, marking their milestones.

2.1 History of ERP and Blockchain

The roots of ERP can be traced back to Material Requirements Planning (MRP) systems developed in the 1960s and 1970s. These systems were designed to manage manufacturing processes, focusing on inventory control and production scheduling [1]. MRP systems evolved into Manufacturing Resource Planning (MRP II) systems, which expanded to cover other aspects of business operations such as finance, human resources, and project management. This evolution marked a shift towards more comprehensive integration of business functions, laying the groundwork for ERP systems [2]. The term "Enterprise Resource Planning" (ERP) emerged as vendors integrated various business functions into a single software solution, including finance, human resources, supply chain management, and customer relationship management [3]. SAP, Oracle, and Baan were among the early pioneers in this space.

The 1990s saw rapid adoption of ERP systems by large organizations seeking to improve efficiency and gain a competitive edge. The impending Y2K issue was a significant driver of ERP adoption during this period, as companies needed to replace legacy systems that were not Y2K compliant.

In the early 2000s, ERP systems continued to evolve with the integration of internet technologies, leading to the development of web-based ERP systems. These systems allowed for greater accessibility and collaboration across geographically dispersed organizations [4].

The late 2000s and 2010s witnessed the emergence of cloud-based ERP solutions, which offered scalability, reduced upfront costs, and easier maintenance compared to on-premise systems [5]. Cloud ERP systems also facilitated better integration with other cloud-based applications, enhancing overall organizational agility [6].

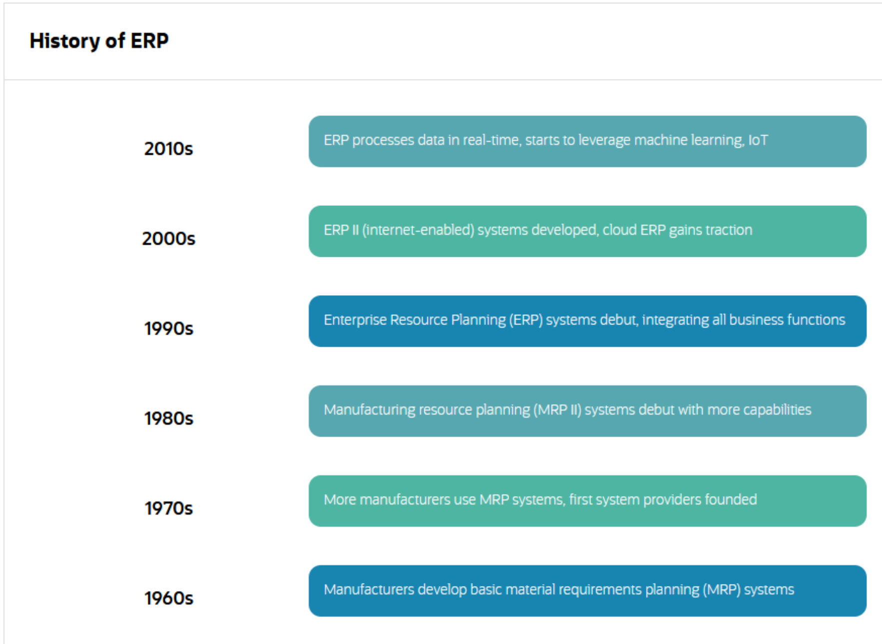


Figure 1. History of ERP systems

ERP systems were distinguished by their ability to provide a unified database and real-time data access across the organization, significantly enhancing decision-making capabilities [7]. ERP systems became more widespread, with companies across various industries adopting them to streamline operations, improve efficiency, and gain better insights into their business processes. ERP systems continue to evolve, incorporating advanced technologies such as blockchain, cloud computing, artificial intelligence, and machine learning to offer more sophisticated functionalities and better integration with other systems.

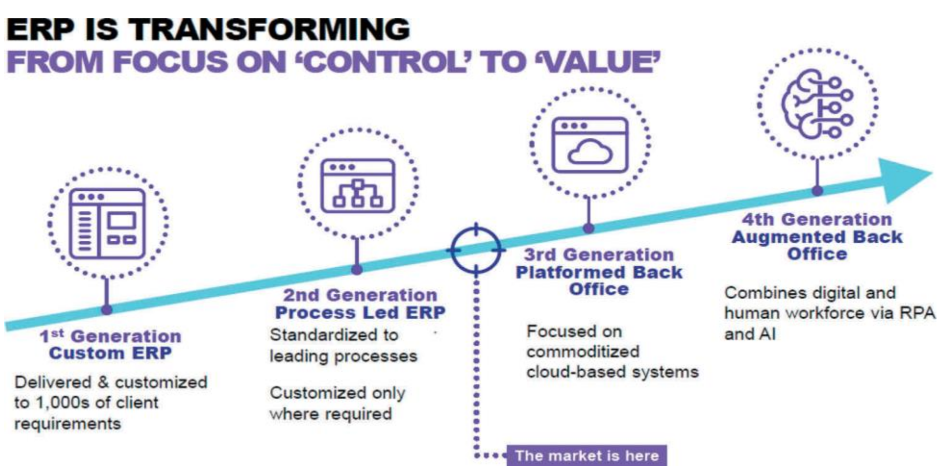


Figure 2. Evolution of ERP systems *[23]*

The theoretical foundations of blockchain can be traced back to the works of researchers like Stuart Haber and W. Scott Stornetta in the late 1980s, who proposed the idea of cryptographically secured chains of blocks to timestamp digital documents. The concept of blockchain gained prominence with the introduction of Bitcoin in a 12-part whitepaper published by an anonymous entity or group of individuals known as Satoshi Nakamoto (2008). Bitcoin's blockchain served as a decentralized ledger for recording transactions securely and transparently.

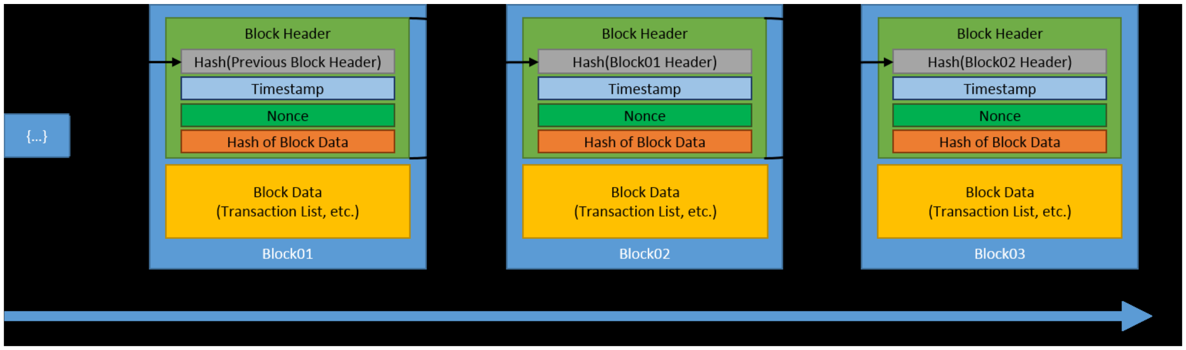


Figure 3. Blockchain: Generic chain of blocks *[43]*

In late 2013, Ethereum, proposed by Vitalik Buterin. Launched two years later (2015), introduced the concept of smart contracts, enabling programmable, self-executing contracts on the blockchain. This expanded the potential use cases beyond simple transactions. Companies started exploring blockchain technology for various applications beyond crypto currencies. Industries such as finance, supply chain, healthcare, and logistics began experimenting with blockchain for its potential to improve transparency, security, and efficiency in processes. Efforts are ongoing to address challenges related to blockchain interoperability, scalability, and energy consumption. Solutions such as interoperable block chains, layer 2 protocols, and consensus mechanism improvements are being developed to make blockchain technology more practical for widespread adoption.

The intersection of ERP and blockchain involves leveraging blockchain technology to enhance various aspects of ERP systems, such as supply chain management, data security, and transaction transparency. Some potential applications include supply chain management, data security, smart contracts, and auditability.

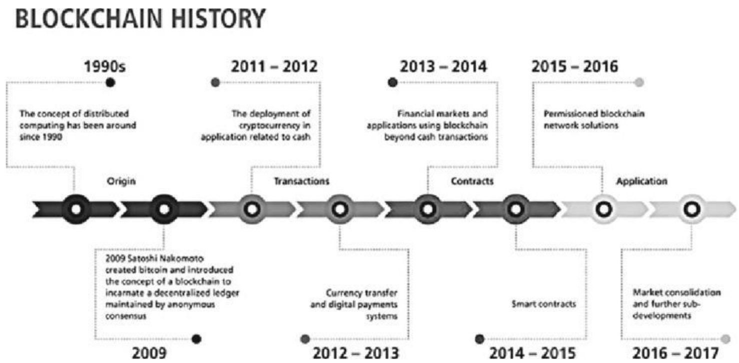


Figure 4. A history of blockchain technology *[18]*

The Figure above illustrates the evolution of blockchain technology from the 1990s to 2017.

2.2 Enterprise Resource Planning (ERP) Systems

Enterprise Resource Planning (ERP) is a sophisticated and comprehensive software suite. Its scope is to integrate and manage core business processes across an entire organization. It serves as a centralized platform that facilitates the flow of information and data across various departments, enabling better coordination and decision-making. ERP systems are particularly beneficial for large and complex organizations where disparate systems and manual processes may lead to inefficiencies.

ERP systems are critical for enhancing supply chain management by integrating various business processes into a unified system. These systems facilitate real-time data sharing and improve coordination among different departments and external partners, leading to increased efficiency, reduced costs, and better decision-making.

The figure below presents the structure of an ERP system, illustrating how various business functions are integrated through a central ERP database. The central ERP database connects multiple applications, including Financial Applications, Manufacturing Applications, Inventory Management, Human Resources Management, Sales & Distribution, and Service Applications. These applications facilitate interaction between Suppliers and Customers, ensuring seamless data flow across different business processes. Additionally, corporate reporting is derived from the ERP database, providing comprehensive insights and analytics for informed decision-making. This integration helps in streamlining operations, improving efficiency, and enhancing overall business performance.

Figure 5. ERP modules [39]

Some of the key characteristics of ERP systems are the following:

- **Integration:** ERP integrates various business functions and processes, such as finance, human resources, supply chain, manufacturing, sales, and customer relationship management. This integration helps in real-time data sharing and ensures consistency across different departments.
- **Centralized Database:** ERP systems use a single, centralized database to store and manage data. The unified database serves as the repository for all organizational data. This eliminates data duplication and inconsistencies that may arise when using multiple standalone systems and reduces the risk of data discrepancies
- **Automation:** ERP automates routine tasks and business processes, reducing the need for manual intervention. This improves efficiency and minimizes errors associated with manual data entry. Workflow management tools ensure that business processes follow predefined, efficient paths.
- **Real-time Reporting and Analytics:** ERP provides real-time insights into business operations through robust reporting and analytics tools. This enables stakeholders to make informed decisions based on up-to-date information.
- **Standardized Processes:** ERP systems often come with predefined best practices and workflows. Implementing these standardized processes helps organizations optimize their operations and adhere to industry standards.

- **Scalability:** ERP systems are designed to scale with the growth of an organization. They can accommodate changes in the size and complexity of business operations, making them suitable for both small and large enterprises.
- **Customization:** While ERP systems offer standardized modules, they also allow for customization to meet the specific needs of an organization. This ensures that the software aligns with the unique requirements of the business.
- **Improved Communication:** ERP enhances communication and collaboration among different departments by providing a unified platform for sharing information. This leads to better coordination and faster decision-making.
- **Mobile and Cloud Capabilities:** Many modern ERP systems offer mobile access and cloud-based deployment options, allowing users to access information and perform tasks from anywhere with an internet connection.
- **Compliance and Security:** ERP systems often include features to ensure regulatory compliance and data security. This is crucial for businesses operating in industries with strict regulatory requirements.

Successful ERP implementation involves thorough planning, training, change management, stakeholder engagement, and ongoing support to realize the full potential of the system, ensure successful adoption, and drive business efficiency. Popular ERP vendors include SAP, Oracle, Microsoft Dynamics, and Infor, each offering solutions tailored to various industries and business sizes. ERP systems in supply chains offer several benefits, such as:

- **Improved Data Accuracy and Accessibility:** ERP systems centralize data, ensuring that all departments have access to accurate and up-to-date information, reducing errors and enhancing decision-making [5][9].
- **Enhanced Collaboration:** By providing a unified platform for different supply chain partners, ERP systems facilitate better communication and coordination, leading to more synchronized operations [10].
- **Increased Efficiency:** Automation of routine tasks and processes through ERP systems reduces manual effort, speeds up operations, and minimizes the risk of human error [9] .

- **Better Inventory Management:** ERP systems help maintain optimal inventory levels by providing real-time visibility into inventory status, demand forecasts, and supply conditions [11], [12].
- **Regulatory Compliance:** ERP systems assist in maintaining compliance with industry regulations and standards by providing necessary documentation and audit trails [13].

2.3 Blockchain Technology

Blockchain is a decentralized and distributed ledger technology that enables secure and transparent record-keeping of transactions across a network of computers. Unlike traditional databases, which are often centralized and controlled by a single entity, blockchain operates on a peer-to-peer network, providing a tamper-resistant and verifiable way to record and verify transactions. At its core is a peer-to-peer distributed ledger. It is cryptographically secure, append-only, immutable and updateable only via consensus or agreement among peers. It can be approached as a layer of distributed peer-to-peer network running on top of the Internet.

The following image depicts the way blockchain works. All the main components are described below.

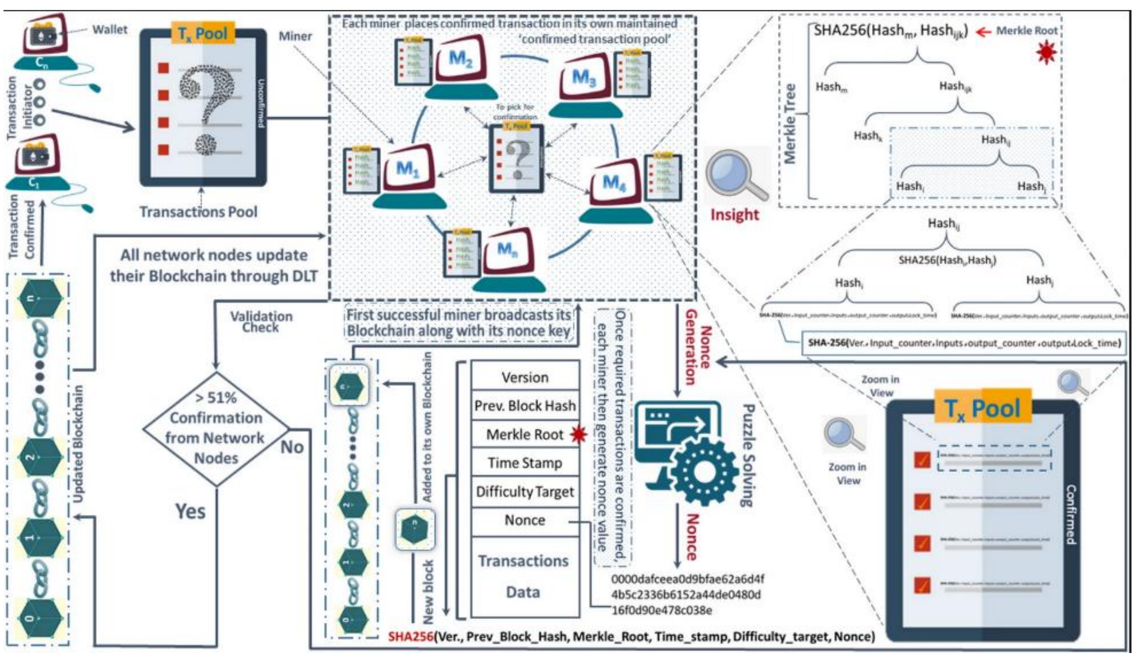


Figure 6. Blockchain main components and the way it works [32]

The main components and features of blockchain are:

- **Blocks:** Each block contains a list of transactions. These transactions are grouped and added to the blockchain in a sequential and chronological order.
- **Blockchain:** The blockchain is a chain of blocks, where each block is linked to the previous one through a cryptographic hash. This creates a continuous and unalterable chain of transaction history.
- **Nodes:** Nodes are individual computers or participants in the network. They maintain a copy of the entire blockchain and participate in the validation and verification of transactions.
- **Consensus Mechanism:** The consensus mechanism is a set of rules that govern how nodes agree on the state of the ledger and validate transactions. Common consensus mechanisms include Proof of Work (PoW), Proof of Stake (PoS), and Delegated Proof of Stake (DPoS), among others.
- **Cryptographic Hash Function:** Blockchain uses cryptographic hash functions to secure the integrity of data within blocks. Each block contains a hash of the previous block, creating a chain that is resistant to tampering [14].

▪ Some of the key characteristics of blockchain include:

- **Decentralization:** Blockchain operates on a decentralized network of nodes (computers), eliminating the need for a central authority. Each node on the network has a copy of the entire blockchain, ensuring that no single entity has control over the entire system. This distributes power and trust among participants [15].
- **Distributed Ledger:** Transactions are recorded in a distributed ledger that is shared among all participants in the network. This ledger is maintained through a consensus mechanism, ensuring that all nodes agree on the validity of transactions.
- **Immutable Record:** Once a block is added to the blockchain, it is extremely difficult to alter or delete the information contained within it. This immutability provides a high level of trust and transparency, making blockchain suitable for applications where data integrity is crucial.
- **Smart Contracts:** Smart contracts are self-executing contracts with the terms of the agreement directly written into code. These contracts automatically execute and enforce terms when predefined conditions are met, reducing the need for intermediaries [16].

- **Transparent and Auditable:** All participants in a blockchain network have visibility into the entire transaction history. This transparency, combined with cryptographic security, allows for easy auditing and verification of the integrity of the data [17].
- **Anonymity or Pseudonymity:** Participants in a blockchain network are represented by cryptographic addresses rather than personal information. While this provides a level of privacy, it also raises considerations related to anonymity.
- **Efficiency**: Blockchain can streamline processes by reducing the need for intermediaries, thereby lowering costs and speeding up transaction times [13].
- **Decentralized Applications (D-Apps):** Blockchain enables the development and deployment of decentralized applications that run on the blockchain network without the need for a central server.
- **Tokenization:** Blockchain facilitates the creation of tokens, which can represent assets or have utility within a specific ecosystem. Tokenization enables new models of ownership and value exchange.
- **Permissioned and Permissionless Blockchains:** Blockchain networks can be either permission (restricted access) or permissionless (open to anyone). Permissioned blockchains are often used in enterprise settings, while permissionless blockchains, like Bitcoin, allow anyone to participate in the network.
- **Use Cases:** Blockchain finds applications in various industries, including finance (cryptocurrencies like Bitcoin), supply chain management, healthcare, voting systems, and more. It is particularly valuable in situations where trust, security, and transparency are paramount.

Blockchain technology has the potential to revolutionize the way transactions are recorded and verified, introducing new levels of security, efficiency, and transparency to various industries. However, it also faces challenges such as scalability issues, energy consumption (in Proof of Work systems), and regulatory considerations. Ongoing research and development aim to address these challenges.

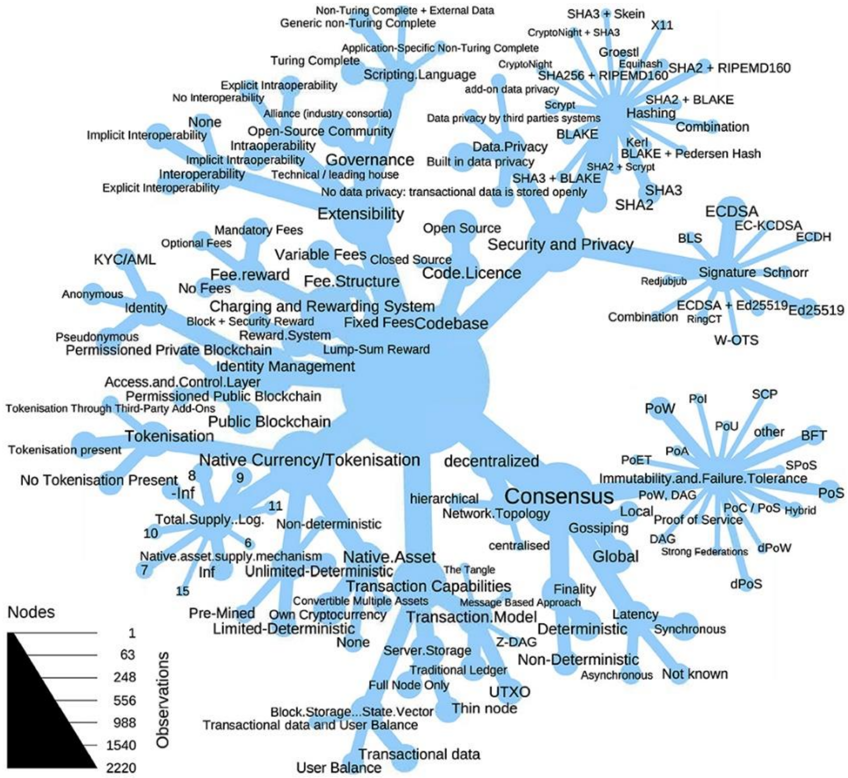


Figure 7. The tree of blockchain illustrates the varying innovation activity within the components [18]

Blockchain technology can be divided into multiple types such as public blockchain, private blockchain, semi-private blockchain, sidechains, permissioned ledger, distributed ledger, tokenized blockchains and many more.

2.4 Benefits of ERP and Blockchain Technology Integration

Integrating blockchain technology into ERP systems offers significant advantages for achieving interoperability in supply chains. Blockchain enhances data security and integrity through its decentralized and immutable ledger, ensuring consistent and reliable information across different systems. It improves transparency and traceability, allowing stakeholders to monitor every transaction in real-time. This integration reduces costs by eliminating the need for complex middleware and intermediaries, while also fostering greater collaboration and trust among participants.

Some of the main benefits of Blockchain-ERP Integration are listed in the table below:

Table 1. List of benefits of ERP and Blockchain Technology integration

List of benefits of ERP and Blockchain Technology integration	
Enhanced Security	Blockchain's cryptographic features can enhance the security of ERP data, providing a tamper-resistant and transparent record of transactions. This is particularly crucial for maintaining the integrity of critical business data
Transparency and Traceability	Blockchain's decentralized and transparent nature ensures that all participants in the network have access to a single version of the truth. This transparency can be leveraged to trace and track products, transactions, and changes within ERP systems.
Streamlined Processes	Smart contracts on blockchain can automate and enforce predefined rules in ERP processes. This automation can streamline workflows and reduce the need for manual intervention.
Reduced Fraud and Errors	The immutability of blockchain records minimizes the risk of fraud and errors in ERP data. Once information is added to the blockchain, it becomes extremely difficult to alter, providing a reliable and auditable record.
Efficient Supply Chain Management	Integrating blockchain with ERP systems can optimize supply chain processes by providing real-time visibility into the movement of goods, reducing delays, and improving overall efficiency.

While integrating blockchain technology into ERP systems offers numerous benefits, it also presents several challenges. One major hurdle is the complexity of integrating blockchain with existing, often legacy, ERP systems, which may require significant technological adjustments and investments. Additionally, the need for widespread adoption among all supply chain participants can be a barrier, as it requires cooperation and coordination across diverse entities. There are also concerns related to data privacy and the management of sensitive information on a decentralized network. The main challenges are listed in the table below:

Table 2. Blockchain-enabled ERP system challenges

Obstacles for a seamless interoperability between ERP and Blockchain systems	
Data Standardization	ERP systems often have proprietary data formats, and achieving interoperability requires standardizing data structures to ensure compatibility with blockchain. This can be challenging due to the diversity of ERP solutions.
Scalability	Blockchain networks, especially public ones, may face scalability issues when handling the high transaction volumes typical of ERP systems. Ensuring that the blockchain infrastructure can scale to meet the demands of large enterprises is crucial
Integration Complexity	Integrating blockchain with existing ERP systems can be complex and may require significant changes to the architecture. Organizations need to carefully plan and execute the integration process to avoid disruptions to daily operations
Regulatory Compliance	Ensuring that blockchain-ERP solutions comply with industry and regulatory standards is essential. This includes addressing issues related to data privacy, security, and legal considerations.
User Adoption	Employees and stakeholders may need training and support to adapt to new workflows and understand the benefits of blockchain-ERP integration. User adoption is a critical factor in the success of any technology implementation.

The Blockchain-ERP interoperability finds applications in various industries, such as:

- **Supply Chain Management:** Integration can enhance traceability, visibility, and collaboration across the supply chain. Blockchain ensures that each participant in the supply chain has access to a secure and transparent ledger.

- **Finance and Payments:** Streamlining financial transactions through blockchain-ERP integration can improve transparency, reduce fraud, and accelerate payment processes.
- **Asset Management:** Blockchain can be used to track and manage assets efficiently. This is particularly useful in industries where asset tracking is critical, such as manufacturing or logistics.
- **Smart Contracts in Procurement:** Implementing smart contracts on a blockchain can automate and enforce procurement processes, reducing manual paperwork and enhancing efficiency.
- **Quality Assurance and Compliance:** Blockchain's transparent and immutable nature can be leveraged to ensure compliance with quality standards and regulatory requirements.

In conclusion, the interoperability between ERP and blockchain technologies offers a powerful solution for organizations seeking to optimize their business processes, enhance data security, and embrace the advantages of decentralization and transparency. As these technologies continue to evolve, businesses should carefully consider the potential benefits and challenges associated with their integration to make informed decisions that align with their strategic objectives. To achieve successful interoperability, organizations should carefully assess their specific needs, choose appropriate blockchain solutions, and work with experienced vendors or consultants to implement the integration seamlessly. Ongoing collaboration and industry-standard initiatives can also play a role in developing interoperable solutions.

2.5 Literature Review

The literature review section of this thesis aims to provide a comprehensive analysis of existing research related to ERP interoperability and the integration of blockchain technology within supply chains. This review will examine the current methodologies employed to achieve ERP system interoperability, highlighting their limitations and challenges. Additionally, it will explore the fundamental principles and features of blockchain technology that make it a viable solution for these interoperability issues. By synthesizing findings from various studies, this section will lay the groundwork for understanding the potential impact of blockchain on enhancing supply chain efficiency, security, and transparency, thereby contextualizing the proposed blockchain-based architecture within the broader academic and industry discourse.

Aslam et al. (2022) propose a blockchain-based architecture to enhance the transaction integrity within ERP systems. Their research emphasizes the use of the Proof of Elapsed Time (PoET) consensus mechanism to ensure secure and efficient transaction validation, thereby improving the reliability of supply chain data [19].

Banerjee (2018) explores how blockchain can provide valuable insights into the supply chain when integrated with ERP systems. The study identifies challenges such as data standardization and interoperability between different blockchain platforms and ERP systems, suggesting that overcoming these hurdles is crucial for maximizing the benefits of the technology [33]. Dasaklis et al. (2021) discuss the benefits and challenges of integrating blockchain with ERP systems, noting that while blockchain can enhance data security and transparency, it also requires significant changes in existing ERP infrastructure and processes. They recommend a phased integration approach to manage these challenges effectively [21].

Dasaklis et al. (2022) conduct a systematic literature review on blockchain-enabled supply chain traceability, highlighting the potential of blockchain to improve traceability and sustainability in supply chains. They argue that integrating blockchain with ERP systems can lead to better tracking of products and raw materials, thus promoting sustainable practices [22]. Saberi et al. (2019) explore the relationship between blockchain technology and sustainable supply chain management. They suggest that blockchain can support sustainability goals by providing transparent and immutable records of supply chain activities, which can be seamlessly integrated into ERP systems for enhanced monitoring and reporting [23].

Dewi et al. (2021) examine the factors affecting ERP implementation in the context of blockchain technology, particularly in creating infrastructure for Society 5.0. Their findings indicate that a well-designed implementation strategy, including stakeholder engagement and robust technological infrastructure, is critical for successful integration [24]. Hader et al. (2020) present a case for integrating blockchain with ERP to improve supply chain management. They emphasize the need for interoperability frameworks that can facilitate seamless data exchange between ERP and blockchain platforms, ensuring that both systems can operate cohesively [34].

Kitsantas (2022) discusses the business and technical aspects of blockchain-ERP integration, identifying current problems and future perspectives. The study highlights the potential for smart contracts and decentralized applications to automate and optimize supply chain processes within ERP systems [35]. Morawiec and Sołtysik-Piorunkiewicz (2022) investigate the adoption of cloud computing, big data, and blockchain technology in ERP implementation methodologies. They argue that these technologies, when combined, can significantly enhance the capabilities of ERP systems, making them more adaptable and resilient [27].

Sokolov and Kolosov (2019) provide a comparative analysis of ERP systems and blockchain platforms, discussing their respective strengths and weaknesses. They conclude that while blockchain offers superior security and transparency, ERP systems provide robust process management capabilities, suggesting that a hybrid approach could leverage the strengths of both technologies [28]. Pérez et al. (2021) design an information architecture for mass customized/personalized manufacturing in Industry 4.0, incorporating blockchain to address key challenges. Their work demonstrates how blockchain can complement ERP systems by enhancing data integrity and enabling real-time decision-making [36].

The authors in [19], propose a blockchain-based architecture aimed at enhancing transaction integrity within ERP systems. Their research highlights the use of the Proof of Elapsed Time (PoET) consensus mechanism to secure and efficiently validate transactions, thereby improving the reliability of supply chain data. Similarly, in [20], the authors explore the insights blockchain can provide when integrated with ERP systems, particularly in the supply chain context. This study identifies critical challenges such as data standardization and interoperability between various blockchain platforms and ERP systems, underscoring the importance of overcoming these hurdles to fully leverage the technology's benefits.

The benefits and challenges of integrating blockchain with ERP systems are further discussed by [21]. They note that while blockchain enhances data security and transparency, it necessitates significant changes in existing ERP infrastructures and processes. A phased integration approach is recommended to manage these challenges effectively. In a subsequent study, [22], conduct a systematic literature review on blockchain-enabled supply chain traceability, emphasizing the potential of blockchain to improve traceability and sustainability. They argue that integrating blockchain with ERP systems can lead to better tracking of products and raw materials, thus promoting sustainable practices.

In [23], the authors examine the relationship between blockchain technology and sustainable supply chain management. They suggest that blockchain supports sustainability goals by providing transparent and immutable records of supply chain activities, which can be seamlessly integrated into ERP systems for enhanced monitoring and reporting. [24], focus on the factors affecting ERP implementation in the context of blockchain technology, particularly in creating infrastructure for Society 5.0. Their findings indicate that a well-designed implementation strategy, including stakeholder engagement and robust technological infrastructure, is critical for successful integration.

In [25], a case is presented for integrating blockchain with ERP to improve supply chain management. The authors emphasize the need for interoperability frameworks that can facilitate seamless data exchange between ERP and blockchain platforms, ensuring cohesive operation. In [26], the authors discuss the business and technical aspects of blockchain-ERP integration, identifying current problems and future perspectives. The study highlights the potential for smart contracts and decentralized applications to automate and optimize supply chain processes within ERP systems.

The adoption of cloud computing, big data, and blockchain technology in ERP implementation methodologies is investigated in [27]. The authors argue that these technologies can significantly enhance the capabilities of ERP systems, making them more adaptable and resilient. In [28], a comparative analysis of ERP systems and blockchain platforms is provided, discussing their respective strengths and weaknesses. The study concludes that a hybrid approach could leverage the superior security and transparency of blockchain with the robust process management capabilities of ERP systems. In [29], the authors propose an information architecture for mass customized/personalized manufacturing in Industry 4.0, incorporating blockchain to address key challenges. Their work demonstrates how blockchain can complement ERP systems by enhancing data integrity and enabling real-time decision-making.

Finally in [30], the authors propose a generic blockchain-based architecture for interconnecting multiple ERP systems, for ensuring data integrity and interoperability. The study lacks practical implementation.

3. Blockchain Architecture for ERP Systems

In this chapter, we will study the proposed architecture for seamless ERP systems and Blockchain technology integration and interoperability. The main elements of the proposed architecture will be discussed in detail along with the implementation details of the system. The challenges of designing such a system will be covered thoroughly. The levels required to interact for a seamless experience are listed in this chapter. Finally, a high-level description of the web application and an overview of the application's capabilities are provided.

3.1 Design and Challenges

Designing an architecture that integrates ERP systems with blockchain technology requires careful consideration of various components to ensure seamless interoperability, security, and efficiency. The proposed system architecture outlined below addresses the key elements for integrating ERP and blockchain technologies, particularly focusing on supply chain management.

3.1.1 ERP System Layer

Core ERP Modules: In the context of our study, the ERP system is tailored to supply chain management. It encompasses specific functions related to procurement, inventory management, order processing, logistics, and supplier relationship management. These modules are essential for managing the end-to-end processes within the supply chain, ensuring efficient operations and data accuracy.

Data Integration Layer: The integration of ERP data with blockchain is facilitated through the establishment of middleware and APIs that enable real-time data synchronization. This layer acts as a bridge between the ERP system and the blockchain, ensuring that data is consistently updated and accurately reflected across both platforms. This integration enhances the transparency and traceability of supply chain transactions.

User Interface: A user-friendly interface is crucial for the successful adoption of the integrated ERP and blockchain system. The interface should allow users to seamlessly interact with both ERP and blockchain functionalities, providing intuitive access to data, reports, and transaction details. This ensures that users can leverage the full potential of the integrated system without requiring extensive technical knowledge.

3.1.2 Blockchain Layer

Blockchain Network: To ensure controlled access and maintain security, an Ethereum private blockchain network is established. The use of Ganache as the testing blockchain serves as the backbone for the implemented web application, providing a reliable and flexible environment for development and testing. This private network allows for better management of permissions and access control, ensuring that only authorized entities can interact with the blockchain.

Smart Contracts: Smart contracts, written in Solidity, are utilized to automate and execute predefined business logic within the blockchain network. These contracts facilitate various transactions and enforce rules, ensuring that business processes are carried out seamlessly and transparently. By automating these processes, smart contracts help to reduce manual intervention, minimize errors, and enhance the efficiency of supply chain operations.

Consensus Mechanism: Although the implementation described here skips the consensus mechanism for simplicity, it is critical to highlight its importance in securing the blockchain network. Typically, mechanisms such as Practical Byzantine Fault Tolerance (PBFT) or Proof of Authority (PoA) would be used to achieve consensus among network participants. These mechanisms ensure that all transactions are validated and agreed upon by a majority of the network, thus maintaining the integrity and security of the blockchain.

Identity Management: A robust identity management solution is crucial for authenticating and authorizing participants within the blockchain network. This system ensures that only verified and authorized users can access the blockchain, protecting against unauthorized access and potential security breaches. Effective identity management also facilitates the tracking of participant actions within the network, contributing to overall transparency and accountability.

3.1.3 Interoperability Layer

APIs and Connectors: Application Programming Interfaces (APIs) and connectors are critical components developed to enable seamless communication between the ERP system and the blockchain network. These APIs and connectors ensure that data can flow smoothly and securely between the two systems, facilitating real-time updates and interactions. By providing a standardized interface, they help in bridging the gap between the ERP system's internal processes and the blockchain's decentralized ledger.

Data Mapping and Translation: To ensure compatibility between the ERP system's format and the blockchain's format, robust data mapping and translation mechanisms are implemented. These mechanisms convert and align data structures and formats, ensuring that information is accurately and consistently represented across both platforms. This step is vital for maintaining data integrity and coherence, allowing for effective synchronization and integration of records and transactions.

3.1.4 Security and Privacy Layer

Encryption and Hashing: Encryption and hashing techniques are implemented to secure data both within the ERP system and on the private blockchain, enhancing data integrity and confidentiality. Access Control: Access control mechanisms exist in the ERP systems and on the private blockchain, regulating user permissions and restricting unauthorized access to sensitive information.

3.2 Supply Chain Main Actors

The supply chain consists of three main actors. Since the point of interest does not focus on each company's internal operations, we focus only on their inventory. That means that we focus only on the incoming and outgoing products and the available quantity of each product.

- The first supply chain actor represents the company that buys wheat and sells flour.
- The second supply chain actor represents the company that buys the flour originated from the first company and sells bread.
- The third actor represents the logistic company that distributes the bread to the consumers.

3.3 Architecture Main Components

The architecture of the web app consists of three ERP systems and one blockchain server. The interconnection of each ERP system with the blockchain server becomes achievable with a REST API service. Notable is the fact that ERP systems cannot interact directly with each other. The interaction is possible only through the Blockchain layer.

As mentioned, there are three supply chain actors in the supply chain. Thus, each actor owns a separate ERP system. Each system consists of three components. These are the frontend component, the backend component, and the database component. More details about the features and functions of these components are listed in the following chapters.

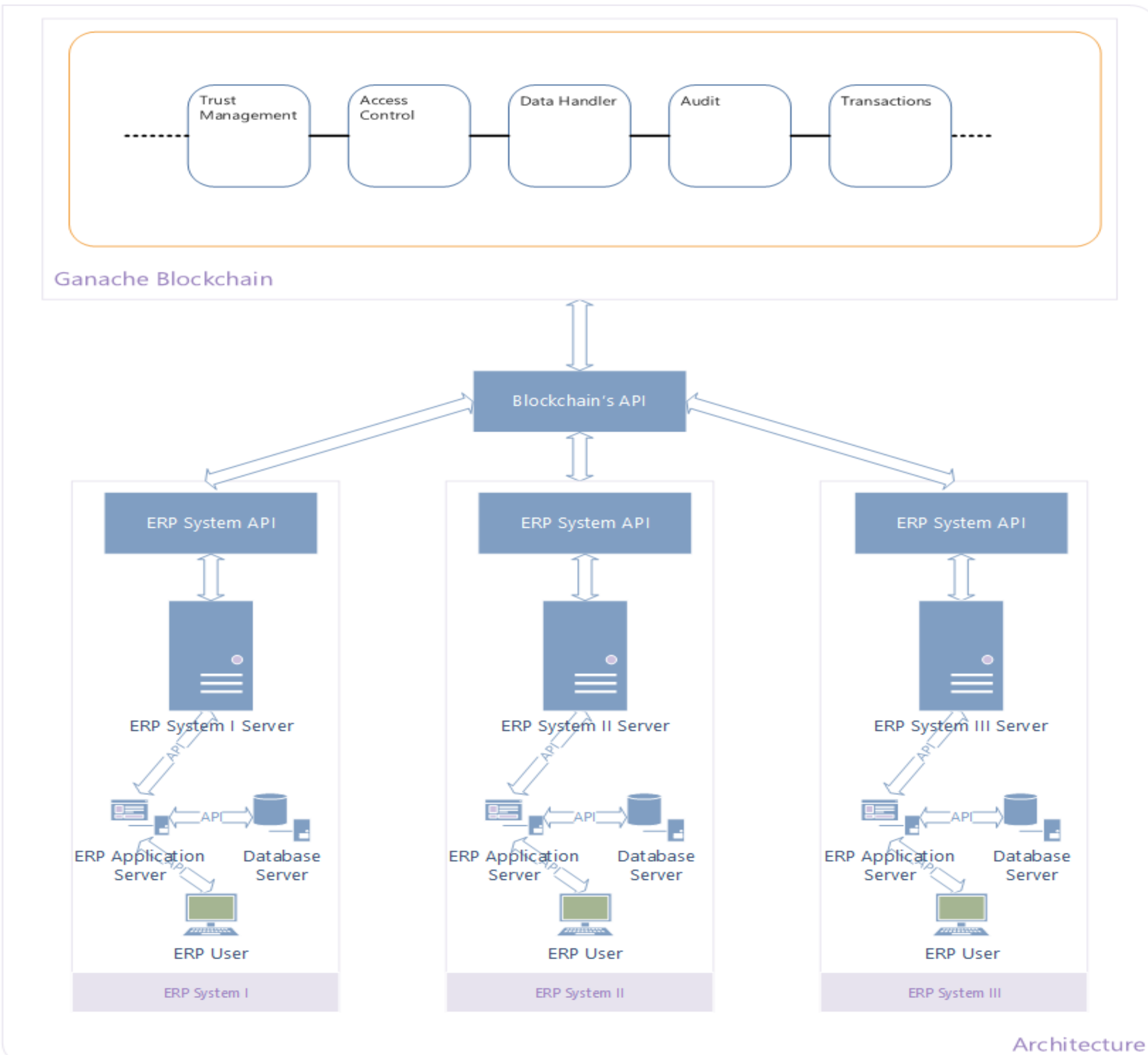


Figure 8. System Architecture Overview I

3.4 High-Level Description

The interoperability between blockchain and conventional ERP systems in the supply chain can be observed in the developed web app. The purpose of this web app is to simulate the way companies can interact with each other and to test the proposed architecture in a real-life scenario.

Each company in the supply chain buys materials and sells its product to another company in the same supply chain. While this procedure is a time-based demonstration, the results are spotted instantly due to the real-time update of each supply chain company's inventory. Each ERP system contains an automated time-based procedure. When the demo starts, the company searches on the blockchain to find companies that sell the products needed. The company orders the product to keep its production line running. A randomly generated number represents the quantity of the product ordered. The order is created and placed using the blockchain layer. The order is stored in the local database of each company involved in the transaction.

An order can have one of the following states: created, placed, and filled. The user can watch the order status in each phase until the order is delivered. At that point, each company's inventory is updated based on the quantities received or sent. The user can search either the local base or directly on the blockchain layer to find an order. The order ID or the blockchain's transaction hash are some of the keys to performing the search.

There are restrictions in place that limit the actions a user can perform. The ERP system administrator assigns the role to the user during the registration process. When the user logs into the web application for the first time, his account is registered automatically in the blockchain server. In this way, the blockchain layer and the application server can recognize the permissions assigned to the user.

From the perspective of the blockchain layer, these controls and permissions are implemented with smart contracts. On the application side, these controls are implemented by the application itself. If the system detects a user's request that is not permitted, then a proper message informs the user. It is worth noting that if a user does not have the appropriate permission to perform a function or action, the system will hide that item from the user.

There are many additional systems that a company needs to ensure business continuity. Implementing a disaster recovery plan is one of them. When a company wishes to implement such a system, additional equipment or costs are required. Using blockchain technology, such a plan is possible at no extra cost. Thus, a DR module is implemented in the web application. An ERP system administrator has the ability to retrieve the company's entire inventory from the blockchain server, provided the local database is in sync with the blockchain server.

3.5 System Implementation Details

The web application was developed using Visual Studio Core. The Blockchain layer was built using the Ganache environment. It is a personal Blockchain for Ethereum development that can be used for testing smart contracts and DApps in a sandbox environment. Consequently, all the smart contracts that enable the various features and functionality are written in Solidity. All ERP system servers as well as the Blockchain server hosting the Ganache environment are built using ExpressJS, which is a NodeJS web application framework. APIs that enable communication and functionality between Blockchain server and ERP systems are hosted on these servers. The frontend part of the web application was built using NodeJS, VueJS Framework, Typescript, and Bootstrap.

Connecting and communicating with the database is possible using Prisma ORM. ApexCharts JS library provided the charts and graphs. Docker is responsible for the containerization of the various components into one application.

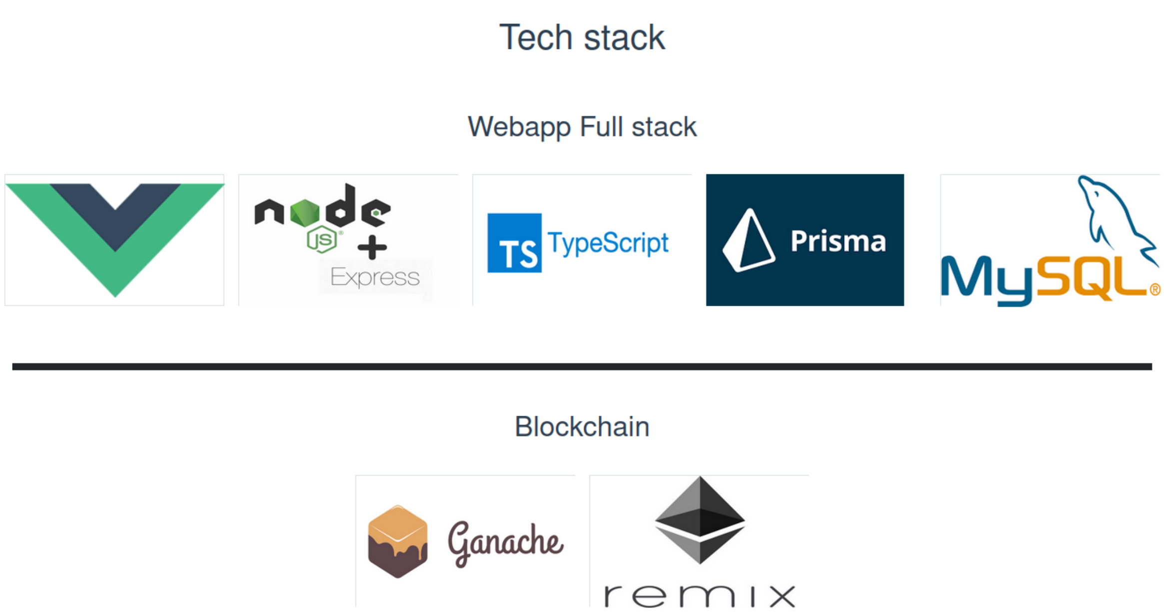


Figure 9. Development stack

4. Case Study: Mock Bread Supply Chain

A simplified version of the bread supply chain has been used as our case study. It consists of three different stakeholders, namely the supplier, the manufacturer, and the distributor. The supplier is the one who buys wheat and provides flour, the manufacturer who buys flour and sells bread, and finally, the distributor who buys bread and distributes it to the consumers.

Each of them operates on a copy of the developed ERP system, personalized for his own needs. However, the Blockchain component is the same for all of the stakeholders and it is the component that brings together all the operations that make the supply chain operational. There are many challenges and issues to address when designing and implementing a blockchain-enabled ERP system. The most important challenges and the steps taken to mitigate them are listed in the table below.

Challenges and issues	
Data Integration	• **Challenge**: ERP systems and blockchain often use different data formats and standards, making integration complex. • **Solution**: Common data standards are established with the use of API service.
Real-time Data Sharing	• **Challenge**: Ensuring real-time data synchronization between ERP systems and blockchain networks can be difficult due to latency and network reliability. • **Solution**: A robust API is implemented and used to update the blockchain layer when a new order is placed. Mandatory is a high-speed network connection to facilitate real-time data transfer.
Traceability and Transparency	• **Challenge**: Maintaining end-to-end traceability and transparency across the supply chain while integrating ERP and blockchain.

	• **Solution**: The blockchain is used for immutable record-keeping and ERP for operational data, with clear interfaces for data sharing. Search capabilities are based on transaction hashes.
Security and Privacy	• **Challenge**: Protecting sensitive data while sharing information across blockchain and ERP systems. • **Solution**: Strong encryption, access controls (role-based implementation and MFAs), and privacy-preserving technologies are implemented to secure data.
Scalability	• **Challenge**: Scaling the integrated system to handle large volumes of transactions and data. • **Solution**: It could be achieved by adopting scalable blockchain solutions (e.g., Layer 2 solutions) and ensuring ERP systems can handle increased loads. It is not needed for this PoC though.
Regulatory Compliance	• **Challenge**: Complying with various regulations regarding data handling, privacy, and supply chain transparency. • **Solution**: Ensuring both blockchain and ERP systems adhere to relevant regulations and standards.
Cost and Resource Allocation	• **Challenge**: The cost and resources required to integrate and maintain ERP systems with blockchain technology. • **Solution**: Conducting cost-benefit analysis and securing investments to support the integration process.
User Training and Adoption	• **Challenge**: Ensuring that employees and stakeholders are

	trained to use the new integrated systems effectively. • **Solution**: Providing comprehensive training programs and user-friendly interfaces to facilitate adoption.

Table 3. System design challenges

4.1 The Architecture of the Developed Web App

A web app has been developed from scratch as a proof of concept which consists of smaller web apps interconnected via APIs. The system architecture is depicted in the Figure 8. **System Architecture**. For our study, the complexity of the developed systems is kept as simple as possible. The main components of the web app are the following:

- Web application frontend
- Web application backend
- Relational Database
- Blockchain layer
- Various security controls

The emulation of an ERP system is achieved by bringing together three different components, namely the front-end component, the backend component, and the database component as depicted in the image below.

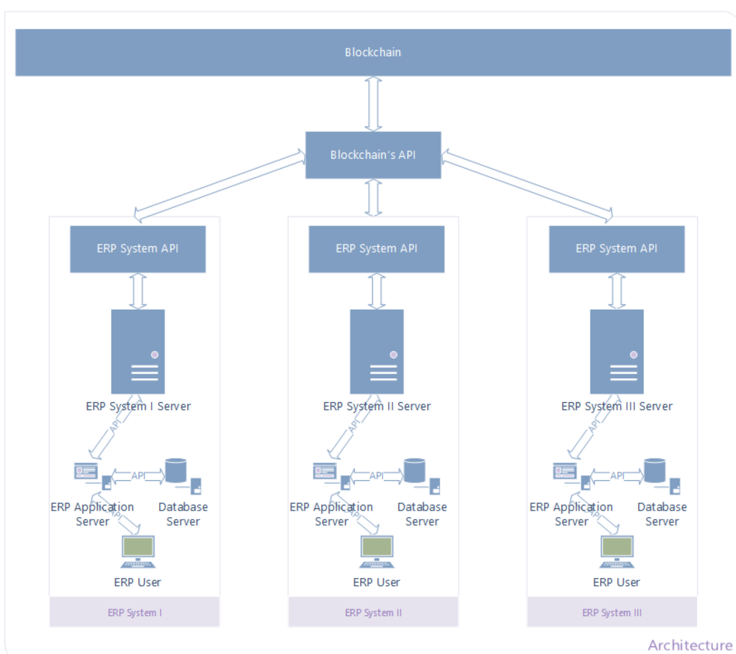


Figure 10. System Architecture Overview II

4.2 System components

The web application consists of three ERP systems and a Blockchain server. Each ERP system contains a frontend server, a backend server, and a relational database server (see Figure 10. **System Architecture Overview II**). All three servers are very similar to their counterparts in any ERP system. Thus, the four servers are described in detail below.

4.2.1 Front End Component

The web app frontend component is the provided UI that visualizes all the operational aspects of the Blockchain’s interconnection. It provides visualization of the inventory held in the local database according to the traditional centralized version of ERPs and at the same time monitors the orders that have been subscribed in the Blockchain layer providing visual analytics through graphs. To demonstrate the interoperability of Blockchain technology and traditional ERP systems, some operations have been split into discrete steps that allow visual monitoring and understanding of them.

The frontend component contains modules for the provided demo. The demo generates in an automated manner orders that are registered into the local database as well as into the Blockchain layer. Except for the supplier who simply produces certain quantities of wheat in standard intervals of time, the rest of the stakeholders of the supply chain, before the creation of each order the Blockchain layer is examined for the availability of the products they need to produce their products. The amount is held and when the order is placed it is subtracted from the seller’s inventory and added to the buyer’s inventory while updating the total available resources on the Blockchain. Search modules exist that make it possible to search an order either locally or on the private blockchain as long as an order ID or a transaction hash is provided. Each stakeholder can search on the Blockchain orders he has submitted or received, making it impossible to explore other stakeholders’ inventory on the Blockchain.

An interesting option has been implemented which serves as a data loss prevention (DLP) feature. If the user of a particular stakeholder has the necessary permissions, he can retrieve the entire history of orders placed or received along with the data that accompanies them. In the case of a catastrophic event where the ERP system database is destroyed, this feature provides an easy way to recover the company's inventory from the Blockchain. Several options exist that enable the user to tweak various aspects of the web application depending on their role and permissions. There are three distinct roles a user can have and these are admin, moderator, and user. Each role is allowed to perform certain operations and the list of the permitted operations varies depending on those permissions.

4.2.2 Backend Component

The backend component is the backbone of the ERP system. It is built using the ExpressJS framework and serves the API that interconnects the frontend component with the database component and the ERP system with the Blockchain API. It has embedded security features such as JSON Web Token (JWT) API authentication, even though the HTTP protocol is used to avoid SSL certificate complexity. The backend component is not accessible to the users. Only the frontend component can communicate and interact with it via its API service.

4.2.3 Database Component

The database component consists of a single relational database that serves the purpose of storing order data. Even though an implementation with a relation database was followed, a non-relational database would have worked, producing the same results. Besides the customer and order info, the relational database contains tables with records of registered ERP system users. These users can register to the ERP system using a dedicated login form. The ERP system administrator is responsible for assigning a role to them. The role is what the ERP system and the blockchain's smart contracts check when the user requests to access data on the blockchain.

4.2.4 Blockchain Component

The Blockchain component is the backbone of the proposed architecture for the supply chain. It is the place where all transactions are subscribed and stored immutably. Stakeholders can search for resources they need for their companies and place orders. Each of them is allowed to see whatever info is available, provided they have the appropriate permissions to see it. The search option is not available to anyone who does not have the permission to perform a search.

Blockchain blocks store information about transactions that have taken place. Details about the quantities of resources bought and sold, the companies that made the trades, the price of the trade, and the order and delivery dates are some of them. Transaction hashes are included, allowing the search for transactions based on the hash. Smart contracts ensure the expected system functionality. Additionally, they enforce access controls, preventing unwanted and unauthorized access to the data on the Blockchain.

When the user with administrative permissions logs into the ERP system for the first time, the local database syncs with the Blockchain. The web application dashboard displays the sync rates. Synchronization of the local database with the Blockchain ensures that there is always a up-to-date backup, ready for retrieval in case of local database's failure. Provided the user has admin rights, he can retrieve company stock from Blockchain. Ganache will provide the blockchain accounts and their private keys. Blockchain accounts are an essential part of the blockchain. When each user and company registers on the private blockchain, the system assigns them a unique account. Thus, users can distinguish themselves on the Blockchain as separate entities.

4.3 Security Controls

On the security side, in addition to the fine-graded access that smart contracts provide, various typical controls have been programmatically implemented in the application's source code. In the frontend component, typical controls of sanitization during registration and login are in place, along with the MFA module which is enabled or disabled based on the user's preference. When an API request is created it contains a JSON web token to avoid unauthenticated access to data. The records in the database are properly encrypted using strong encryption algorithms along with additional salt and the credentials are stored as hashes.

4.4 Containerization

The complete web application consists of three ERP systems, as our stakeholders are three in total and a Blockchain server. This means that a database server, a frontend server, and a backend server for each ERP are mandatory and must be deployed. Calculating the number of servers needed, a total of nine servers for the three ERP systems plus one for the Blockchain server are required. Although the number of servers is relatively low, it is difficult to monitor and manage all of them at the same time.

To face that issue each component was containerized. Each time the demo starts we issue a single command to launch it and new containers are created dynamically from the images we have built during containerization. The fact that certain database records need to be persistent was also taken into consideration, seeding that information stored in the deployed database.

4.5 Implementation in Mock Bread Supply Chain

The web app is a containerized application. Docker is used to build the images. Containers are created from these images that run the server instances of the web application. When the application launches, the Blockchain server and three EPR systems are running. Users can access the three landing pages of each ERP system and log in or register to one of the ERP systems. However, direct access to the Blockchain server is not permitted.

As shown in Figure 9. **Development stack**, an ERP system user logs into the ERP Application server that serves the frontend component. The ERP System server hosts the backend component that authenticates and authorizes the user. Once the user is authenticated and authorized, certain features appear on the web page based on the role and privileges the user is assigned. A company has to register to the Blockchain to make itself visible to other blockchain users. Registration is an automated procedure. It takes place the first time an ERP system user with administrative rights logs into the system. Once the company is registered on the Blockchain, the registration process cannot be performed again. However, whenever an administrative user logs into the ERP system, the system checks the company's registration status on the blockchain.

The ERP system implements a role-based scheme. When a user registers on the ERP system, a system administrator evaluates the application. If everything is in order, he assigns a system role to the user and can toggle the user's registration status to the blockchain (see Figure 10). The user's ability to perform certain actions and use certain application features depends on the permissions and blockchain registration status the user is assigned. Permissions are based on the role a user can have. There are three roles in the ERP system:

- **Administrator**: An administrator can grant or revoke user permissions or toggle blockchain user registration status (see Figure 11. **Registering users on a private blockchain**). He can start the Demo feature, and search for customers and orders on the local database and blockchain. Finally, he can use the DR feature to retrieve the company's inventory.

- **Moderator**: A moderator cannot grant or revoke user permissions or toggle blockchain user registration status. However, he can start the Demo feature, and search for customers and orders on the local database and blockchain. Finally, he can use the DR feature to retrieve the company's inventory.
- **User**: A simple user cannot grant or revoke user permissions or toggle blockchain user registration status. He cannot start the Demo feature, search for customers and orders on the local database and blockchain, or even use the DR feature to retrieve the company's inventory. A simple user is unaware of the existence of the blockchain as he cannot see content related to the blockchain.

During the company's registration on the Blockchain, the company's information is registered. The company's inventory, customer, and order list are registered on the Blockchain when an administrative user commences the procedure. When the registration finishes, the company's inventory is fully synchronized with the Blockchain ledger. The interoperability of the interconnected systems is based on the services running on the ERP system servers and the Blockchain server. When a Blockchain record of a new customer or order is registered, two sets of controls are triggered. The first set runs in the source code of the ERP system and the second is on the Blockchain. It is a cross-checking approach that increases transaction security and policy enforcement. This hybrid approach is possible due to the events and event listeners running in the web application combined with Blockchain smart contracts.

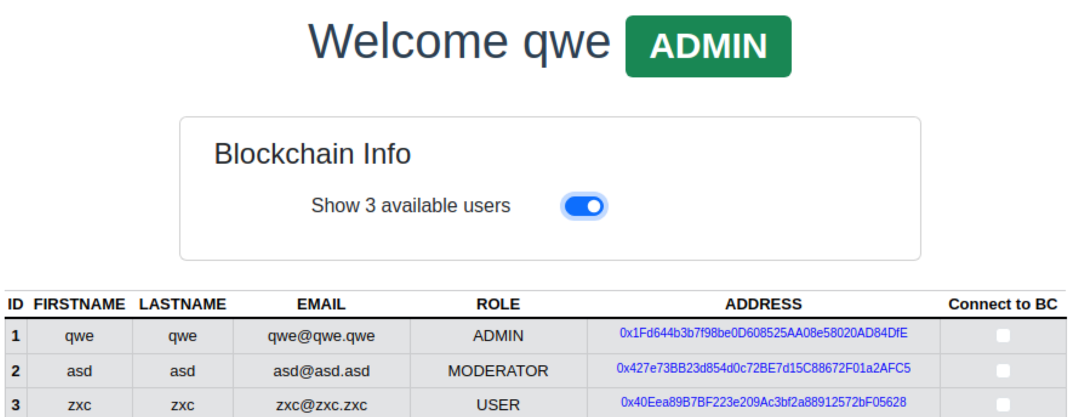
4.6 Description of the Application

For the needs of this thesis, a demo was developed based on the proposed architecture that aims to simulate the Bread Supply Chain that we studied. With this demo, the advantages of the proposed architecture can be highlighted. The source code of the developed web application is stored in a GitHub repository. After the source code is downloaded, packages and libraries must be installed to make the web application operational. The installation is performed with the help of NodeJS framework.

Every company has its own ERP system. Starting with the first company in the supply chain, namely Company_A, it buys wheat and sells flour. The first time the user visits the landing page of Company_A's ERP system, he has two options. The first is to register to the system if the user is new. The second option is to log into the ERP system.

The demonstration begins with the user's login. Once the user is authenticated and authorized, certain features appear on the web page based on the role and privileges the user is assigned. The demonstration is designed to show the full range of its capabilities when a user with administrative rights logs into the ERP system. Certain procedures are executed that are not visible to the user. Smart contracts are where the heart of the interoperability lies along with certain controls from the ERP systems. Solidity provides the modifiers which are keywords that help implement the fine-graded security perspective. Certain methods and procedures cannot be commenced or even be available to the user unless he has been given certain permissions from the administration like the DLP/DR module.

The next step is the company's registration to Blockchain. Once the registration is completed, the administrative user must assign roles to the existing users. Each user has a check box that toggles the Blockchain connectivity (see Figure 11. **Registering users on a private blockchain**). Even though the user can see the check box, he cannot click on it, if he does not have the appropriate permissions.



ID	FIRSTNAME	LASTNAME	EMAIL	ROLE	ADDRESS	Connect to BC
1	qwe	qwe	qwe@qwe.qwe	ADMIN	0x1Fd644b3b7f98be0D608525AA08e58020AD84DfE	
2	asd	asd	asd@asd.asd	MODERATOR	0x427e73BB23d854d0c72BE7d15C88672F01a2AFC5	
3	zxc	zxc	zxc@zxc.zxc	USER	0x40Eea89B7BF223e209Ac3bf2a88912572bF05628	

Figure 11. Registering users on a private blockchain

After the connectivity to Blockchain is enabled, the "*Fetch Customers*" button appears. When the user clicks the button, every customer registered in the local database is registered on the private blockchain (see Figure 12. **Customer registration on the private blockchain**). Each time the user clicks the "*Fetch customers*" button, the system scans the local database for new customers. If a new customer is found, the system will register him on the private blockchain.

The connection and synchronization speed depend on Blockchain implementation. Ganache framework provides a fast and robust environment, suitable for the needed implementation.

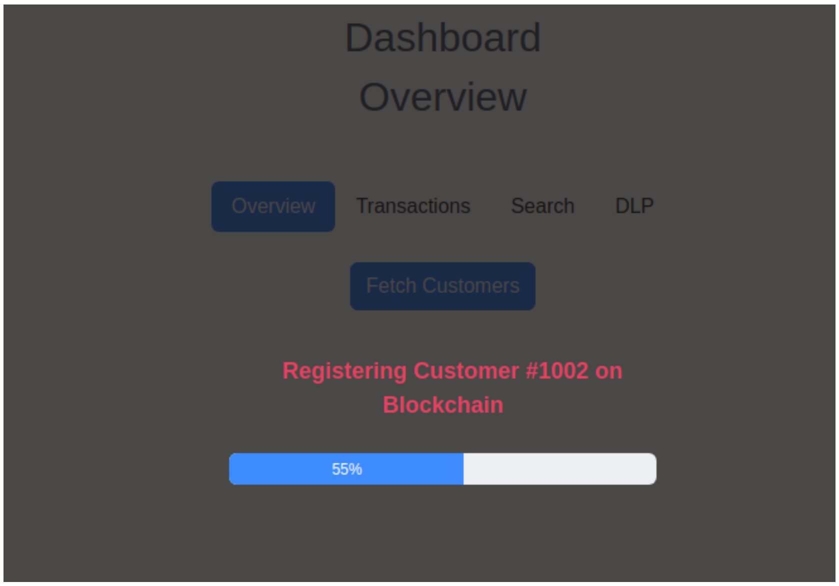


Figure 12. Customer registration on the private blockchain

When all customers are registered on the private blockchain, a table appears containing selected information about each customer. There are two columns, the Incoming and Outgoing, in which the total sum of the amount ordered by the customer is calculated. The "Incoming" and "Outgoing" labels relate to the product that the company buys and sells (see Figure 13. **Customer list**). The red arrow in the following picture points to the location where when the demonstration starts the values in each field are filled based on the orders registered on the private blockchain.

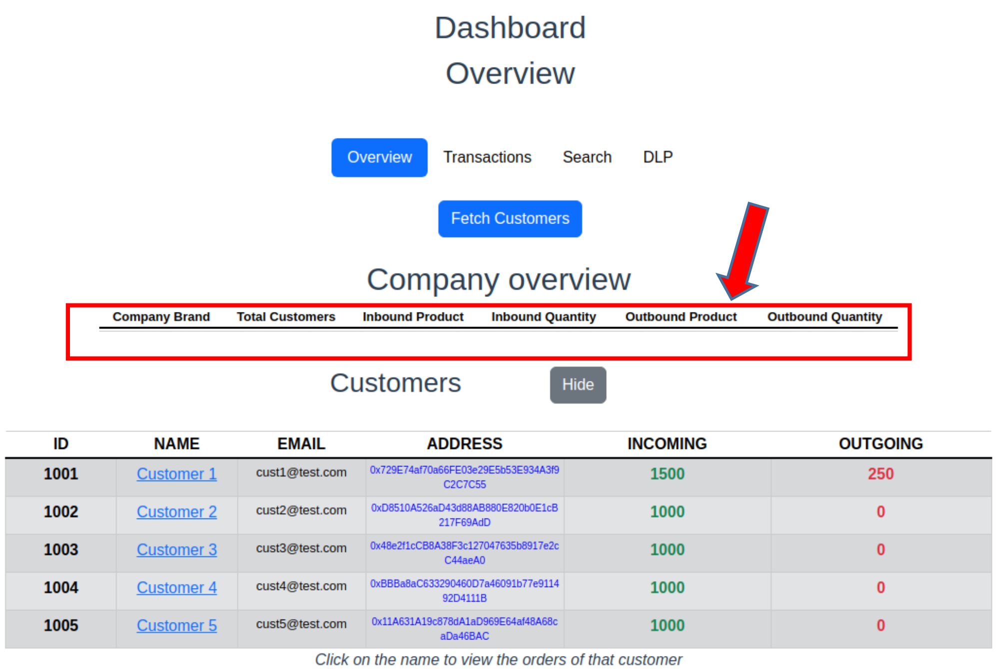


Figure 13. Customer list

If a customer's name is clicked, the system retrieves their order inventory from the local database and each order is registered on the private blockchain (see Figure 12. **Customer registration on the private blockchain**). Each time the user clicks the "*Fetch customers*" button the system repeats the procedure described. If a new customer is found, the system registers the new customer to the private blockchain, and if the user clicks one of the latest customer's orders the order is registered to the blockchain.

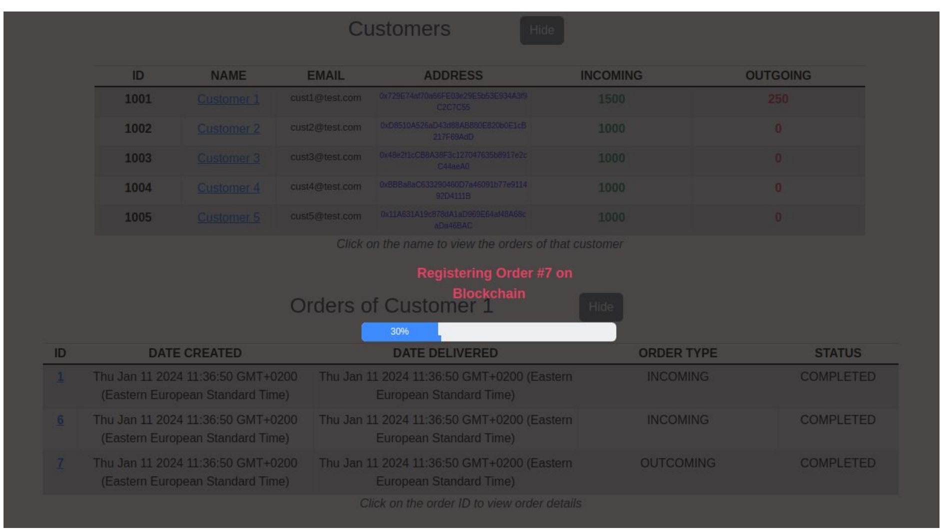


Figure 14. Order inventory registration private blockchain

Both the customer and order tables contain info from the local database. If the user clicks on the customer's name, the order inventory registration to the private blockchain will start. When the user clicks on an order ID, the order information will appear in a new table, including information about the registration on the private blockchain, as shown below.

Orders of Customer 5 Hide

ID	DATE CREATED	DATE DELIVERED	ORDER TYPE	STATUS
5	Thu Jan 11 2024 11:36:50 GMT+0200 (Eastern European Standard Time)	Thu Jan 11 2024 11:36:50 GMT+0200 (Eastern European Standard Time)	INCOMING	COMPLETED

Click on the order ID to view order details

Order #5 details Hide

ORDER ID	5
CUSTOMER ID	1005
RECEIPT ID	7
PRODUCT	WHEAT
AMOUNT	1000
CREATED AT	Thu Jan 11 2024 11:36:50 GMT+0200 (Eastern European Standard Time)
DELIVERED AT	Thu Jan 11 2024 11:36:50 GMT+0200 (Eastern European Standard Time)
ORDER TYPE	INCOMING
ORDER STATUS	COMPLETED
BC STATUS	Registered on blockchain
SEND TO	0xa65685a06fa6774637a222BB86639042618cC4Ff
RECEIVED FROM	0x11A631A19c878dA1aD969E64af48A68caDa46BAC
BLOCK HASH	0x7a9d0ea2f79d3dadbebf7e0a71f7332057756a30f26379eb4fbb7495531f066d
BLOCK NUMBER	176
TRANSACTION	0x5c2c1ffab2a5c4334684046b8dfb3a319f6af82a253261f569f583c981b89612

Figure 15. Order information

Every time a customer or order is registered on the private blockchain, the visual component that contains charts and graphs is updated. Up-to-date information is reflected in the graphs and charts corresponding to the proper state of the company's inventory. The figure below illustrates the fully synchronized data in the local database and private blockchain. If an order from the local database is not registered yet on the private blockchain or vice versa, the graphs and charts will vary accordingly.

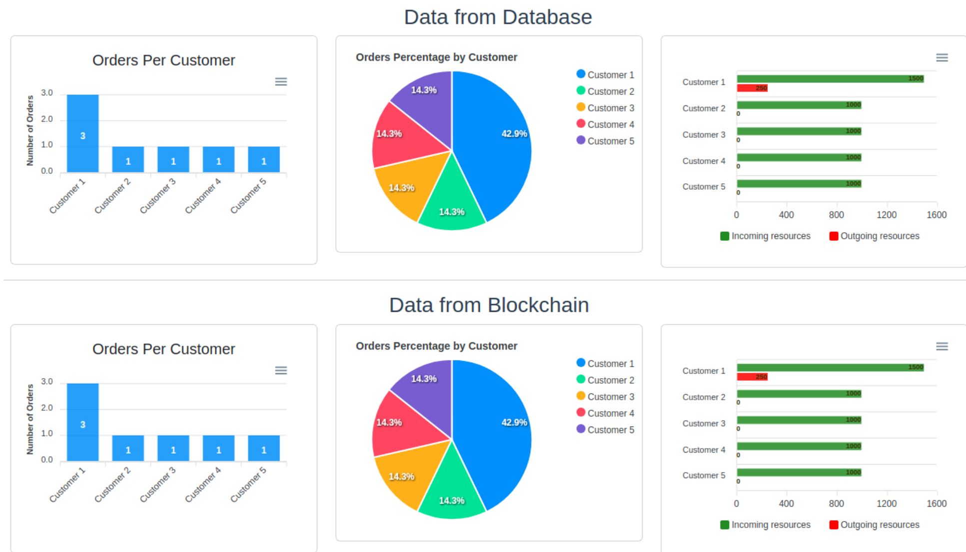


Figure 16. Inventory synchronization

User experience and set of actions are based on the role each user has in the web application. The logic behind this subtle role-based experience is to showcase the power of smart contracts and various application-based controls. The following flowchart contains a high-level overview of the procedures run when an administrative user logs into the ERP system or when the system registers the customer list and their inventory to the private blockchain.

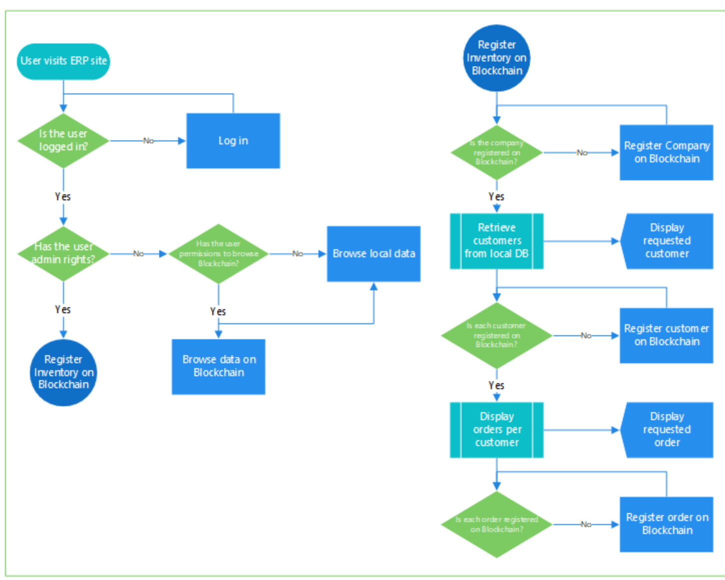


Figure 17. Log in and inventory registration to private blockchain

4.6.1 Main demo

In this section, the interoperability of ERP systems and Blockchain technology is presented in detail, as has been implemented in the web application. When an administrative user completes the step described in the previous section, the "Demo" feature in the "Transaction" tab in the web application is ready. All three ERP systems operate in the same way. Thus, the description of one of them will suffice.

The first company in the supply chain, namely Company_A, buys wheat and sells flour. The main demo starts when the user clicks the “Start Demo” button.

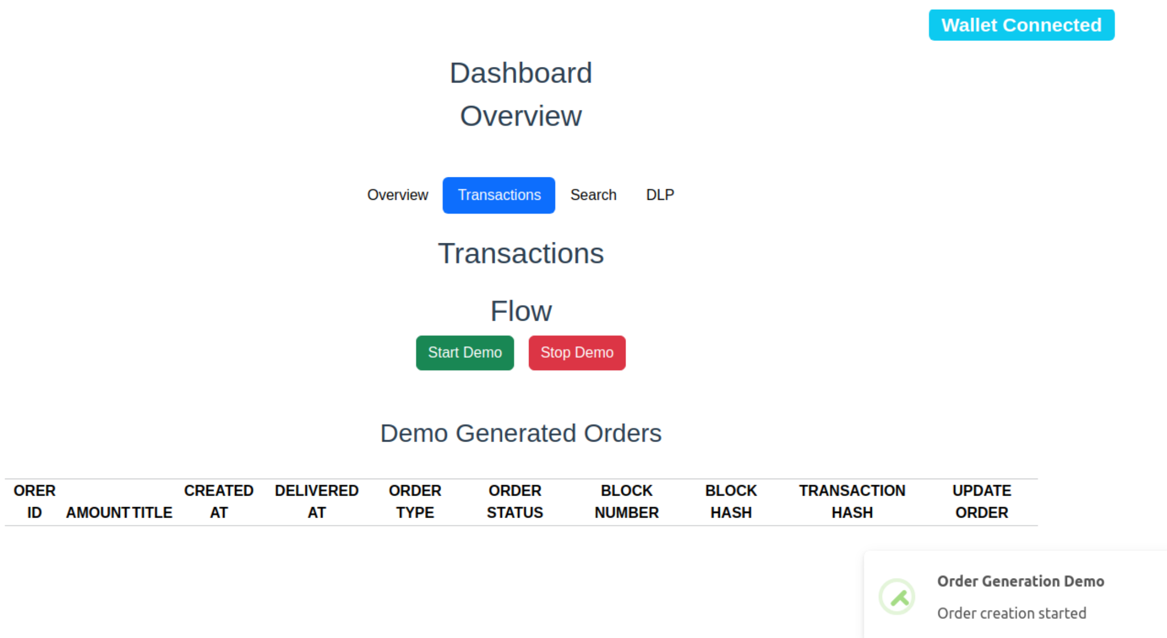
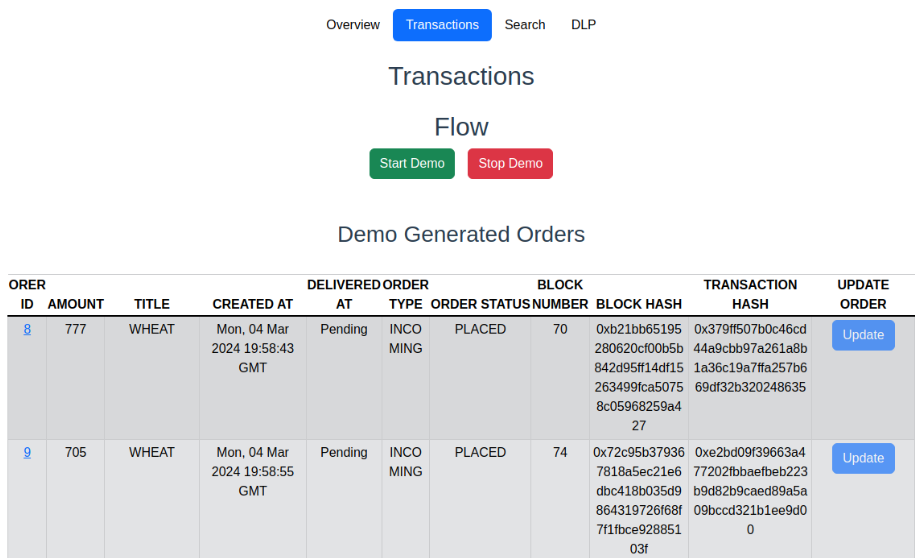


Figure 18. Demo control buttons

When the demo starts, certain procedures are executed that are not visible to the user. Smart contracts are where the heart of the interoperability lies along with certain controls from the ERP systems. Solidity provides the *modifiers* which are keywords that help implement the fine-graded security perspective. Certain methods and procedures cannot be commenced or even be available to the user unless he has been given certain permissions from the administration like the DLP/DR module.

A virtual order is created every fifteen seconds. The 15 seconds is chosen randomly. Its purpose is to slow down the whole process so that it is noticeable. When a new order is created, the ERP system makes an API call to the private blockchain to get the available amount of the product the company needs to buy.

If the amount available is equal to or greater than what the mock order needs, it is reserved for the order and subtracted from the available. If the amount available is less than the amount the mock order needs, the whole available amount is then reserved. The created order is stored in the local database and then follows the registration to the private blockchain. When the registration is completed, the local database is updated with the transaction hash value. The vendor on the private blockchain is informed about the transaction. His inventory is updated to depict the correct amount of new available resources. All the available info is presented in the table of the following figure.


Overview Transactions Search DLP

Transactions

Flow

Start Demo Stop Demo

Demo Generated Orders

ORER ID	AMOUNT	TITLE	CREATED AT	DELIVERED AT	ORDER TYPE	ORDER STATUS	BLOCK NUMBER	BLOCK HASH	TRANSACTION HASH	UPDATE ORDER
8	777	WHEAT	Mon, 04 Mar 2024 19:58:43 GMT	Pending	INCOMING	PLACED	70	0xb21bb65195280620cf00b5b842d95ff14df15263499fca50758c05968259a427	0x379ff507b0c46cd44a9cbb97a261a8b1a36c19a7ffa257b669df32b320248635	Update
9	705	WHEAT	Mon, 04 Mar 2024 19:58:55 GMT	Pending	INCOMING	PLACED	74	0x72c95b379367818a5ec21e6dbc418b035d9864319726f68f7f1fbce92885103f	0xe2bd09f39663a477202fbbaefbeb223b9d82b9caed89a5a09bccd321b1ee9d00	Update

Figure 19. Completed mock orders

Each order has two different dates. One is for the date of creation, and the other is for the date of deliverance. When the order is created the second date is blank. If the user clicks the "Update" button at some point later, the date of deliverance will change. Both records in the local database and the private blockchain of the order will be updated with the new date.

The demo's duration is 60 seconds. When 60 seconds pass, the demo stops. An early stop is available when the user clicks the "Stop" button. Each created order is stored in the local database and then registered to the private blockchain. When the user clicks the "Update" button, the deliverance date and the order status change. The order status is updated from "PLACED" to "COMPLETED". The order stored in the local database is updated first and then the order's updated field is updated on the private blockchain.

The flowchart below illustrates the mechanism described above.

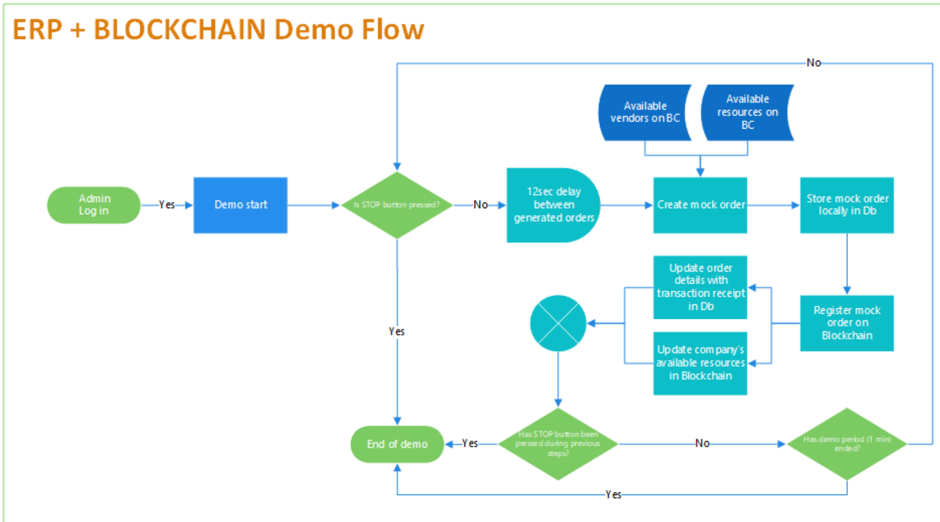


Figure 20. Demo flow

4.6.2 Evaluation

What is described above is what happens in a single EPR system. Since all three companies own the same ERP system, the demo must start for each company. A different administrative user must log in to each ERP system.

Each user has to click the "Start Demo" button. When the three demos run concurrently is the time the web application simulates a fully operational supply chain. Each ERP system generates its orders. The resources needed to create a new order come from the company logically placed in a previous place in the supply chain. After the one-minute period ends, we can observe the results by reviewing the tables generated in each ERP system. The demo stores the created orders in the local databases and automatically reserves the resources from the companies registered to the private blockchain. After the demo finishes, the user has to click the "Fetch Customer" button. ERP systems will find new customers in their inventory. These new customers are the companies in the supply chain registered to the private blockchain. They are considered new customers when the demo runs for the first time. If the user clicks the "Start Demo" button again, this step will be omitted.

The registration procedure for the order inventory will start as it happened when the user logged in to the system for the first time. The dashboard charts in the "Overview" tab will be updated and all charts present the up-to-date state of the system.

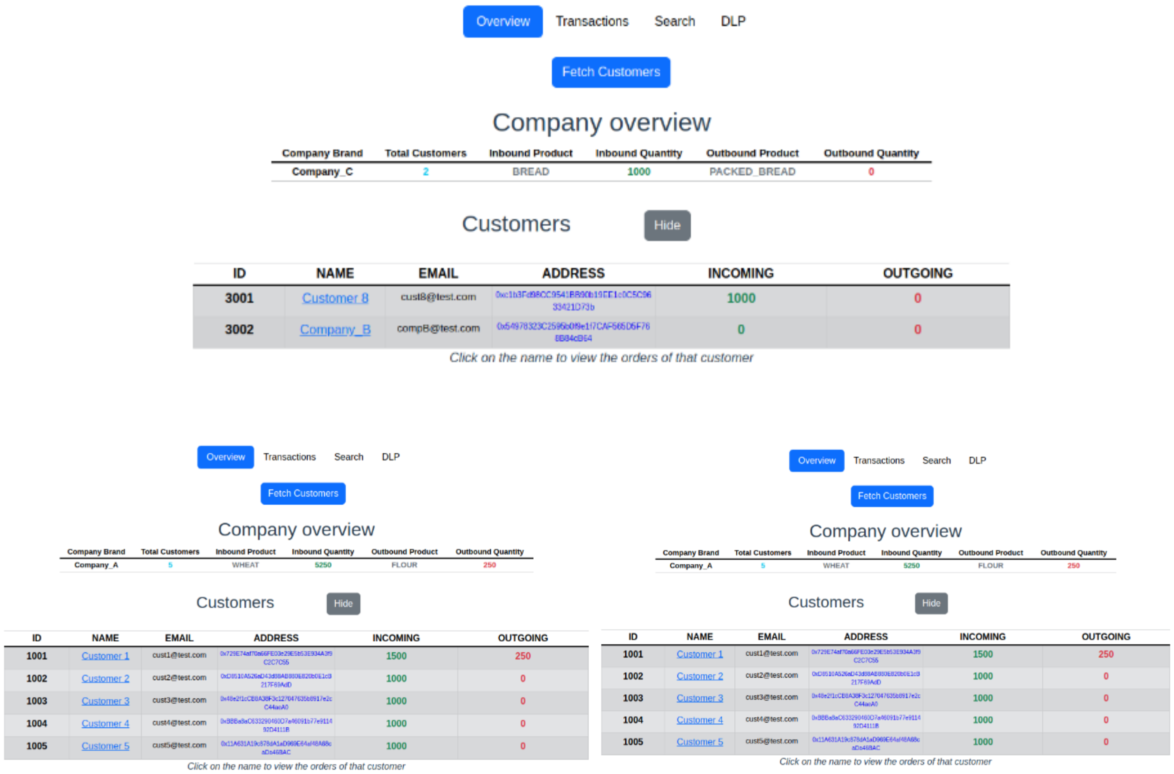


Figure 21. Supply chain figures before the demo start

4.6.3 Search

Users can search for customers and orders stored in the local database or registered on the private blockchain. The search feature is available to users with an administrator or moderator role. The user can search for order details in the local database or directly on the private blockchain. The search can be performed using customer details or order details (see Figure 22. **Search module**). If the user is searching using customer details, the customer ID or email is required. The search results for a customer are shown in Figure 24. **Customer search in the local database**

For a blockchain search, the user can search the private blockchain using customer or order details as in the local database search (see Figure 26. **Blockchain search**).

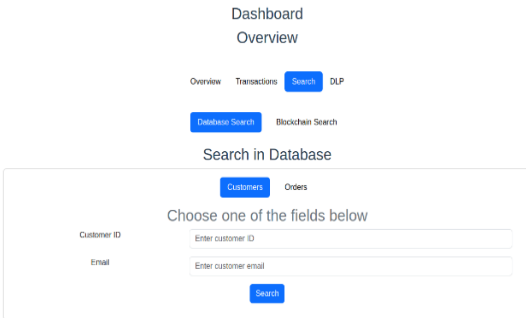


Figure 22. Search module

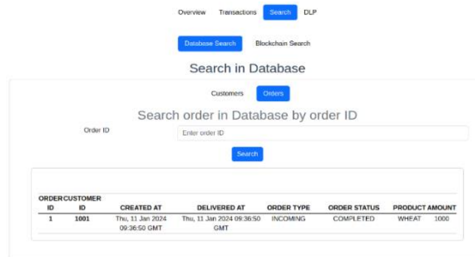


Figure 23. Order search in the local database

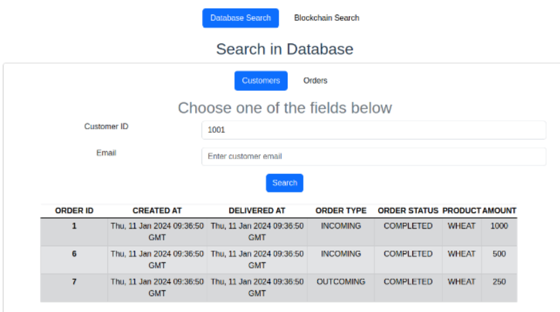


Figure 24. Customer search in the local database

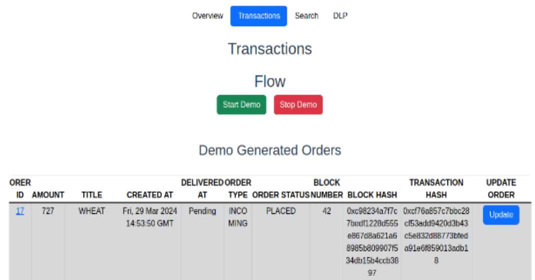


Figure 25. Order info and transaction hash

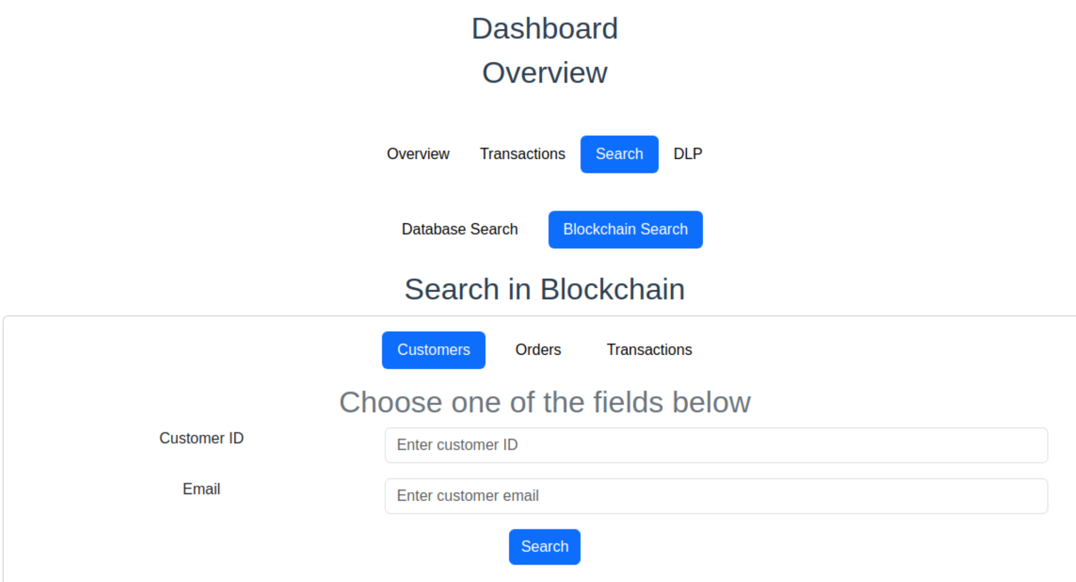


Figure 26. Blockchain search

In addition to the keys as the local database search, the user can use a transaction hash. The search result using a transaction hash is shown in the picture below.

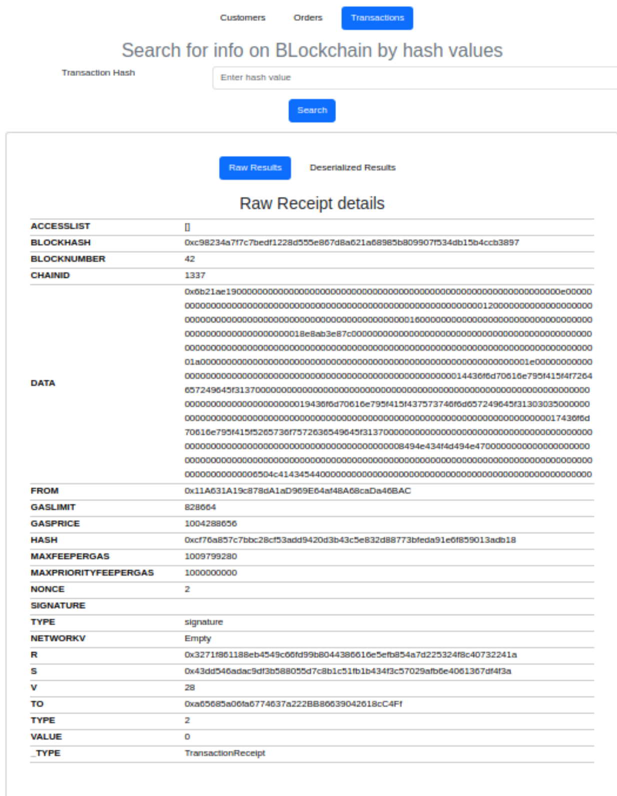
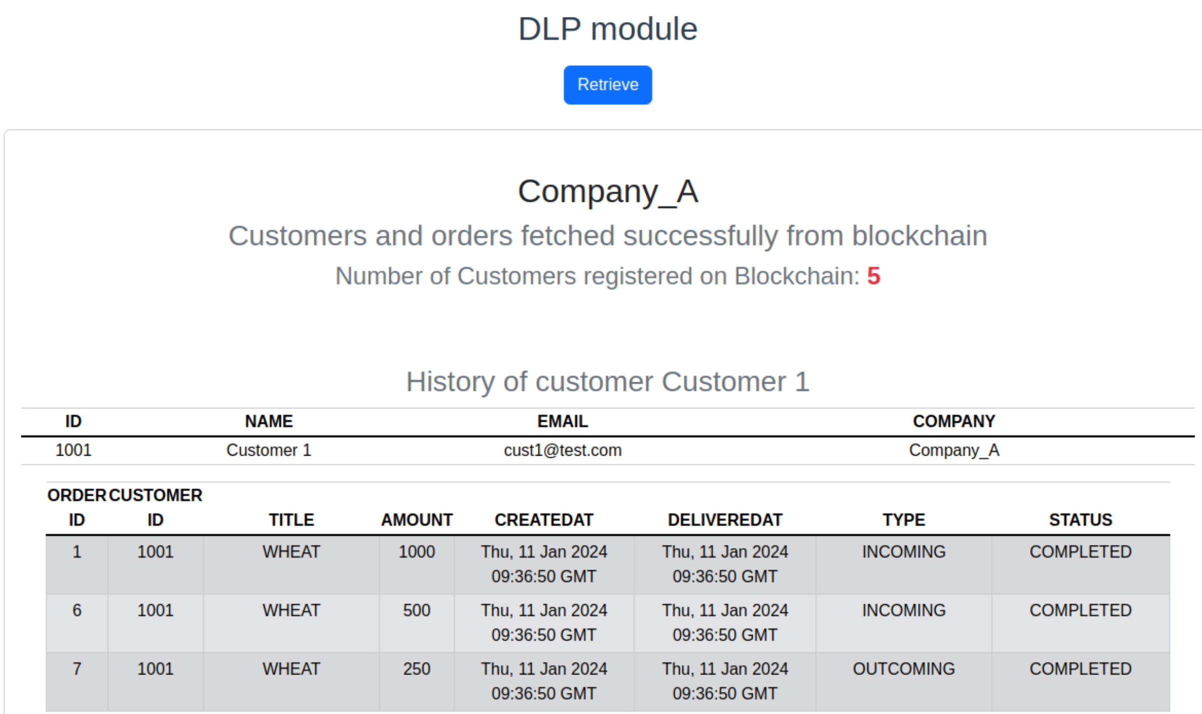


Figure 27. Order search in the private blockchain

4.6.4 DR Module

Another use of the private blockchain is as a DR solution. If the local database is not functional, or records from the local database are deleted or modified for any reason, the order list can be retrieved from the private blockchain. DR functionality is available only to users with administrative privileges. In the demo, when the user clicks the "Retrieve" button, all registered customers and their inventory are fetched from the private blockchain. In the demo, when the user clicks the "Retrieve" button, all registered customers and their inventory are retrieved from the private blockchain. Functionality is limited to retrieving the company's customer and order list, regardless of the order type (incoming or outgoing).

In the following picture, the table contains the result of the DR functionality.



DLP module

Retrieve

Company_A

Customers and orders fetched successfully from blockchain

Number of Customers registered on Blockchain: 5

History of customer Customer 1

ID	NAME	EMAIL	COMPANY
1001	Customer 1	cust1@test.com	Company_A

ORDER ID	CUSTOMER ID	TITLE	AMOUNT	CREATEDAT	DELIVEREDAT	TYPE	STATUS
1	1001	WHEAT	1000	Thu, 11 Jan 2024 09:36:50 GMT	Thu, 11 Jan 2024 09:36:50 GMT	INCOMING	COMPLETED
6	1001	WHEAT	500	Thu, 11 Jan 2024 09:36:50 GMT	Thu, 11 Jan 2024 09:36:50 GMT	INCOMING	COMPLETED
7	1001	WHEAT	250	Thu, 11 Jan 2024 09:36:50 GMT	Thu, 11 Jan 2024 09:36:50 GMT	OUTCOMING	COMPLETED

Figure 28. DR module

4.6.5 Security features

The web app implements various security features. The purpose is to prove that the concept is solid and safe.

An MFA option is available. This option can be toggled from the User Profile Information tab. The system will issue a 6-digit number. An app like Google authenticator is required to scan the QR. After scanning the QR, the 6-digit number appears on the screen. The user punches in the number and if the numbers match, the MFA mechanism is activated. The next time the user logs in, a modal window will appear where the user enters the 6-digit number from the authentication application for a successful system login.

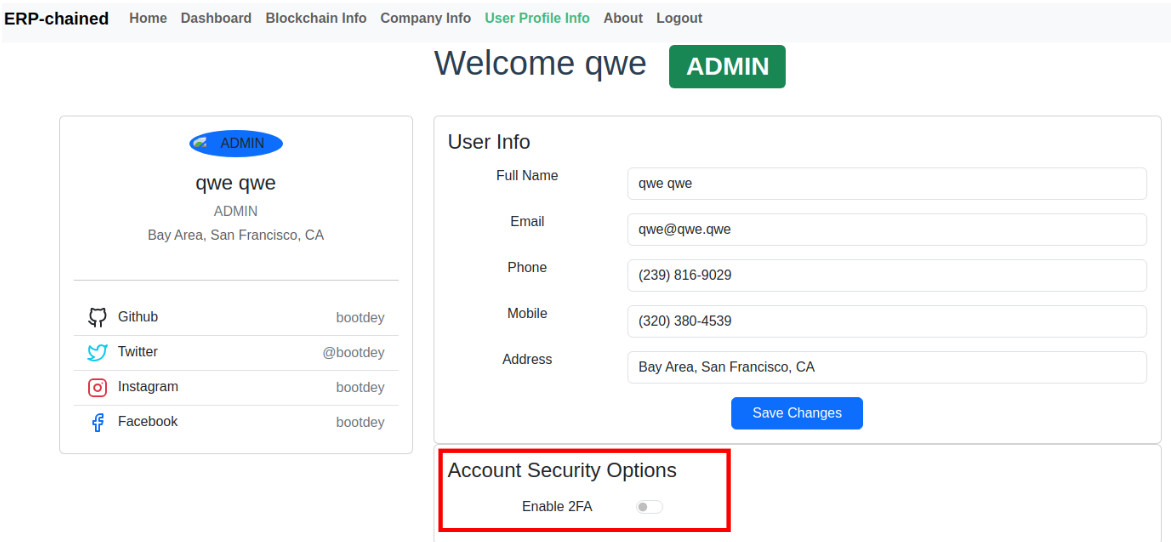


Figure 29. MFA toggle button

Figure 30. MFA validation

All API calls include JSON Web Tokens. A JSON Web Token (JWT) is a compact, URL-safe token used for securely transmitting information between parties as a JSON object. It consists of three parts: a header specifying the token type and signing algorithm, a payload containing the claims (such as user information and metadata), and a signature created by encoding the header and payload and signing them with a secret key. These three parts connect using the dots. JWTs are commonly used for authentication and information exchange, ensuring data integrity and authenticity. They are popular due to their simplicity, self-contained nature, and ease of use in stateless authentication systems.

The token expires in a pre-defined time. When the server receives a request, it checks for the JSON web token's existence. If the token is found and validated correctly, the request is processed and the server issues the response. However, if the request presents an expired token or the token is absent, the server will issue a negative response (HTTP 401 Unauthorized). It is worth noticing that in the web application, the private blockchain server is not directly accessible to the users. The requests from the ERP system backend servers to the server do not include the JSON web token.

4.7 Validation

Validation of the developed web application focuses on system stability. The web application generates system logs. These log files contain various errors and warnings that may occur. After running the demo several times, the logs were checked for errors related to the stability and overall proper system functionality.

Cross-checks were performed on the local database and private blockchain. The purpose of these checks was to verify that the information registered to the private blockchain was successful and correct. Tests were performed to check the implementation of various security controls and policies. These audits focused on API calls and Blockchain functionality. Postman is a powerful tool for performing integration testing with APIs. The tool was used to make API calls to check the expected operability and the proper implementation of JSON web token.

The system is based on smart contracts. They are the heart of the provided blockchain features. They are responsible for the user role-based checks on the private blockchain. The Remix IDE, which is a great IDE for writing and testing smart contracts on Blockchain, was used to check the correctness of the implementation of user role-based checks.

The overall speed of the system and web application was very satisfactory. The only problem was spotted when the demo was running and the time interval between generated orders was too short. In that case, the user experienced a little lag, and a bottleneck was observed in the private blockchain server. Scarcely, the private blockchain server even crashed. However, this could be due to the Ganache test server and its configuration.

5. Conclusions and Future Work

In this chapter, conclusions are drawn based on the proposed architecture and functionality of the developed web application. Also presented are some thoughts on future work and the directions that ERP systems and blockchain technology can take in the supply chain.

5.1 Conclusions

The interoperability between ERP systems and blockchain technology in the supply chain offers a transformative potential for enhancing transparency, security, and efficiency. By addressing integration challenges and investing in technology, training, and strategic planning, businesses can unlock significant benefits. This integration paves the way for more resilient, agile, and trustworthy supply chains, positioning companies to better meet the demands of a dynamic market and regulatory landscape.

The following table contains the benefits and impacts of such an integration.

Conclusions on ERP Systems and Blockchain Technology Interoperability		
Conclusion	**Benefit**	**Impact**
Enhanced Transparency and Traceability	Integrating ERP systems with blockchain technology significantly improves the transparency and traceability of the supply chain.	Real-time, immutable tracking of products from origin to destination ensures better quality control, compliance with regulations, and increased consumer trust.
Improved Data Integrity and Security	Blockchain's inherent security features, such as cryptographic hashing and decentralization, enhance data integrity and security.	ERP systems benefit from reliable and tamper-proof data, reducing the risks of fraud and data breaches, thus fostering a more secure supply chain environment.
Operational Efficiency and Automation	The interoperability of ERP systems and blockchain can streamline supply chain operations through automation of processes.	Reduced manual interventions lead to lower operational costs, minimized human errors, and more efficient supply chain workflows, enabling faster response to market demands.
Compliance and Auditability	Blockchain's immutable ledger provides a clear and unalterable record of all transactions, simplifying	Businesses can more easily meet regulatory requirements, conduct thorough audits, and improve governance practices, reducing

	regulatory compliance and audits.	the risk of non-compliance and associated penalties.
Collaboration and Trust Among Stakeholders	The decentralized nature of blockchain fosters a collaborative environment where all stakeholders have access to the same transparent and reliable data.	Improved collaboration and trust among supply chain partners lead to stronger relationships, better coordination, and enhanced overall supply chain performance.
Scalability and Performance Considerations	Ensuring the combined system can handle large volumes of transactions and data without compromising performance.	Utilizing scalable blockchain solutions and optimizing ERP systems for high performance can address these challenges, ensuring the system can grow with business needs.
Cost and Resource Allocation	The integration and maintenance of interoperable systems can be resource-intensive and costly.	Conducting a detailed cost-benefit analysis and securing necessary investments can justify the expenses and ensure long-term benefits outweigh the costs.
User Training and System Adoption	Effective use of the integrated system requires adequate training for all users.	Implementing comprehensive training programs and designing user-friendly interfaces can facilitate system adoption and ensure users can leverage the full capabilities of the integrated systems.

Table 4. Conclusions on the interoperability

5.2 Future Work

Future research and development efforts should focus on creating robust, scalable, and secure interoperability solutions between ERP systems and blockchain technology. By addressing issues such as standardization, scalability, security, and regulatory challenges, and by leveraging advanced technologies like AI and smart contracts, businesses can unlock the full potential of this integration. This will lead to more efficient, transparent, and resilient supply chains, better equipped to meet the demands of a rapidly evolving global market.

Current trends in ERP systems include the incorporation of artificial intelligence (AI), machine learning, and advanced analytics to provide predictive insights and automation. Additionally, ERP systems are increasingly focusing on user experience, mobility, and real-time data processing to meet the demands of modern businesses **Error! Reference source ot found.**. The following table summarizes the proposals for future work.

Conclusions on ERP Systems and Blockchain Technology Interoperability		
Proposal	**Focus**	**Impact**
Standardization of Data Formats and Protocols	Developing industry-wide standards for data formats and communication protocols to facilitate seamless integration between ERP systems and blockchain technology.	Standardization would simplify interoperability, reduce integration costs, and enhance data consistency across the supply chain.
Scalable Blockchain Solutions	Researching and implementing scalable blockchain solutions that can handle large volumes of transactions and data without compromising performance.	Scalability is crucial for widespread adoption, especially in industries with extensive and complex supply chains.
Advanced Security Measures	Enhancing security protocols to protect sensitive supply chain data while maintaining transparency and immutability.	Ensuring robust security measures will increase trust and adoption among stakeholders, mitigating risks related to data breaches and fraud.
Interoperability Frameworks	Developing comprehensive interoperability frameworks that outline best practices, tools, and methodologies for integrating ERP systems with blockchain technology.	Frameworks can provide a roadmap for businesses to follow, reducing the complexity and uncertainty associated with integration projects.
Smart Contracts and Automated Processes	Exploring the use of smart contracts to automate various supply chain processes, such as payments, compliance checks, and inventory management.	Automation through smart contracts can significantly enhance efficiency, reduce operational costs, and minimize human errors.
Real-time Data Analytics and AI Integration	Integrating real-time data analytics and artificial intelligence (AI) with ERP-blockchain systems to provide actionable insights and predictive analytics.	Enhanced analytics capabilities can improve decision-making, optimize supply chain operations, and anticipate potential disruptions.

Table 5. Proposals for future work

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