Blockchain-Based Smart Contracts for Enhancing Transparency and Efficiency in Supply Chain Management

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Abstract

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This thesis aims to see what further improvements can be made in the scope of transparency, efficiency and traceability within the supply chain using the technology of blockchain and smart contracts together. Yet, traditional supply chain systems are inefficient due to the issues of lack of transparency, centralized control and unnecessary cost. The blockchain and other such decentralized, immutable ledgers excel at addressing data integrity and precisely instantaneous sight ability. For this research the system developed uses React, Express.js, and a database created with user interaction. In contrast, it can also automatically validate and execute agreements through smart contracts and simultaneously record supply chain transactions. Further, an administrator can define trigger conditions, to validate transactions before getting on the chain. Interesting new results with respect to transparency, security and cost efficiency are shown. Still, it has the problems of scalability and energy consumption. This novel use of blockchain technology is also highly complementary with other novel solutions to supply chain reliability (such as artificial intelligence), and it is anticipated that further development of blockchain technology could further enhance supply chain predictive capability and resilience. This study's findings contribute to the understanding the limitations that is practical and advantages of blockchain in supply chains with high visibility, are therefore of value to the literature on possible applications of blockchain in supply chain management.
Keywords Blockchain, Smart Contracts, Supply Chain Management, Transparency, Traceability, Decentralization, Data Integrity, Scalability, Frontend, Backend, React, ExpressJs, Json, Framework

Contents

Abbreviations

API: Application Programming Interface

DTO: Data Transfer Object

HDS: Hierarchical Data Structure

IBM: International Business Machines

IoT: Internet of Things

JSON: JavaScript Object Notation

LAMI: Low and Middle Income

PoS: Proof of Stake

PoW: Proof of Work

RFID: Radio Frequency Identification

SHA: Secure Hash Algorithm

SCM: Supply Chain Management

TCE: Transaction Cost Economics

1 Introduction

In this world where the supply chain has become very sensitive, globalized world and integrated markets, there are many stakeholders and subcontractors spread internationally. Transparency and Accountability, or Supply Chain Visibility are hugely important issues that arise with this complexity in the chain. Problems such as fraud, counterfeiting, information asymmetry and delays that impede supply chain management also plague traditional supply chain management systems that manage these supply chains (Saberi, et al., 2019).

Though, today, blockchain technology appears to be a decentralized, immutable, and transparent potential solution for these problems (Hughes et al., 2019). In essence, the integrated utilization of blockchain and Smart contract (Mihaylov et al., 2018) enhances supply chain activities. One example is smart contracts (digital code of contracts executed once programmed and deployed, that execute on the transactions between parties as the set conditions are met, resulting in no 3rd party intervention and possible disagreement (Yermack, 2017).

Recently, research has proved the remodeling from blockchain in supply chain management. For example, transaction verifying and immutability of blockchain is applied within different scenarios to verify and facilitate immutable transactions, to increase level of consumers trust and decrease risks of frauds (Alkatheiri et al., 2023) like goods traceability. Second, blockchain supply chain utilizes efficiency of supply chain by reducing the transaction cost and accelerating production process (Rejeb et al., 2021).

Though blockchain has been adopted in supply chain management there are some challenges also that is faced. However, to achieve its full potential, issues like scalability, regulatory compliance and how to integrate blockchain into existing systems must be taken up (Francisco, Swanson, 2018a). However, the erratic nature of this technology as it is having made their implementation challenging, however, this does not reduce the significance of the growing research on the use cases blockchain has, if implemented, can greatly increase supply chain transparency and efficiency with a competitive advantage for early adopters (Rejeb et al., 2021).

The prospective developments of this thesis aim to improve the supply chain's efficiency, traceability, and transparency through the use of blockchain-based smart contracts in supply chain management. To begin, this study demonstrates how supply chains, especially ones with strict traceability requirements, like those in the food and pharmaceutical industries, might be made a strong basis for the use of blockchain technology and smart contracts.

1.1 Aim and Research Questions

In order to create the best blockchain technology solution for supply chain management, this study aims to incorporate some of the core concepts of blockchain. Specifically, it considers immersion, transparency, and smart contracts, which can improve task execution, accountability, and information sharing and exchange. As a result of these findings, the embellishments of such essentials as fraud, counterfeiting, and the information asymmetry among parties and across the supply chain will be reduced while contractual functionality and data exchange between parties would address both supply chain reliability and efficiency.

To accomplish this goal, the study seeks to answer the following research questions:

- In conventional SCM, what are these inconsequential obstacles and how can blockchain and smart contract concepts fix them?
- Given the blockchain based smart contract architecture, how can a pattern be designed and used to strengthen the supply chain, a pattern which can be used in places such as the food or pharma industry?
- How well does the proposed blockchain system enhance transparency, lower costs and offer best of breed solutions to real business in 3rd Party Logistic Supply Chain Management?

1.2 Scope

The design and performance analysis of a blockchain-based smart contract framework for supply chain improvement is the only subject of this study; with special reference to operations that necessitate high supply chain transparency in such industry as the food and pharmaceutical industries. Due to seasonality, decentralized nature, and criticality of the items of these industries, they are particularly vulnerable to fraud, counterfeiting, inefficiencies, and compliance problems tied to centrally and globally integrated supply chains (Saberi et al., 2019).

An example from the food industry makes it obvious that there is a need to provide credible checksums on the origin and legitimacy of foods and the safety of any food at various stages during processing and during its delivery to the final consumer. Blockchain can provide a durable record of these transactions so that all the participants can gain accurate, real-time information and thereby increase the accountability and transparency levels laid (Kshetri, 2018). The same problems plague the pharmaceutical industry regarding the problem of fake drugs and regulatory compliance with blockchain making the chain of custody better and making it harder to flood the market with fakes (Francisco & Swanson, 2018a).

This research will also consist of how blockchain can be added into the existing supply chains of these industries and real problems like regulatory and legal frameworks, data privacy and compatibility issues (Korpela et al., 2017). The appropriateness of the technology in specific industries will be assessed through the deployment of technical, legal, and operational measures where blockchain has to work under strict regulations that call for compliance standards such as transparency and accountability (Yermack, 2017). These sectors have been chosen as the study's target since, based on shared changes in transparency requirements, they can be extended to other industries like luxury, electronics, automobile, etc.

Additionally, the study investigates how blockchain technology might be used in supply chains to improve their efficiency and rebuild supply chain costs for various businesses. As a result this includes being able to explore how blockchain can also enhance, perform and automate contractual delivery, remove the middlemen, and decrease the time it takes to execute the contracts while improving the data's integrity as well as its security (Hughes et al., 2019). The results of this work are likely to result in practical guidelines for the integration of the technology in complicated and heavily regulated fields, which represents a model that can be applied to other industries with similar requirements for accountability and speed.

1.3 Justification for the Project

With today's global economy, exigent supply chain management solutions for increased transparency, efficiency, and security in supply chain management become even more exigent. Modern supply chains present several shortcomings including dynamism of current supply chains, fraud and opacity that can rob supply chains of big losses and attendant reputational damage to companies. Blockchain technology has actually become a solution for these problems because it has made record keeping accurate and easily tracked (Sharabati & Jreisat, 2024).

The smart contract expands blockchain in the supply chain even more by using the contractual platform to create self-executing contract. The automation of this not only removes the necessity of the middlemen as Law (2017) highlights but reduces the possibility of disagreement and provides fairly real time information to all relevant parties.

This project is warranted by the increased need for new solutions in the supply chain area to promote transparency and increase cost efficacy and overall effectiveness. Thus, by proposing the smart contract framework on the blockchain, this research tries to make its own contribution to the process of supply chain management's modernization and searching for solutions to the problems that businesses face in this area (as cited in Alkatheiri et al., 2023).

2 Unleashing the Power of Blockchain in Supply Chain Transparency

2.1 Introduction to Supply Chains

Chain of institutions that carry a product and/or service through which the flow of people, materials, activities and technologies is involved, is called Supply chain. Supply chain management is about the smooth flow of products and services in systematic ways in order to remove the costs of operation and meet customer satisfaction (Christopher, 2016). Today's world whose supply chain links extend to other countries beyond the borders of the nation is even more overwhelmed in supply chain management. At the same time, this interdependence complicates the prospects and problems related specifically to such factors as transparency, efficiency and security in supply chain activities.

Indeed the management of supply chain influences all organizational factors, ranging from the quality of products to organizational profits. Time overruns and higher cost of business, as well as even deterioration of brand image, are all very important reasons organizations need to explore various ways of improving supply chain efficiency (Mentzer et al., 2001).

2.2 Supply Chain Complexity and Globalization

As supply chains get global their management poses even more of a challenge. Supply chain networks today involve the cooperation of many agents in distinct geographical locations. They are governed by distinct regulations, trade relations, and restrictions on the movement of products. Manufacturing industries ranging from the food industry up to the pharmaceutical industry for example, bear in mind that the products that they produce are sensitive in regards to quality and safety considerations and are vulnerable to disruptions, counterfeits and fraud (Tian, 2016).

Globalization tends to extend both sweet and bitter for supply chain management. Still, having global markets and obtaining materials through global suppliers to different markets is rather expensive, vulnerable to lead time growth, has to deal with different regulations increases dependency on global factors such as geopolitical conflicts or pandemics, and can lead to production disruptions and inefficiencies (Ivanov & Dolgui, 2020). For instance, supply chain networks are not prepared to withstand such disruptions as are the current COVID 19 pandemic and therefore the need for supply chain transparency, supply chain risk management and real time supply chain visibility (Queiroz et al., 2020).

Where questions of product safety and identification are of great importance, for example, the pharmaceuticals, globalization has introduced another social evil of fake goods in the market, which has been linked to several health calamities not only losses but also of genuine firms. The World Health Organization estimates that counterfactual products, particularly medicines, have been found to have caused the death of at least 700 000 people every year, especially in LAMI countries. To counter these risks, improved tracking and verification mechanisms have to be applied in the industry, and here, the chain has multiple utilities.

2.3 Key Challenges in Traditional Supply Chain Management

Conventional supply chain structure entails the use of a central database base, other manual means and, mostly, ineffective means of communication with other parties. There are some of the primary challenges in traditional supply chains that are:

Lack of Transparency and Traceability: The problem with this traditional view is there is no real time visibility of visibility by supply chain managers to track products and enforce compliance across every channel of the supply channel. However, a fixed and open transaction recording system is missing, the validity of the products can usually not be easily validated especially in case the controlling measure must be strictly implemented, for example in pharmaceutical or food industry etc. (Tönnissen & Teuteberg, 2020).

Vulnerability to Counterfeiting and Fraud: Piracy products are one of the major issues in supply chains across the globe. If one think that it's only in food supply chain that is wrong because it's also in the pharmaceuticals, electronics and luxury products industries. Supply chains are severely hit due to lost money and reputation, because traditional supply chain infrastructures do not have the needed security features to prevent and identify fake products that end up in the marketplace (Bai & Sarkis, 2020).

Inefficient Processes and High Operational Costs: Inefficient Processes and High Operational Costs: Because one or more intermediaries and verification processes are involved, many of the traditional supply chain concepts present numerous challenges. For example, a necessity of supply chain activities, such as cross border goods transportation, involves filling and signing forms, which are resource consuming and with a high possibility of human error. Secondly, intermediaries amongst them customs agents, brokers and other financial institutions also create high transaction costs and time (Grover 2019).

Data Fragmentation and Communication Barriers: In fact, what this really does is make the supply chain appear to have numerous stakeholders within its cycle that may use different systems or media of communication. This fragmentation of data makes there to be information leverage as all the stakeholders in business are not at the same time to access the information. Indeed, this can result in such problems as delays, mismatched inventory, and unsound decision making (Hofmann et al., 2018).

2.4 The Need for Innovation in Supply Chain Management

These problems are inherent in traditional supply chains, and so innovation is required to improve the concept. In particular, blockchain technology is inherently decentralized, immutable, and transparent, and brings high value to resolving many of these challenges. Real time control and paper checks can make supply chains more automized, secure, on the blockchain model, (Morkunas et al., 2019).

The adoption of a blockchain in the supply chain is particularly useful and issues of transparency and traceability are important in many industries. For example, in the food industry, blockchain can be used for the pathway of the food item from farm to consumer table assures the pathway of this food item to consumer table with a secure and transparent record of truth of the food they are consuming (Tian, 2016).

For example, blockchain applies to the pharmaceutical industry to solve some of the problems related to exploiting counterfeit drugs while creating an unalterable record for the drugs, such that all the stakeholders verify the real nature of the drug and other essential conformity to the legal specifications of a drug (Li et al., 2019).

2.5 The Role of Supply Chain 4.0 and Emerging Technologies

The 4.0 Industry is also noticed the presence that the supply chain management has been changed along with the change of IoT, Blockchain, and Artificial Intelligence technologies. The convergence of such technologies to optimize supply chain functions through automation, data analytics, and integration (Ivanov et al., 2019) is called Supply Chain 4. 0.

When applied in conjunction with IoT sensors, blockchain can provide even more supply chain operations data. For example, connected devices in IoT may inform temperature, humidity, and location data in transit as perishable goods like food and other products. This means that this data can be placed on the blockchain, so that similar stakeholders can track the condition of the good along the entire supply chain (Pearson et al., 2019).

3 Theoretical Framework

Prior to using blockchain-based smart contracts to manage supply chain flows, let's walk around concepts that regulate this technology. This section introduces three ideas: On TCE, blockchain and smart contracts and how these are applicable to the supply chain management.

3.1 Transaction Cost Economics (TCE)

Oliver Williamson developed the economic theory known as Transaction Cost Economics, or TCE, which explains the cost of market transactions. Here the basic assumption is that businesses strive to decrease the transaction cost of their good and service. These expenses encompass information and search, negotiation and judgment, and law enforcement and policing (Williamson, 1981).

3.1.1 Relevance to Blockchain and Smart Contracts

The fundamental economic theory applied to evaluate the cost of exchange processes is transaction cost economics (TCE), introduced by Oliver Williamson, prominent work. According to TCE firms will undertake the transaction in the context of such a structural form as to minimize the final sum of transaction costs, including business search and informational costs, bargaining and decision constraints, and policing and check costs. Advantageously, the proposed blockchain and smart contracts development are likely to significantly decrease transaction costs involved in the execution of contracts (Williamson 1981; Rejeb et al. 2021).

At the time when a transaction happens, the specific characteristic of blockchain is the distributed ledger that stores all the transaction data and makes it available to other relevant parties thereby minimizing the search and the information cost. The elimination of the intermediaries in execution is even more efficient in smart contracts as it does away with bargaining and enforcement costs. It can be related to the authors' TCE framework where the intention is to keep costs low, in order to enhance organizational effectiveness.

3.1.2 Application in Supply Chain Management

A larger interest of supply chain management is that transactional costs can likely be very high based on scale and nature of processes realized. They include the cost incurred in searching for information, bargaining and planning on ways of overseeing contracts between multiple individuals or organizations (Williamson, 1981). This, in turn, leads to high transaction costs due to the use of intermediaries, differentiated structures of organization functions, and a lengthy and exhaustive process of verification that adds to the time taken as well as the probability of errors (Grover et al., 2019).

Because the blockchain and smart contracts use can speed up transaction processes and reduce the role of the middleman, these problems are solved. The utilization of smart contracts which are self-contained programs where essential contract details are programmed into code to be executed systematically when certain triggers are activated, would enable the reduction of human errors and unnecessary delays that might be caused by individuals waiting on other people to execute certain transactions as might be expected in traditional 'wet contracts' (Zheng et al., 2019). With smart contracts defined as the structure for the transactions these options can efficiently enhance the precision as well as the speed of the supply chain of the enumerated companies. For instance, when a delivery is completed and verified, payments can be automatically transmitted, which reduces all sorts of interferences and chances of the occurrence of disagreements between the involved parties (Casino et al., 2019).

In pharmaceuticals and food industry, blockchain coupled with Transaction Cost Economics (TCE), can be a useful implementation that helps solve issues such as traceability and compliance. Because of these reasons, such industries are subjected to many pressures, as it has to do regulatory mandates and have to assure the safety and the original of products within supply chain (Tönnissen & Teuteberg, 2020). This is so that people who are permitted have a record of every transaction that is being carried out, since any altered record that is preserved is prevented by the usage of blockchain technology. In addition, CSAL also makes the supply chain more reliable by using technology to monitor fake product infiltration of market, which enables CSAL (Li et al., 2019). In industries that focus on output, such as the food industry and parts of the pharmaceuticals, automation of processes and reducing the number of the intermediaries that are associated with them allows for lower transaction costs and improves the performance of the supply chain totally (Wang et al., 2019).

Like Blockchain, the integration of TCE also serves minimizing the search and information costs. Another problem of conventional supply chain is an authentic time and a costly consumption of time for conducting checks about operations, transactions and genuineness of products which is also time consuming (Kouhizadeh et al., 2021). Blockchain implementation reduces transaction costs such as dispute resolution triggered by fraudulent activities because the decentralized ledger facilitates real time validation of transactions and grants access to the right information to all parties involved in the supply chain (Chang et al., 2020).

3.1.3 Benefits

The application of TCE together with the tendency of using blockchain and smart contracts presents some advantages to supply chain management. These benefits are more relevant for industries where downsides of traditional tracking & monitoring methods are apparent including but not limited to food, pharmaceuticals & logistics industries (Kouhizadeh et al., 2021). Based on the TCE framework and technological possibilities of blockchain, we theoretically show how firms can minimize transaction costs, raise the degree of transparency and increase the security of their supply chains.

Cost Reduction: One of the major benefits to being able to apply the blockchain is the reduction in the cost of implementing TCE. Business activities performed by intermediaries include authentication of transactions, tracing of goods and implementation of contract conditions. Most of these activities (Wang et al., 2019) are addressed by blockchain. This strategy will lessen the need of third-party involvement thereby cutting down on pre and post processing of transaction and other administrative burdens (Grover et al., 2019). In addition, smart contracts facilitate perfect automation of contracts reducing unnecessary costs on account of errors and misinterpretations between the contract parties. For example, once the condition to execute is met (consider, in the delivery of goods), then payment and other specified steps are initiated and issued without further human intervention (Zheng et al., 2019). The result is a lower cost (less expensive) in supply chain that is end to end model (Morkunas et al., 2019).

Increased Transparency: Because blockchain technology prevents any changed records from being retained, this is done so that those who are authorized have a record of every transaction that is being carried out. The blockchain is something that records every transaction as a single check within the publication of the ledger, and anyone have the ability to engage in an audit of this information that you write on the block chain. In some ways this helps to improve trust members of the supply chain as everyone sees the same thing and nothing can be changed without the agreement of the rest of the network (Chang et al., 2020). For food and health products focused manufacturing industries, which need to meet regulatory and accreditation requirements (Li et al., 2019) transparency becomes even more paramount to the application of technology. It is the immutability of the records in the blockchain that enables it to achieve these requirements because everyone can trace the path a good take from origin, rendering it almost impossible to operate fraud and deceit (Casino et al., 2019).

Enhanced Security: The security of such a transactional activity lies in the decentralization of supply chain through blockchain technology (Zheng et al., 2019). Therefore, it should be noted that in conventional supply chain, stored data in them are in centralized database, and are therefore susceptible to hacking, corruption of data as well as fraudulent cases. But actually, the blockchain is a distributed ledger and every node has a copy of the same record on the other side. Now this is quite a decentralized system and therefore hard for wrong people to manipulate or even commit fraud by putting bad info, as this has to go through consensus among the participants that are the most of the network (Casino et al., 2019). Moreover, blocks make use of complicated algorithms which do not let hackers change the records of transactions (Saberi et al., 2019). This improved security is proved to be helpful in cases like pharmacy, where counterfeit drugs are the common thing to be found in the market. The information of products is secured by blockchain and not allowing fake' s engulf in the market (Li et al., 2019).

3.2 Blockchain Technology

Blockchain is a distributed electronic record keeping technique that keeps track of several transactions in such a manner that registered transactions cannot be manipulated. This technology guarantees basic principles such as openness, integrity, and the inability to be altered (Crosby et al., 2016).

3.2.1 Key Features of Block Chain

Blockchain solutions possess specific properties that make them appropriate for increasing the effectiveness of various industries and become a useful tool in supply chain management. These features include:

Decentralization: Because of that, blockchain is based on a decentralized network, meaning you're not storing information in a single server. Whisperings also destroy the middlemen and central authorities; however, all the members of the network have the same uselines (Rejeb et al., 2021). This is beneficial from the point that the supply chain process can be decentralized, starting with the fact that it can help in eliminating the fraud since the supply chain participants play as an equal; the supplier, the manufacturer, and the retailer (Alkatheiri et al., 2023). Moreover, by check-pointing the records at every node, it does away with the possibility of tampering or manipulating data, and assures credibility and transparency (Casino et al, 2019).

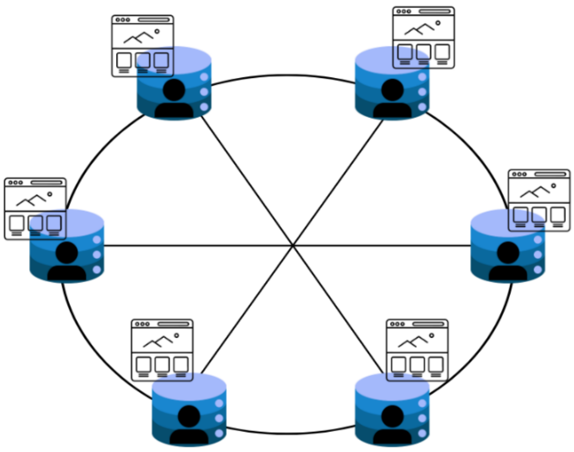

Figure 1. Decentralized blockchain network showing interconnected nodes, each maintaining an independent copy of the ledger

The figure 1 shows the figure of network of nodes, which follow a decentralized block-chain where each node has its own copy of the ledger. All participants in the network share the same data and these nodes are connected to each other. This structure eliminates a central authority, and, should a line failure occur, increases fault tolerance, while also creating transparency and trust among the participants. Transactions are validated by independent nodes and the blockchain system can remain this way pre-serving integrity.

Immutability: Because data within a blockchain is, over time, difficult or impossible to delete or amend, they stay permanently in the system. These requirements mean that all transactions are recorded and are permanent, giving a good transaction audit trail (Sharabati & Jreisat, 2024; Nakamoto, 2008). In the management of supply chain, it is a material aspect that is the preservation of records that will enable the tracking of when different supply products and services have been delivered to meet their intended requirements and fight the vice of fake products or scam services. It gives confidence because it guarantees the integrity of records while in distributed networks (Francisco & Swanson, 2018a; Kshetri, 2018).

Transparency: With blockchain, every transaction is recorded in one shared, public, or distributed ledger, and all approved participants have an equal, and in fact consistent, point of view as to how the information is presented. This transparency improves trust with supply chain members because it provides an opportunity for them to verify the authenticity of goods and that goods are in the correct condition in the appropriate time (Yigit and Dag, 2024; Bai and Sarkis, 2020a). In addition, blockchain stimulates visibility across the supply chain, helping to mitigate information asymmetry and coordinate throughout supply chain, therefore the efficiency of it operations and accountability (Kouhizadeh et al., 2021; Tönnissen & Teu-teberg, 2020).

Security: Blockchain's use of cryptography ensures that accurate data is recorded and that no information is altered. Since each block contains both its own hash number and the hash number of the preceding block, it is nearly hard to change a record on the blockchain (Rejeb et al., 2021). This design proves to greatly improve security by protecting it from unauthorized changes and guaranteeing the network's ability to counteract cyber threats. Furthermore, since blockchain has no middle personality, it reduces vulnerability to crime whereby a single point of control makes the technology strong and almost intact from break-ins (Nakamoto, 2008; Conti et al., 2018). This kind of architecture minimizes risk and fosters confidence among the members of a network in applications, including the supply chain (Kshetri, 2018).

Smart Contracts: Blockchain also has the capability of enabling smart contracts. The provisions of an agreement will be automatically enforced by these self-executing contracts as long as specific requirements are fulfilled. Smart contract use in supply chain management changes the way processes are paid for, checked for compliance, and updated the inventories thereby increasing efficiency and eliminating delays due to third party intervention (Francisco & Swanson, 2018b; Morkunas et al., 2019). Additionally, by lowering the possibility of fraud and human mistake, such automation helps streamline the sometimes laborious and complicated non-human contact procurement and supply chain procedures, enhancing supply chain transparency and confidence (Zheng et al., 2019; Kouhiza-deh & Sarkis, 2018).

Consensus Mechanisms: An additional consensus solutions such as proof of work and the proof of stake are needed in order to apply blockchain technology to verify transactions. The consensus procedures add the all-important dimension of verifying that no other than the actual transactions are added to the blockchain which ensures the veracity of the record. As opposed to the PoW, which is based on the validation of transactions through solving complex cryptographic puzzles requiring, absurdly, a lot of power, the PoW mechanism is secure. On the other hand, PoS is cheaper and more environmentally friendly since the amount of cryptocurrency to stake depends on the amount of that specific cryptocurrency, which the validators use to verify the transaction (Nakamoto, 2008; Saleh, 2021). The implementation of the supply chain by these consensus mechanisms results in noticeable improvements in the accuracy and reliability of the records. This is particularly important since information dispersed by use of blockchain is distributed, so it cannot be controlled and therefore affected by one party and this leads to transparency of the stored information and small opportunities for tampering (Xu et al., 2019). In addition, these mechanisms eliminate fraudulent activities in the supply chain as only correct and authenticated transactions are recorded in the system and the book keeping shows the real state of goods and services (Sharma et al., 2020). The nature of the blockchain itself, as distributed and unmodifiable, makes it very difficult for an adversary to be able to modify the data (Rejeb et al., 2021).

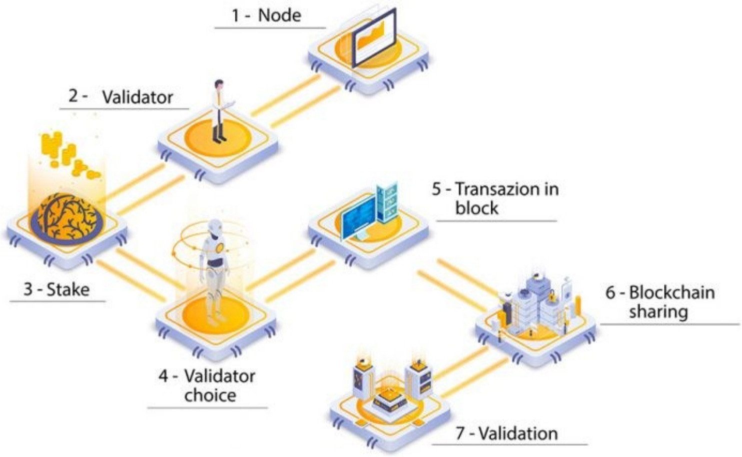

Figure 2. Consensus Mechanisms in Blockchain. The blockchain validation process, illustrating the flow from node initiation to validation and ledger synchronization (retrieved from Affidaty 2019)

3.2.2 Cryptography in Blockchain

When it comes to the operation of the block chain cryptography play very important role since it is what underpins secure and unchangeable transactions. The encryption technique is a core feature of blockchain, since it applies sophisticated cryptographic techniques to provide secured, valid, and private information about the supply chain net-works to enable trustless system (Rejeb et al., 2021).

In the blockchain domain, hash functions take a value as input and apply it to a cryptographic algorithm: in my opinion the most common being SHA-256 (Secure et al.). Hashing is an algorithm which produces a hash of 256 bits (64 characters) to identify the data of the input (Sharabati & Jreisat, 2024). Here's how the process works:

Input Data: It can be made clear that the input can be any message: transaction, document or smart contract.

Hash Algorithm: A hash function is a function that takes as input any arbitrary sequence of bits (or other small object) and returns as output an element of a named type of some fixed length, in which the output represents, in some arbitrary sense, some (usually small) portion of the structure of the input. Thus, the purpose of this mechanism was to ensure you get a totally different hash even with the slightest change in input, maintaining data identity and security efficiently (Yigit & Dag, 2024). Of greatest importance in regards to blockchain technology is hashing, which essentially links blocks together utilizing cryptographic hashes to ensure the immutability of the data by preventing unauthorized modifications (Nakamoto, 2008; Conti et al., 2018). Additionally, hash function characteristics such as SHA 256 makes them trusted in distribution, as they are the same input is always the same output, making verification processes honest and trustworthy (Zheng et al., 2019).

Output: As it will be shown further, the size of the hash is constant regardless of the input size, and is commonly called output. Various attributes of hash functions make them effective in comparing large data sets and among them is the fixed size (Francisco & Swanson, 2018a).

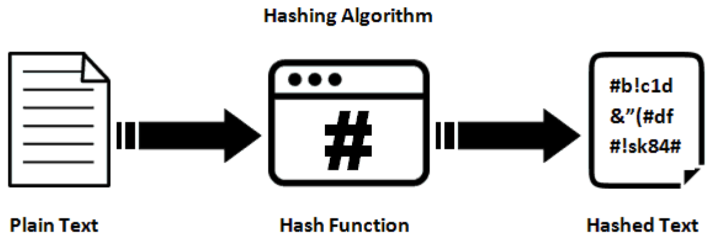

Figure 3. Hashing process illustrating the transformation of plain text into hashed text using a hashing algorithm

For example, if we move the input by one character, the hash acquired will be entirely different. This property allows us to track even very minor changes in a block of data, whether it's a transaction or something else (Swan, 2017).

In a blockchain, the hash of the subsequent block is far more significant than the hash of a previous block. Other than that, it just means we have to connect blocks by their virtual cryptographic hash link to the last other. Additionally, a malicious individual will see that even if they undertake a "replay" attack to alter the contents in one block, the hash of that block and the hashes of the subsequent blocks will change. Rewriting the proof of work for all subsequent blocks is nearly impossible, and it is nearly impossible to alter the blockchain's contents (Rejeb et al., 2021).

Block Header: The hash of the previous block is all integrated to the hash together with the timestamp of the block and that is what I am talking about of as critical metadata. Merkle root hash, is a hierarchical structure to ensure the data integrity verification within time and security problems (Sharabati & Jreisat, 2024; Zheng and et. al, 2019) which means take the hash of all transactions of a block. This is the base structure of blockchain technology and makes it possible to validate transactions more efficiently, while preserving the cryptographic link between blocks required to maintain the structure and changing it (Nakamoto, 2008; Conti et al., 2018).

Merkle Trees: To validate as well as categorize many transactions at large scale accurately, these HDS are used. Inside a block, each transaction has it hashed, and these signed transaction hashes, 'hashed and 2 by 2' together, are called the parent hash. A Merkle root, as it is known, is a single, unique hash generated by combining the various parent hashes in a way that yields its creation. Additionally, this also makes it easy to confirm the transaction details without actually having to see the whole blockchain (Swan, 2017).

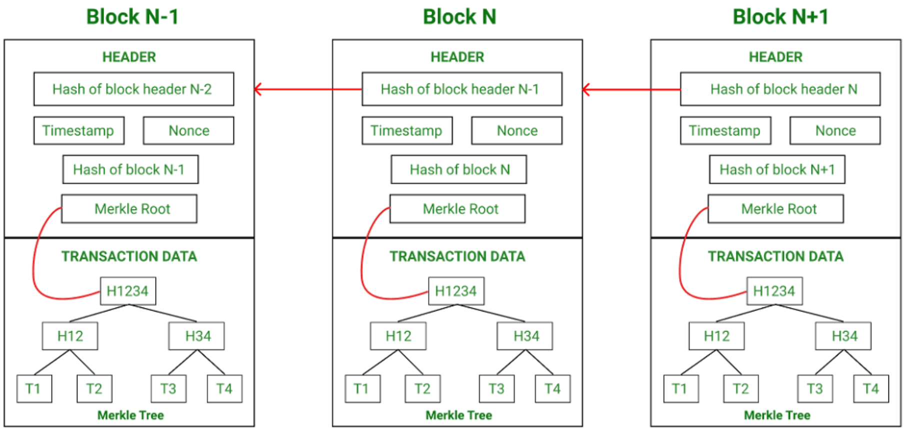

Figure 4. Blockchain structure illustrating the linkage between blocks using cryptographic hashes and the organization of transaction data within a Merkle tree (retrieved from GeeksforGeeks 2022)

As shown in Figure 4, blockchain is made of a series of blocks where each block contains header blocks, and units of transactions. Such values as the hash of the previous block, Time, nonce and Merkle root, i.e. summary of all the transactions of the block is placed in block header. The transactions are processed, and the information is structured in the Merkle tree which will be used to verify the transaction effectively. The integration of the blocks to an encrypted sequence provides the concept of making the blocks completely immutable, since changing one block means that all subsequent blocks in a chain will also need to be changed.

Another important thing about hash functions is that they allow the block chain to operate in behalf. All of the data that goes in the block cannot be changed without changing the hash of this block and every following block. Such immutability intuitively accords a high level of confidence in ag-ent participants as one can be confident that a piece of record, in this case transactions or con-tracts, were not altered (Francisco & Swanson, 2018a).

Collision Resistance: Or the probability that two different inputs would each produce the same hash value is very much disallowed or impossible. It's called 'collision resistant'. As for blockchain this translates to every block with a unique hash, it cannot have the same hash as two different blocks (Sharabati & Jreisat, 2024).

It is easy enough to compute hash functions so blockchain systems can easily validate a new transaction entering the chain and adding to the chain. In addition it is Proof of Work (PoW) — the fact that this much hashing power was required to locate a hash that meets specific parameters is considered evidence of the amount of power spent. That is what makes it expensive to attack the network or the people doing the work on the blockchain behind the credit (Rejeb et al., 2021).

Some real-world examples of Hash-Function in Blockchain are given below:

Bitcoin: What one can see from this is that the distinguishing characteristic here is that the Bitcoin blockchain hashes transactions with a SHA-256 and block hashes into a cognitive cryptographic hash function. Moreover, these create a network of secure and verifiable transaction chains (Narayanan et al., 2016; Wang et al., 2019) where each block tied the previous block by the block header hash. Since the same applies for blocks following it, this also guarantees assured data integrity, given that a change to a block would require re-calculation of all hashes after it, a mathematical feat infeasible even for an attacker using a probabilistic method to mine (Bonneau et al., 2015). In addition to Bitcoin, many other blockchain implementations rely on being based on SHA-256 as that SHA-256 inherent tamper resistance and trust has been a major component to secure Bitcoin. (Dinh et al., 2018).

Ethereum: The blockchain of Ethereum uses the same cryptographic hash functions as Bitcoin for concluding whether the transactions are verified. Ethereum 2.0, which would force it from Proof of Work (PoW) consensus mechanism to Proof of Stake (PoS), is the one it is working on. In a nutshell, the PoS makes computationally intensive hashing to prove consensus obsolete and changes its very fabric, as proof of consensus ceases to be accomplished through computational hashing, and instead power of a few validators (Saleh, 2021; Buterin, 2014). Unlike mining blocks, though, they won't do much in the way of ensuring data integrity and transaction validation (Wüst & Gervais, 2018; Xu et al., 2021), but in line with Ethereum's architecture, they'll be doing it in a diminished role.

Public and private keys are the basic elements of blockchain's cryptographic security. Because of the use of such keys in an asymmetric cryptographic set guarantying data confidentiality, transaction's execution, and data's credibility confirmation without a middle party, these are such keys. Different users in the blockchain can use this system to do transaction, to prove you are who you are, or to prove the information being exchanged in the network is valid. (Swan, 2017).

The two types of keys in Blockchain cryptography are described below:

Public Key: An asymmetrical cryptographic system has an essential requirement, a public key derived mathematically from the private key, a large alphanumeric string. Public keys are used to encrypt bits of information or verify digital signatures from the point of transactions. As seen in blockchain technology public keys 1 facilitate transparent and secure interaction between participants that have something to do with the origin coming from and they shield against accountability (Bonneau et al., 2015; Kshetri, 2018). The robust form of public key cryptography has been adopted in blockchain systems which support trustless environments, such as Supply chain and financial transactions (Narayanan et al., 2016; Antonopoulos, 2017).

Private Key: The user actually knows the private key, and it is used exclusively for the generation of digital signatures that prove a transaction's authenticity. However, as it is mathematically related to the public key, it cannot be reverse-engineered to the user assets (security) provided by the user (Conti et al., 2018; Xu et al., 2021). However, the private key's importance also introduces a significant risk: The loss of blockchain stored data or assets results permanently and irreversibly from its inaccessibility (Sharabati & Jreisat, 2024). The risks above require research to implement backup mechanisms or use hardware security modules to ensure private keys (Bonneau et al., 2015; Eskandari et al., 2018).

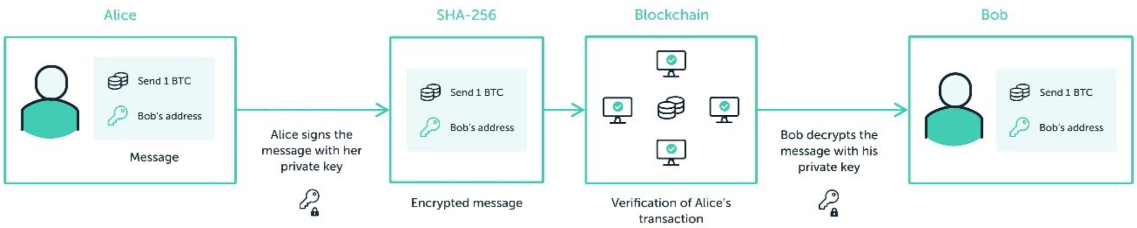

Figure 5. Blockchain transaction process illustrating the encryption, verification, and decryption of a transaction between two parties using Public and Private keys (retrieved from ReadMe.io.)

Figure 5 shows the described flow of blockchain transaction which begins with Alice's signature (using her private key for example to send 1 BTC to Bob). The message is encrypted using the SHA – 256 algorithm and transmitted to the blockchain to be confirmed. The network approves the transaction for Alice's and writes it into the block chain public record. Finally, Bob uses his to decipher the message, and completes the transaction to confirm 1BTC.

Every blockchain system must have both public and private keys as they work together to provide safe and secure execution of encrypted transactions. There are several benefits to using the public and private key scheme in blockchain technology.

Transaction Creation: To kick off a transaction, like sending crypto, users use their private key to generate a digital signature. Here the signature authenticates and proves the transaction (in the case of assets transfer), and confirms that the applicant is an owner of the assets involved (Francisco and Swanson, 2018; Bonneau et al. 2015). The only user to start transactions is guaranteed by the private key, which ensures it and avoids unauthorized entry or encryption fraud (Antonopoulos, 2017).

With the digital signature, it has a tamper proof mechanism to relate the transaction to the owner's private key without revealing it (Eskandari et al., 2018). The accounts in this system are used by

Blockchain protocols like Bitcoin, to verify ownership and securely execute transactions (Nakamoto, 2008; Conti et al., 2018).

Verification Process: The blockchain network verifies a transaction after it has been digitally signed. The digital signature of the transaction is verified by the network members using the sender's public key. Without access to it (Yigit & Dag, 2024; Kshetri, 2018), they ensure you can do this to guarantee that we debit the signature to the signer's private key.

This includes the fundamental part of the securing of blockchain security by decentralized verification between participants (Zheng et al., 2019). By adding only allowed transactions into the blockchain, it will be possible to avoid gaps (double spending or fraud) in the blockchain using verification (Bonneau et al., 2015; Xu et al. 2021). This is exactly why blockchain is the perfect application to verification; since such a decentralized version of varication.

Secure Communication: Distributed Trusted Organizations (DTOs) and peer-to-peer (P2P) networks make secure communication possible through public and private key pairs. Assume that one is a single user who transmitted a secure communication that can be encrypted using the public key of the recipient. The recipient can decrypt the message (Swan, 2017) only if the private key that is used to encrypt it matches the each other private key and is not just a set of numbers. That is why this is a mechanism preventing confidentiality and nonpermitted access (Narayanan et al., 2016; Xu et al., 2021).

This encryption process is widely applied in blockchain technology to secure transactions and communication, including the sensitive data transfer that goes from contract details to supply chain records, between two parties (Conti et al., 2018). However, public private key systems advance the security of blockchain implementations in all industries (Eskandari et al., 2018; Antonopoulos, 2017) by making sure that end to end encryption.

Public and private key pairs offer several security benefits that make them ideal for blockchain technology (Rejeb et al., 2021):

Authentication: It (the private key) proves that you own the assets or data and that you are who you say you are. As a result, no unauthorized entity can tamper with blockchain records and the only ones who can sign transactions are from the private key (Francisco & Swanson, 2018; Bonneau et al., 2015). Private keys are considered a fundamental authentication mechanism for blockchain systems (Kshetri, 2018).

Integrity: Digital signatures ensure data or transactions don't change during transmission. The digital signature becomes invalid if any alteration occurs, and the participants are warned of the fact of unauthorized modifications. This property of blockchain records is used particularly in applications with data protection demand, for instance, healthcare and finance (Sharabati & Jreisat, 2024; Zheng et al., 2019).

Confidentiality: Only the private key is known to those involved and everyone has the public key. Public key encryption is such that use of the corresponding private key allows for data encrypted using a public key to be decrypted; sensitive information cannot leak out (Swan, 2017; Narayanan et al., 2016). It avoids the improper access to blockchain data (Xu et al., 2021) so information will not pass on to any unauthorized person, making a huge threat to our information and blockchain.

3.2.3 Relevance to Supply Chain Management

The term blockchain typically denotes a distributed ledger system in which transactions occur across multiple computers to attain security and transparency and to render data nonchargeable. By eliminating the presence of any central controlling or regulatory body in the network, this decentralization helps to eliminate any record about all the transactions taking place in the network by the network's members (Nakamoto, 2008). Every transaction dealing with an asset, the transaction gets recorded as a block on a chain of prior transactions serving as a sequence of events that cannot be changed. Due to this feature, the implantation of the blockchain is particularly suited to industries with the highest need for trust, transparency, and security, such as the management of supply chain (Chang et al., 2020).

The reason that blockchain provides value is because there's no need for information to be stored as information flows quickly and efficiently throughout the supply chain at all stages of production and distribution. Supply chain business consist of various parties as suppliers, manufacturers, distributors and retailers which require timely information in real time fashion. Zheng et al (2019) observes that by utilizing blockchain as a decentralized platform, it helps all the parties in supply chain to have an advantage point of seeing the status of the products in the supply chain thereby making the concept as transparency and accountability much easier to achieve. This is also the case where the increase in data quality (an effect of using the blockchain) is coupled with the increase of data efficiency (Morkunas, Zhang,licted, 2019).

One of the other key ideas around using blockchain to the supply chain is its many benefits for developing the trust of the participants among themselves. T He absence of communication between the organizations in addition to the stakeholders in integrated SC can make the chain slower, even though there are mistrust among the partners (Queiroz & Wamba, 2019). When a transaction happens with blockchain, it means that validation of this transaction is involved and it is recorded simultaneously, so all these people can trust what this data contains right now, because already been checked. This allows the supply chain participants to confidence levels and makes processes and flow to be more efficient.

In addition, blockchain's ability to track the source and distribution of products is a game changer for industries where authenticity or compliance matters. Ensuring raw materials come from suitable sources and products maintain the right quality and pass regulatory requirements is very important for many industries such as pharmaceuticals, electronics and food (Tönnissen & Teuteberg, 2020). But the greatest power of blockchain is that it chases every trans-action from the purchasing of raw materials to the populating of the last product to consumer, end to end. The reason for such traceability level is that any defects or contamination will likely be traced and identified very quickly, thereby, reducing the likelihood of product recalls and improving overall supply chain reliability (Francisco & Swanson, 2018a).

Blockchain also contributes greatly to counterfeiting and fraud, areas rampant in industries with a wide and complex supply chain. The counterfeit products are a threat in the sectors like luxury goods, pharmaceuticals and electronics both at the consumers and the legitimate businesses end (Bai & Sarkis, 2020). Blockchain helps companies trace every single product's journey in the supply chain, ensuring that each product journey is necessarily recorded and easy to verify for authenticity anywhere in the supply chain. A level of transparency like this is vital for fraud and counterfeit goods likely to dent brand reputation and represent a danger to consumers if not detected in time (Li et al., 2019).

3.2.4 Benefits

There are several main arguments for the advantages of supply chain management using blockchain technology:

Transparency: It then means the blockchain logs of every transaction on the blockchain then creates an open and an auditable record available to all parties that are authorized to do so in the supply chain. At this level, the level of transparency allows the stakeholders to trust each other and also monitor real time supply chain activities (Alkatheiri et al., 2023; Bai & Sarkis, 2020). Like the first advantage, having transparent records limits information asymmetry and increases operational effectiveness through logging everyone's access to verified data (Tönnissen & Teuteberg, 2020). Blockchain enhanced transparency enables increased accountability and lower frauds and counterfeit goods cases in industries like pharmaceuticals, as well as food supply chains (Casino et al., 2019; Kouhizadeh et al., 2021).

Traceability: This means blockchain is a catalyst for helping to trace products within the supply chain all the way from production, with the final destination when it's being sold. It permits the participants to confirm the origin and movement of products, which are in accordance with the quality and ethical standards of the production work (Sharabati & Jreisat, 2024; Wang et al., 2019). The blockchain uses immutable records to identify bottlenecks and inefficient applications, to help improve the overall supply chain performance. Traceability is very useful when fighting against counterfeits and in verifying the respect of and compliance with the regulatory requirements in, for example, the electronics, agriculture and luxury goods industries (Francisco & Swanson, 2018; Caro et al., 2018). In recent implementations, blockchain has shown great promise for improving supply chain product recall efficiency and locating defective batches (Zheng et al., 2019).

Security: The security levels are also highest since because of decentralized architecture in it there are no single points of failures in providing such high increase in security levels. Commonly, transactions are stored in multiple nodes hence the risk of tampering (Yigit & Dag, 2024; Nakamoto, 2008) and data breaches. As further security of transaction records, blockchain technology, like all cryptographic mechanisms, uses hash functions and digital signatures to ensure that these records are immutable and resistant to unauthorized modifications (Conti et al., 2018; Narayanan et al., 2016). Because blockchain's secure infrastructure has been widely adopted in sensitive applications such as financial systems and government record-keeping, data integrity in healthcare systems is paramount (Xu et al., 2021; Dinh et al., 2018).

3.2.5 Empirical Evidence

The examples given on the many applications of blockchain technology in supply chains demonstrate how well it may be used. For example, Walmart increased the length of time it used blockchain technology to track the mango supply chain from one week to two days. Blockchain technology may increase the efficacy and transparency of the supply chain, as demonstrated in this instance (Alkatheiri et al., 2023).

3.3 Smart Contracts

Digital agreements which directly code the terms of the contracts are smart contracts. Due to their ability to perform and implement contractual conditions as soon as certain conditions are met, they act and operate as independent parties that eliminate the need for third parties, and provide increased effectiveness (Christidis & Devetsikiotis, 2016).

A smart contract is not a legal document in the usual context but a self-executing computer protocol when specified conditions are met. Due to this self-execution feature, they are preferred for decentralized applications and systems where trust between parties is difficult, for instance, in a supply chain, financial and real estate contracts (Rejeb et al., 2021).

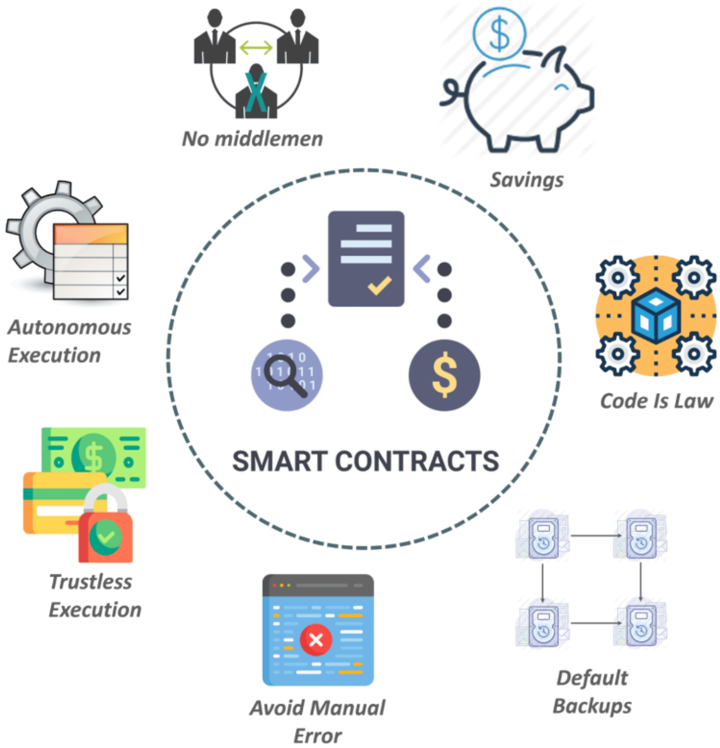

Figure 6. Key benefits of smart contracts, including autonomous execution, trustless operations, and cost savings through automation (retrieved from Edureka n.d.)

3.3.1 How Smart Contracts Work

A smart contract concept is simple. It is based on an if, then type of idea. When the established predefined conditions are attained then the contract is followed by the said actions. The following steps describe the basic working process of smart contracts:

Agreement Setup: First stage is when parties specify terms of the agreement (what needs to be done, what does the contract entail when breached, etc.). They are literally coded, typically utilizing Ethereum based programming languages like Solidity which allows for terms to be executed directly, without uncertainty (Antonyopoulos & wood, 2018; Xu et al., 2021). Through encodings of agreements to smart contracts, reliable decentralized systems are not only more efficient, but also more trusted (Morkunas et al., 2019; Zheng et al., 2019).

Blockchain Deployment: After we write the smart contract, it’s time to deploy it on the blockchain, and it’s now immutable for everyone that has authorization to use. The structure of the cryptographic ensures the transparent data of the blockchain's data and data integrity itself (Francisco & Swanson, 2018; Dinh et al., 2018). However, this on chain, the deployed contract can now be trusted since the contract is deployed and is set to carry out programmed actions once it is triggered (Buterin, 2014; Kouhizadeh et al., 2021).

Triggering Events: Event-driven: Smart contract is triggered by a given input or event. Often, these triggers are feeds of external data sources that feed live real-world data into the blockchain, such as Oracles. For instance, price changes, delivery confirmations or weather conditions can be made available by Oracles to make contracts execute properly (Sharabati & Jreisat, 2024; Xu et al., 2021). As smart contracts are often race conditions vulnerable to sudden changes in the environment and can therefore not operate without the integration of external data, this relieves smart contracts (Caro et al., 2018; Wang et al., 2019).

Execution: A smart contract predefines parameters, and when these parameters are met, the contract takes the next action given, such as releasing funds, transferring ownership, or revoking access permissions. The blockchain network consensus mechanism validates this execution, and the action is recognized to be an accurate action that is tamperproof (Zheng et al., 2019; Narayanan et al., 2016). Because of its automatic and deterministic nature, it does not suffer from delays and human error, which makes them invaluable for a time-sensitive operation (Antonopoulos & Wood, 2018; Morkunas et al., 2019).

Finalization: Once there is an execution of the instance of smart contract, the result of smart contract is stored on the blockchain. On blockchain, the transactive outputs become immutable and verifiable so that any transactional history is stored permanently in the distributed ledger (Francisco and Swanson, 2018; Sharabati and Jreisat, 2024). Such finalization ensures independent (stakeholders) verification of the results and provides for increased accountability and trust in the system (Xu, et al., 2021; Bonneau, et al., 2015).

For example, when applying it to supply chain, a smart contract will require paying a supplier whenever products are delivered to different geographical coordinates through GPS. In the case, a third party does not have to trigger the payment once the delivery is acknowledged, according to the signed contract (Francisco & Swanson, 2018b).

3.3.2 Structure of a Smart Contract

Several key components that form the structure of a smart contract give it both effectiveness and security that are:

Contract Code: The logical logic underlying smart contracts, as well as the rules they enforce, is the contractual code. It specifies the circumstances when it should (contract) execute and what (tasks) should be done when the conditions are fulfilled. The code, written using blockchain-specific programming languages such as Solidity for Ethereum, facilitates unambiguous agreement execution in order to reduce the possibility of dispute (Antonopoulos & Wood, 2018; Christidis & Devetsikiotis, 2016). In the finance, supply chain, and insurance industry, the automation and precision provided by contract code serve to save time and costs (Frantz & Nowostawski, 2016; Tsankov et al., 2018).

Blockchain Storage: That means the current state of that contract is not something we can tamper with, we can transparency like look at the state of the contract stored on the blockchain. In contract speak, the "state of the contract" is the current status of the proposed deal or (not only) in software development: Was the contract executed or not, was the pre-condition met or not? It is both tampering risk free and provides independent verification on any specific time for any specific parties (Buterin, 2014; Gatteschi et al., 2018). Blockchain encourages more reliability because as the number of copies of the contract on all nodes of the blockchain become identical (Xu et al., 2021; Wang et al., 2019).

Decentralized Execution: As the decentralized network of blockchain nodes is able to execute smart contracts autonomy, the whole operation is dead to trust and open for the world to see. Adopting decentralization eliminates a single entity's possibility of manipulation and improves trust among the participation (Rejeb et al., 2021; Christidis & Devetsikiotis, 2016). Smart contracts can be executed (Kosba et al., 2016; Dinh et al., 2018) without intermediaries, with an order of operation and in an extremely efficient manner.

Oracles (Optional): Oracles are specialized services that are used to solve the problem of smart contracts, by providing necessary external data on which they run. These external information sources may come from dynamic external environments like a price feed, a shipment tracking data or a weather update and oracles offer the real time information (Yigit & Dag, 2024; Nazarov et al., 2019). While extremely valuable, reliance on such oracles introduces new security issues about how accurate and trustworthy the data provided is (Caro et al., 2018; Zhang et al., 2020).

3.3.3 Advantages of Smart Contracts

Automation: Automation brings one of the most widespread benefits — smart contracts. Since smart contracts execute actions automatically upon predefined conditions, without human intervention (Francisco & Swanson, 2018; Christidis & Devetsikiotis, 2016), they are also referred to as code-interpreted as opposed to code enforced. Complex workflows are automated by smart contracts, making them ideal in industry such as logistics, finance and real estate, where delays and human errors can have a huge impact (Morkunas et al, 2019; Frantz and Nowostawski, 2016). Furthermore, automation lowers the likelihood of any disputes as the conditions and actions are both clear and their execution not ambiguous (Xu et al., 2021).

Cost Reduction: One powerful advantage of Smart contracts is that they reduce costs (transaction costs) significantly by removing the costs associated with using lawyers, agents, and having notaries.

These contracts would automatically execute, without the help of any third party (Antonopoulos & Wood, 2018; Swan, 2017). Supply chains (Caro et al., 2018; Zheng et al., 2019) and financial systems [for example escrow services] are seeing the replacement of the need for oversight agencies by smart contracts that reduce their fees. As such, smart contracts are the best option for SMBs to offer less expensive and more efficient solution (Gatteschi et al., 2018; Kosba et al., 2016).

Transparency: One of the biggest advantages of smart contracts is their near complete transparency: you know its terms and how they will be executed as this will be recorded on blockchain, which is the decentralized ledger and cannot be altered. Making sure that all party can see the terms and conditions there is nothing for them to hide and no foul play can be played these terms cannot be misinterpreted (Sharabati & Jreisat, 2024; Wang et al., 2019). Furthermore, blockchain is a transparent (open) book, which can make auditing of contract for all transactions once made while being able to trace these transactions backward for history and guarantee the adherence of the regulatory and ethical standards (Kouhizadeh et al., 2021; Christidis and Devetsikiotis, 2016). While transparency and the visibility that comes with transparency therefore increases trust specifically when it comes to Multi Party Agreements (Tönnissen & Teuteberg, 2020).

Security: Other than storage on distributed blockchain networks and complex cryptographic algorithms, there's nothing smart that really needs to be secured. Once deployed, a smart contract is immutable – it's impossible to change it subsequently (e.g., to add new transactions), preventing tampering and cyberattacks (Yigit & Dag, 2024; Conti et al., 2018). To increase the reliability of the contracts, for instance, in sensitive applications like healthcare and finance (Zhang et al., 2020; Gatteschi et al., 2018), cryptographic safeguards are provided to prevent only authorized parties from interacting with the contracts. Since blockchain is a decentralized system, smart contracts play an important role in securing these digital ecosystems (Nakamoto, 2008; Kosba et al., 2016) because it minimizes single points of failure in its nature.

3.3.4 Following are the Real-world Examples of Smart Contracts

Traditional ideas of how things should be done in some or more fields were challenged with smart contracts that get rid of the utility of the middleman and spark higher rates of performance. You have contracts on smart contract platforms (such as Ethereum) called the smart contracts, which are triggered whenever a particular set of conditions are met. Many industries could apply smart contracts but need efficient solutions in future operations.

Supply Chain Management:

Even so, we concluded that smart con-tracts could be beneficial for increasing efficiency and reducing how obfuscated operational management is when it comes to the supply chain. The activities of this supply chain have usually been quite huge and complex comprising a chain of suppliers, buyers and service providers from different sites hence raising the burden on time, costs, confusion and liability. Smart contracts, on the other hand, address these challenges by removing a lot of human intervention from important steps such as payment, shipment management and issuance of compliance certificates (Wang et al., 2019). For example, smart contracts can release payment when delivered goods are confirmed to have been delivered, which will diminish cases of disputes. These may not require (Francisco & Swanson, 2018a). For example, in bioindustries including the pharma, food and logistics industries, which require traceability, smart contracts certify that the compliance information would have been entered into and recorded on blockchain in real time to trace (Morkunas et al., 2019).

So, shipment tracking is also made more effective by adding IoT devices to the smart contract. The use of IoT sensors allows monitoring of consignments temperature, humidity, geographical location in real time and launching of such data in the form of smart contracts, where the payment can be released or notification sent if values are not within a desired range (Chang et al., 2020). Furthermore, this enhances production performance and assures timely delivery reports to shipping and transportation exceptions devoid of fraud or human error (Tönnissen & Teute-berg, 2020).

Financial Services:

Financial smart contracts are pioneering. These contracts are deemed to be executed manually with the intervention of third parties now being fully automated. Smart contracts are used most often in this sector for the facilitation of actual financial transactions like lending, provision of loans, escrow services and cross border payments (Swan, 2017). In fact, they can release the funds to be paid to the borrower, if the loan is approved or if the collateral is checked and approved. In so doing, the time to complete a transaction would be hastened, as would be its associated expenses (Kouhizadeh et al., 2021), for example those associated with the services of intermediaries such as banks, escrow companies or lawyers.

Furthermore, smart contracts provide much additional transparency and security in all financial operations. That is because the terms of the contract are hashed into the blockchain and are hard coded and cannot be tampered with, so all of the parties know that when the term of contract is executed, it will happen as agreed without any short cut, cheat or fraudulence (Mougayar, 2016). This is much useful when a lot of middlemen are involved plus different legal systems which will surely slow down the deal or make it costlier instead. Smart contracts remove these hurdles, enabling the real time checking and transferring funds in international trading (Zheng et al., 2019).

The financial scenario may then employ smart contracts as well, this time to create and manage escrow accounts. In a conventional escrow, the funds are being held with a third-party escrow company until some conditions are met and actioned. The lack of an outside intermediary reduces the time, expense, and hazards involved in manual escrow administration (Morkunas et al., 2019), including the escrow agent: the funds are released by default once the provisions of the contract are fully met.

Real Estate and Insurance:

Smart contracts are also moving to the real estate and insurance industries, in addition to the SCM and global financial services. In real estate, smart contracts can be used to ensure the property deal only complete once buyers receive payment and place the deed on the blockchain (Franzoni and Schouten, 2019). It does this by reducing the need for middlemen like real estate agencies and title companies and in addition speeds up the time required in the case of a property deal.

Smart contracts, for instance, can automate the handling of insurance claims. When a claim is filed and the policy's terms (such as the sensors and documents) meet the specified requirements, a smart contract can automatically release money to the claimant (Nuryyev et al., 2020). It saves the time usually spent evaluating and awarding the payouts for the various claims and ensures the claimants get paid as quickly as possible, making them happy customers.

3.3.5 Relevance to Supply Chain Management

Smart contracts are programs written in computer language that allows self-execution without third party intervention. In essence, these contracts are 'self-activating' in the sense that the conditions of the con-tract, in themselves, satisfy the conditions of the con-tract once the predetermined conditions in the contract have been met to the satisfaction of the transacting party, keeping both 'on their wrist'. Smart contracts have an exponential applicability in supply chain management for the processing of orders, the release of payments and release of compliance checks with minimal human interaction aimed at improving productivity (Yigit & Dag, 2024).

In short, the modern contract automation opportunity offered by smart contracts can deliver an important executive significance on a supply chain scale to improve efficiency. In this case for example, automatic release of payment can be made when delivery status of goods has been confirmed without or with the reduction of the need to do manual checking or bring in a third party. It is much faster than this many transactions with normal means, increasing chance of error and disputes (Wang et al., 2019). Like, smart contracts can enter to automate the order processing cycle, ensuring that if orders are to be treated, for example, quantity, quality, and time of delivery are implemented according to the terms of agreement, hence by Morkunas et al. (2019). Furthermore, the smart contract integration that in compliance checks enables the stakeholders another chance to confirm, that all the regulatory compliance measures have been kept in check before forwarding products to the next level in the supply chain (Chang et al., 2020).

But this execution does not only guarantee phenomena of transparency in managing supply chain management, but can also optimize the work process. All the participants in this market (Casino, 1993) have the real-time records of the contracted terms since within these records, the chances of conflict are very rare and the chances of cheating are well and truly minimized (Casino et al., 2019). For instance, specifically useful in industries where traceability must be transparent among the supply chain partners (e.g. drugs, food, logistics) where the overall compliance and most importantly the authenticity of products is a major concern (Li et al., 2019). For example, in supply chains of pharmaceuticals which pose one big problem – fake products violating health standards, who would only be allowed to enter the supply chain under condition of authenticity (Italian & Swanson, 2018a).

A second striking feature of smart contracts is that they are self-executing meaning that third parties do not need to be involved, and if present can be a source of dispute and additional expenses. In traditional supply chains, time delays and cost overheads due to orthogonal use of banks, brokers, and other legal entities in intermediary roles as the third party (Kouhizadeh et al., 2021). Additionally, they also saves the intermediaries as the smart contract terms are already self-executing without the need for continuous monitoring. By doing so, they not only reduced the transaction cost, but also lowered the possibility of conflict because the rules of the contract are well set and impartially applied by the smart contract (Zheng et al., 2019).

3.3.6 Application of Smart Contract

Smart contracts work well when they are applied to supply chain management issues. The food business, for instance, may make use of smart contracts, such that, if the authenticity of the product is verified, then payment to the suppliers will be triggered. It therefore facilitates timely payment in addition to reducing bureaucratic burden on the buyers as well as the suppliers (Law, 2017).

Not only can smart contracts be used to automate many of a business's processes, they can also be used to track customers' orders and automatically restock products when the quantity is low. With this automation, stockouts can be avoided, and supply chain processes can be delivered effectively (Alkatheiri et al., 2023).

3.3.7 Benefits of Smart Contracts in Supply Chain

Application of smart contract in supply chain management has several opportunities which increase the usefulness, reliability and cost effectiveness of the process. Smart contracts allow parties to write contractual terms in code, hence enabling the fulfillment of the provisions through code without having to refer to people to interpret the articles.

Automation:

Contract execution is made automatic such that the role of human beings as the principal stakeholders on the contract diminishes. Similar to contract provisions, smart contracts operate automatically when self-enforced conditions are met, as it con notes (Xu et al., 2021). However; this automation of supply chain management activities differs from the traditional management of supply chain where snags resulting from errors, confused or holdups, are no longer there hence increasing supply chain efficiency. This is, for example, when sensors around IoT confirm the receipt of supplies, payment is made and the supplier. This type of automation turns it faster due to rate of transactions, reduce time taken to process transactions, also reduce cases of conflict either targeted by the two parties (Treiblmaier, 2018). Furthermore, this ensures that compliance can be checked in industries where a supply chain is multipolar, e.g. electronics manufacturing or pharmaceutical production without any inconvenience to the stakeholders because every requirement listed is in place from one side of the supply chain to another. This reduces the time lapsed and effort invested in the stakeholders (Kim & Laskowski, 2018).

Cost Efficiency:

In the use of smart contracts for the application to the use of a supply chain management cost usage factor is the second most obvious. Consequently, such exchanges should almost completely eliminate intermediaries (such as banks, brokers and legal entities, who usually authenticate and thus make such an exchange much more costly than via smart con-tracts [Peters & Panayi, 2016]). These third-party intermediaries add not only a cost element through these guys not incrementing & & organically without them costing extra but also time, because most of them require time for paperwork & & a time consuming additional verification. In smart contract cases, these procedures are integrated and there's no involvement of third parties, as it is with other contracts. This has helped reduce intermediaries, means of enhanced cost control and better cost efficiency in performing business operations that have made supply chain activities more effective and less expensive (Mendling et al., 2018).

Accuracy:

In terms of accuracy, smart contracts also help increase how accurately contracts are fulfilled in different ways. Standard written agreements can always be explained enough and causes problems when specified written agreements have warps or when parties don't enforce their parts. Written as it is with the terms of the contract and insurances of the tenets of the contract being satisfied as prescribed or otherwise, smart contracts, one the other hand, eliminate this uncertainty (De Filippi and Hassan, 2018). This is perhaps all the more important in business sectors in which compliance with law and related regulations is crucial. For example, in the pharmaceutical industry supply chain, smart contracts should only be able to deliver products that have passed set regulatory standards to prevent violation and the potential for legal repercussions (Chapman et al., 2017). Two advantages of smart contracts that relate to its non-ambiguity include improved legal compliance and improved contract performance as well as reduced instances of contract breach (Reyna et al., 2018).

Furthermore, the blockchain, the technology that powers smart contracts, is an unchangeable technology, it cannot be tampered with, and the reason being is that it eliminates the need for third parties such as brokers. Once you fit in the terms of a contract, and there is no way you can reverse it for that matter, you put it into the blockchain system and leave it permanently available to all the members, in the form of audit trial (Bai et al., 2021). With regard to supply chain process optimization, supply chain process improvement with regard to supply chain efficiency, and supply chain performance, this degree of precision surpasses participants' arguments for disagreement.

3.4 Integrating Blockchain and Smart Contracts in Supply Chain Management

This is a vision for future supply chain with blockchain smart contract enhancement. Using blockchain, all participants can see through each operation (indeed, it may be thought of as a log) and can be guaranteed that no operation takes place outside of the blockchain. These transactions are overseen by smart contracts which execute the legal conditions without a third party (Swan, 2017).

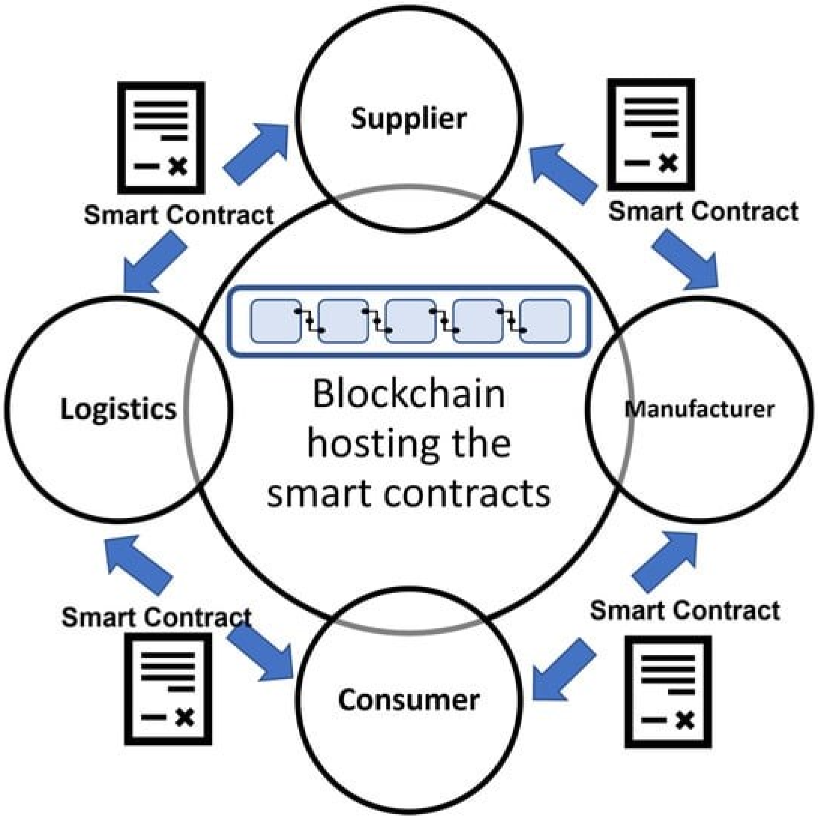

Figure 7. Blockchain hosting smart contracts for automating and connecting the supply chain processes among suppliers, manufacturers, logistics, and consumers (retrieved from MDPI Electronics. 2023)

As illustrated in Figure 7, the blockchain acts as the central platform hosting smart contracts that automate and streamline transactions among key supply chain participants: buyer, producer, distributors and end-users. Every participant is working through smart contracts, which set the conditions that have to be followed on the blockchain platform, so one can have confidence that everything is fair, fast, and open. These are contracts that impose certain actions, for instance the sending of payment release or a confirmation of delivery should some conditions be met thereby doing away with intermediaries.

3.4.1 Case Studies and Empirical Evidence

Several papers explain examples of applying block chain and smart contracts in the supply chain. Take IBM Food Trust which is powered by blockchain; it makes sure that you have all updated information about food items as they are moving from one supply chain to another. Hence, the for marketeers, the 4Ps are only 1 adaptation that most producers have incorporated in the products in current times to address increased meals safety; to reduce wastage, and increase customer believe (Alkatheiri et al., 2023).

Another good example of another blockchain based platform is Maersk's Trade Lens platform for global trade digitization. For this Trade Lens has cut costs and time in the process of shipping documents to ensure integrity of international trade (Sharabati and Jreisat, 2024).

3.5 Challenges and Future Directions

Although there are several obstacles, there are also substantial advantages to use smart contracts for supply chain management – scalability, interoperability – that can be too steep to ignore. In order to improve the adoption of smart contracts while utilizing blockchain technology in the supply chain, further work needs be done to address these problems (Korpela et al., 2017).

3.5.1 Scalability and Performance Issues

Since supply chain management involves a large much of transaction processing, scalability is one of the major concerns of current blockchain networks. For example, current blockchain solutions can work through the number of transactions required by supply chains in need of at least millions of transactions in a timeframe. Several solutions have been suggested to overcome this problem, including sharding, side chains, and off-chain transactions, with all ideas basically the same, sharding, dividing the load into sub-processors, or dividing the load into other smaller chains, or conducting off the block chain (Yigit & Dag, 2024; Treiblmaier, 2018).

Moreover, as the blockchain system scales in size and the number of transactions, there may be some challenges in managing the size of the blockchain itself that prevent further use of the blockchain in a large scale supply chain. Also, works in progress like the Lightning Network for Bitcoin and Plasma for Ethereum may enhance this scalability downsides brought by blockchain for supply chain purposes (Sharabati & Jreisat, 2024).

3.5.2 Regulatory and Legal Compliance

While Blockchain and smart contracts bring many benefits, mostly, there are also important legal problems that prevent businesses from adopting Blockchain on their supply chain. Discusses regulations related to the creation of digital contracts, data privacy and money transfer through the legal systems of different world regions, and points to the significant challenge to the global adoption of blockchain solutions on it (Alkatheiri et al., 2023). Information in blockchain is distributed, and the process is decentralized, making it difficult to reverse or cancel a transaction after it is put onto a block, and has implications for integrating blockchain into existing legal frameworks (Peters & Panayi, 2016).

The other than legal issues involve legal compliance which is required for all the set upments right from the health and manufacturing industries to the food industry. However, the development of these two industries lay down considerable pressure on traceability, data integrity and responsibility when it comes to blockchain to exhibit impressive prospects (Kim & Laskowski, 2018). However, the benefits of which are realized will depend on good working relations with legal consultants and regulatory bodies in developing blockchain implementations to conform to legal requirements (Yigit & Dag, 2024). For example, deployments, such as traceability and immutability characteristic of the blockchain, can be especially well adapted to compliance, only in compliance with the sector-specific compliance (Swan, 2017).

3.5.3 Integration with Existing Systems

In order to apply blockchain and smart contracts in supply chain we have to explore its integration with existing technologies. In other words, standard and open data communication formats as well as stable and standardized API connections between existing and future blockchain based supply chain solutions and inherent supply chain information systems (SCISs) (Sharabati & Jreisat, 2024) will be required. One big issue of the current blockchain technology state is disintegration due to unification, a lack of ability of one company blockchain network to be easily connected to another without hitches.

Therefore, it is important to develop and implement standardized protocols and frameworks across the ledgers (the Interledger Protocol (ILP) for cross ledger transactions and blockchain interoperability platforms). These standards should help different blockchain systems join together creating the possibility for organizations to seamlessly integrate Blockchain in already existing supply chains without disrupting routine practices (Law, 2017; Saberi et al., 2019).

3.5.4 User Adoption and Change Management

The adoption of blockchain technology and smart contracts in supply chain management, reporting and data privacy and data sharing areas is hinged on change management strategies. Users of the system may be completely surrounded by tangibly resisting the change to new technologies because the system is used to the old ways of work. This resistance must be overcome and users must be educated on the importance of including blockchain and the manner blockchain is functioning (Treiblmaier, 2018).

Additionally, the recommendations for change management are early involvement of the stakeholders, their concerns identification and the explanation of possibilities of blockchain through pilot implementation, successful examples, etc. According to Yigit and Dag (2024) and Law (2017), if businesses support other stakeholders during the transition process of applying blockchain technology and smart contracts, increasing the trust among them, supply chain will be more transparent and efficient.

3.6 Summary and Implications of Theoretical Framework

This theoretical framework combines aspects of blockchain technology as well as cryptographic systems, intelligent contracts, and Transaction Cost Economics (TCE) to determine the influence embodied in the SCM. Blockchain and related technologies are introduced by the framework to remodel traditional operations of supply chains and alleviate corresponding problems.

3.6.1 Blockchain Fundamentals and Cryptographic Security

The following advanced characteristics of blockchain implementations in supply chain give them the following characteristics: Immutable records, decentralisation, transparency and security. Cryptography play essential role as blockchain cannot run without it, as the methods ensuring proper business and data protection are based on cryptography. Adjusted to the blockchain system, the data in a supply chain is highly secure thanks to the help of hash functions, and public key cryptography (Rejeb et al., 2021; Yigit & Dag, 2024). Block chaining has proven to be very secure in hashing functions more cannot be manipulated, the input and output of public or private keys is input to maintain confidentiality, to prove and the webmaster to show the stake holders the transactions to authenticate without authority but software (Swan, 2017).

3.6.2 Smart Contracts for Automation and Trust

By having a way to do transactions, without any third party involved, we can make blockchain even better, which smart contracts provide. Since the supply chain partner grows with the amount of links, that can add delays and expenses because the intermediaries have to offer assurances that the supply chain partner will adhere to its agreed terms. Automated execution of rules avoids extensive monitoring by third parties and shortens transaction time (Sharabati & Jreisat, 2024). It also brings down conflict, lowers the cost of the business and strives towards promoting the openness and integrity culture among the supply chain actors (Alkatheeri et. al., 2023).

3.6.3 Reducing Transaction Costs Using TCE

An economic view of the complexity of blockchain adoption can be sought by tying the work to Transaction Cost Economics (TCE). Furthermore, TCE has demonstrated how transaction costs (information costs, bargaining costs and policing costs) need to be eliminated so that organizations can reduce transaction costs and thus be efficient in business activities (Williamson, 1985). Real time information implementation in blockchain alleviates information asymmetry, smart contract reduces the negotiable cost and the cost to enforce the contract (Kshetri, 2018). The TCE does all these through blockchain which delivers the procedures obtained by TCE thereby enhancing the management of the supply chain.

3.6.4 Implications for Supply Chain Management

The supply chain management has no weak spot by the integration of blockchain technology, cryptographic method, smart contracts, and pieces of TCE. Because data is transparent, unchangeable and well protected, if combined with enormous data amounts, smart contracts and stakeholders, increased confidence (Francisco & Swanson, 2018a). Furthermore, because such a combination of these technologies is very interesting for industries characterized by high requirements in terms of traceability and security, e.g. the food industry, the pharmaceutical industry or the luxury goods industry. Provides a glimpse at how blockchain could improve the visibility of products along the producer to consumer supply chain and guarantee that the products within the chain are legitimately made but reduce the cost of the supply chain (Chain, 2019; IBM, 2018; Trade Lens, 2023). The finding from these platforms has demonstrated increase in efficiency of food safety, fraud reduction and eventually cost savings (Sharabati & Jreisat, 2024).

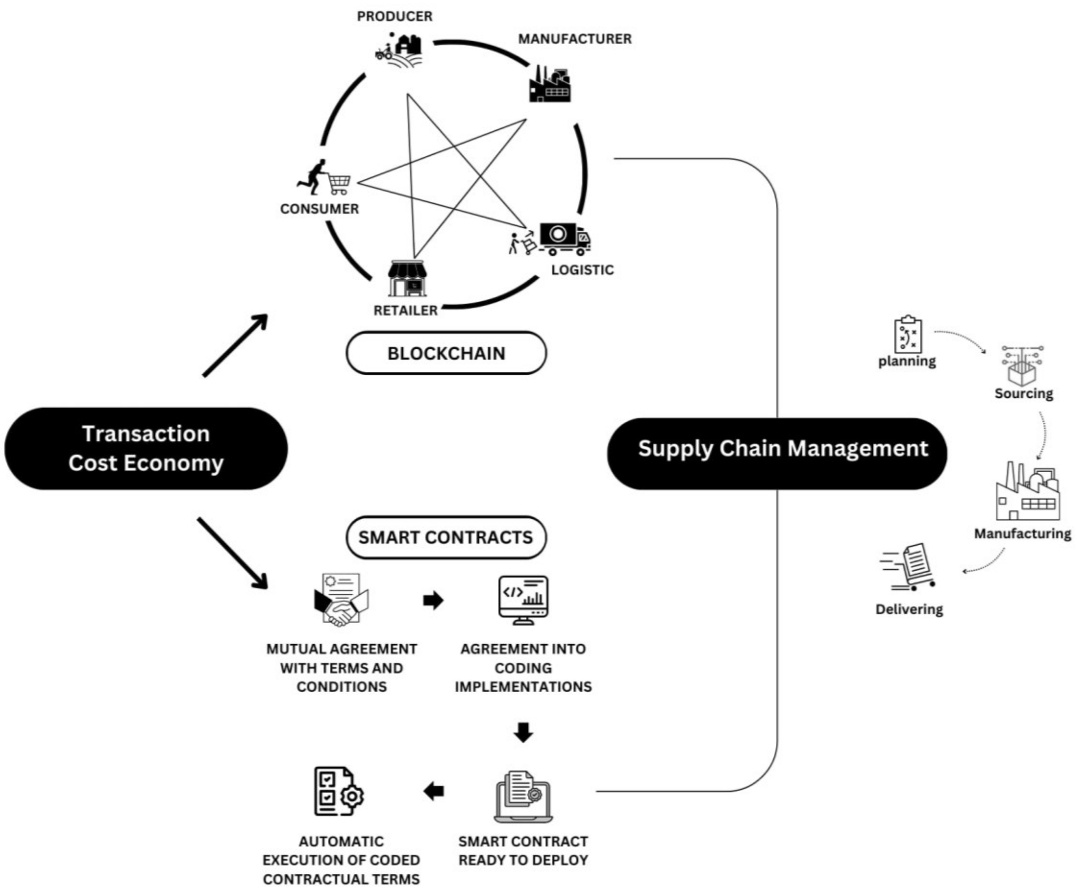

Figure 8. Blockchain and smart contracts integrated into supply chain management demonstrate the workflow from transaction cost reduction to automated supply chain processes

From the figure 8 we can see that how by integrating blockchain and smart contract with supply chain management the main players like producer, manufacturer, logistics provider, retailer, and consumer can work efficiently. Business transparency and precise accountability are solved by blockchain mechanisms, whereas smart contracts help to fix definite agreements and implement them when specific conditions are met. A paper by Zhang et al (2014) explains how this increases efficiency in planning, sourcing, manufacturing and delivery as represented in the figure 8. The nexus between transaction cost economy and supply chain automation presents the disruptive effect of blockchain technology.

4 Methodology

4.1 Research Approach and Implementation

Saunder’s Research Onion framework (2019) was employed as the guiding model for the research methodology of this study to furnish with a structured foundation. Based on this framework of multiple layers, a philosophical stance of the study, the strategy and technique of study were defined. The layers gave clarity to the decision and keeping aligned to study’s objectives.

The research is pragmatic in nature, looking at practical problem solving and deriving actionable insights to promote supply chain management that is faced with challenge of efficiency and transparency. In part, pragmatism allowed the study to integrate the theoretical with the applied. A deductive method was used. From a thorough literature review on blockchain and smart contracts (Rejeb et al., 2021) hypotheses are given.

We thoroughly examined the blockchain and smart contracts in a real-world supply chain situation because it was a case study approach. Through our blockchain based, real world, web application, we were able to dynamically generate our dataset for our study based on users' interactions and get real time data in context. It is this approach that has become relevant to and directly applicable to supply chain management.

The research approach is development of a blockchain web application and potential applications to supply chain management. Here used React for the frontend & Express.js for the backend. To improve integrity and transparency around data, blockchain was used. The proof of concept showed how effective a blockchain is as a way to establish trust in supply chain operations and as a platform to execute immutable transactions.

Support for user interaction was provided through a web-based interface where users can add transactions and mine new blocks on the blockchain. Trigger conditions could be defined by administrative users, who define when transactions will be added to the blockchain. This was to give another layer of verification by which only validated transactions made it to the miners. Once the transactions were mined and thereby immutable, the system was supplied with a high degree of trust and transparency.

The records and transactions that were stored in the blockchain were in JSON files on the backend for analysis. To mimic the flow of supply chain activities on supply chain real time, real data (user input in this case), this system was built to run on real time. The case study strategy was aligned with the dataset alignment to highlight an interactive use of blockchain in supply chains.

It assumed the time horizon cross-sectional, meaning data were generated at arbitrary times in the system's system interactions. Consequently, the system performance metrics like transaction processing, data integrity, and customer engagement (Francisco & Swanson, 2018a) were used to evaluate the system.

4.2 Data Collection and Dataset

The web application used to generating this dataset is a blockchain based web application which was dynamically generated as the users interacted with it. Real-time data collection was ensured under this approach, which simulates practical supply chain scenarios. Transactions were added, approved based upon trigger conditions, and mined into new blockchain blocks as users interacted with the application in line with the case study strategy that has been followed in this research (Yin, 2018).

The dynamically generated dataset included the following transaction details:

- **Sender:** Persons who traded.
- **Recipient:** It is the person who get the product or service.
- **Product Details:** Name, description of the product being transferred.
- **Quantity:** A term meaning quantity or amount of the product.
- **Location:** High level of detail about transaction, related to geographical location.
- **Status:** It is 'Pending', 'Approved' or 'Mined', that is its transaction state.
- **Temperature:** Sensitive product under environmental condition.
- **Delivery Date:** The actual or expected delivery date.

Every transaction was put in a pending state and put to validation according to predefined trigger conditions established by the administrator. This meant that the blockchain should only contain only valid transactions and exclude all frauds and errors. Data immutability of the blockchain structure was maintained using unique hashes and proof of work value linking each block to its predecessor crypto graphically (Fran-cisco & Swanson, 2018a).

The data was proxied through a REST service which stored it on the server in JSON format, acting also as storage of the blockchain ledger. It included:

- **Blocks:** It included the list of transactions and the initial hash of the current block. Additionally, there was the preceding block's hash, proof of work, index, and timestamp.

- **Transactions within Blocks:** Infinite minable blocks with valid transaction records.

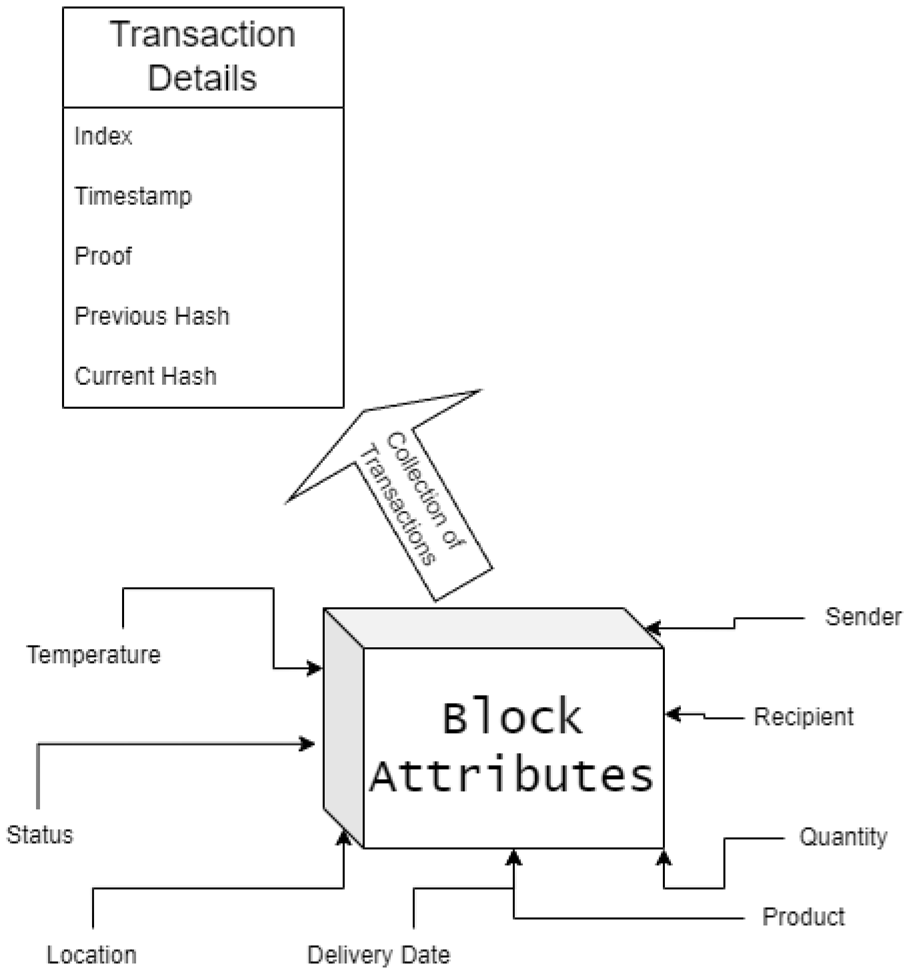

Figure 9. Dataset Overview. A blockchain block, highlighting transaction details and specific attributes that are stored within each block

As seen in the figure 9, each block in the blockchain involves key attributes and transaction details about the business. The information that changes hands in the transaction involves an index, time of the transaction, proof, previous hash, and the current hash to check for any alteration. It also keeps micro-data about the specific transaction including the sender, the recipient, the product, how many, where it was shipped, at what temperature, when and its current status. These attributes collectively make up the block content, which is then added to the blockchain as a verified set of transactions thus ensuring optimization of the record transparency and accountability.

This dataset possessed the inherent flexibility to allow for scalable, flexible collection and replay ability of the data. One way the system could be used, is that the system could simulate some conditions or events, such as reloading JSON files, and using the system to test out different scenarios of the supply chain. The positive side to this is that the focus of study did not need to involve the classical data preparation and analysis, but rather the practical application of the block chain concept.

Using dynamic, real-time data as a lever, the research demonstrated that blockchain can process and validate transactions in a fast and cost-effective manner in line with real world supply chain operations. These are in keeping with Saunder's Research Onion frame-work in terms of which method is most appropriate for case study re-search (Saunders et al., 2019).

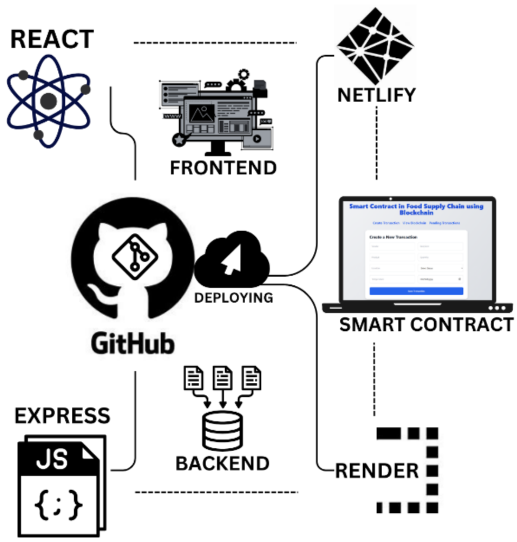

Figure 10. System architecture for deploying a blockchain-based smart contract application, illustrating the interaction between frontend, backend, and hosting platforms

Based on the system context diagram shown in figure 10, there are several components that make it possible to deploy a smart contract application based on blockchain. Frontend is developed using React and is deployed to Netlify for user interface functionalities. Backend development is done with the aid of Express.js for handling server routes and DB queries; they are hosted with Render. For the purpose of managing the version on GitHub facilitates the versioning of the code while the entire application and smart contract code reside on it. This architecture implies the scalability, efficiency and smooth deployment of the smart contract functionalities.

4.3 System Design

The system was developed using the design science research methodology and was built iteratively and evaluated against real world problems (Peffers et al, 2007). This methodology was based on which the block chain-based system design, implementation and validation were done with a purpose to improve the supply chain management efficiency and transparency.

The system had two main components. The frontend was a React and the backend a JavaScript using Express.js. Frontend side was also provided, providing easy to use interface for client to input transactions, temperature to observe and status on moving supplies in the chain of supply products. Transactions had been recorded as standby or pending status prior to the incorporation into the blockchain.

The second unique aspect of the system was that trigger conditions were defined by administrators. That meant you could preset parameters like product quantities, temperature and delivery dates in the user's browser's local storage. To be mined, the state of the blockchain compared the incoming transactions against these conditions during vali-dation. The combination of these features gave us an incredibly powerful tool to control misbehaving parties from adding fraudulent or erroneous data to the blockchain.

To make data ingesting and responses efficient and managing blockchain, the backend was written with Express.js. As it has been used to store and parse all pending transactions and blockchain data to store for access, scalability in the analytical process. We used REST API to easily communicate between frontend and backend, the data flowing from one to another.

Key blockchain design features included:

- **Immutability:** Validated and mined, it was immutable — it could not be modified.
- **Cryptographic Security:** Every previous block was different, each block had the block hash, the hash of the previous block and it's proof of work value which no one could chance everything without breaking or altering the entire chain.
- **Replay ability:** The system used JSON based storage to reload and simulate specific conditions or events for testing.

With the application of design science research methodology, I show that this system design could be both practical in applying blockchain for supply chain management and iterative tested and validated to make sure that the system is actually fit for purpose. Using modern technologies such as React and ExpressJs, it could scale easily and flexibly, as well as generate dynamic data in real time with respect to actual supply chain activities.

4.4 Development Tools and Data Flow

By using GitHub for version control, we were able to update code and fixed bugs in development efficiently. To optimize the scalability of the app I kept frontend and backend running on separate platforms (Netlify for frontend, Render for backend).

Product details, sender and recipient information and timestamps, which part of the transaction details stored in the blockchain. So, this way the blocks continued to have a hash of the previous block, so the chain was immutable and the changes in most cases were not possible for an unauthorized person. Initial hash functions (Francisco & Swanson, 2018a) that were composed of Security Hash Algorithm (SHA-256) were dictated to ensure data integrity in a transaction.

4.5 System Workflow and User Interaction

4.5.1 User Roles and System Access

The system has two primary user roles:

- **Administrator:** In this role, the administrator would be setting trigger conditions verifying transactions and mining the processes**.**
- **General User:** It can view blockchain data and track the flow of products through the supply chain with the new transactions created by the general users (suppliers, distributors and consumers).

4.5.2 System Workflow

The system workflow is derived from the applied research strategy scenario. The inherent indicators (named KPIs) for SCM, while using the blockchain, were evaluated on the smart contract architecture. The input phase of the workflow examined data regarding general research questions formulated according to literature and case study method; the transform phase focused on specific research questions for each workflow phase from data input to contract execution.

The overall system workflow can be broken down into several stages: Then you calculate the proof of work, then you get the proof of work and you make a transaction, you validate the data, you put it in pending transactions, then you mine the block. There is a user-friendly interface for each stage of the transaction which communicates with the backend API to pass it. A detailed overview of each process is supplied below.

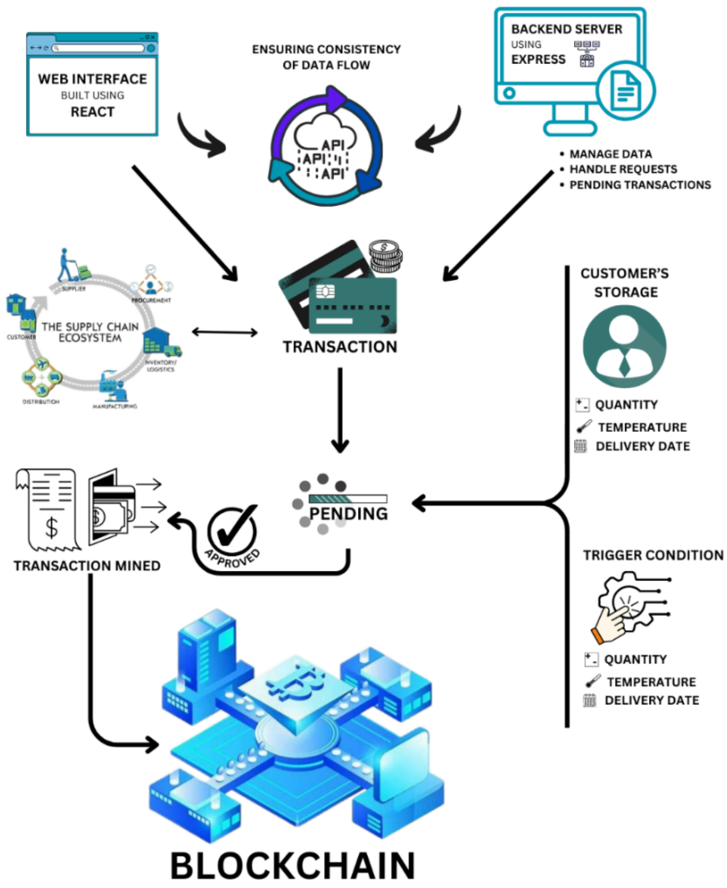

Figure 11. Workflow overview of a blockchain based supply chain system, depicting web interface – backend server interaction, transaction flow, and blockchain integration

Creating a Transaction

It all starts when a user starts a new transaction from the front end.

- **Input Form:** We provide an input form to our users to give us essential information which includes:

    i. Sender and recipient details

    ii. Quantity and product information

    iii. Requirements in terms of location and temperature

    iv. Delivery date

- **Form Submission:** Once we submit the form, the backend API goes through the transaction data. The backend will only add the transaction to pending list once all the fields are checked for the transaction and the only way the transaction will be added to pending list is when all checked.

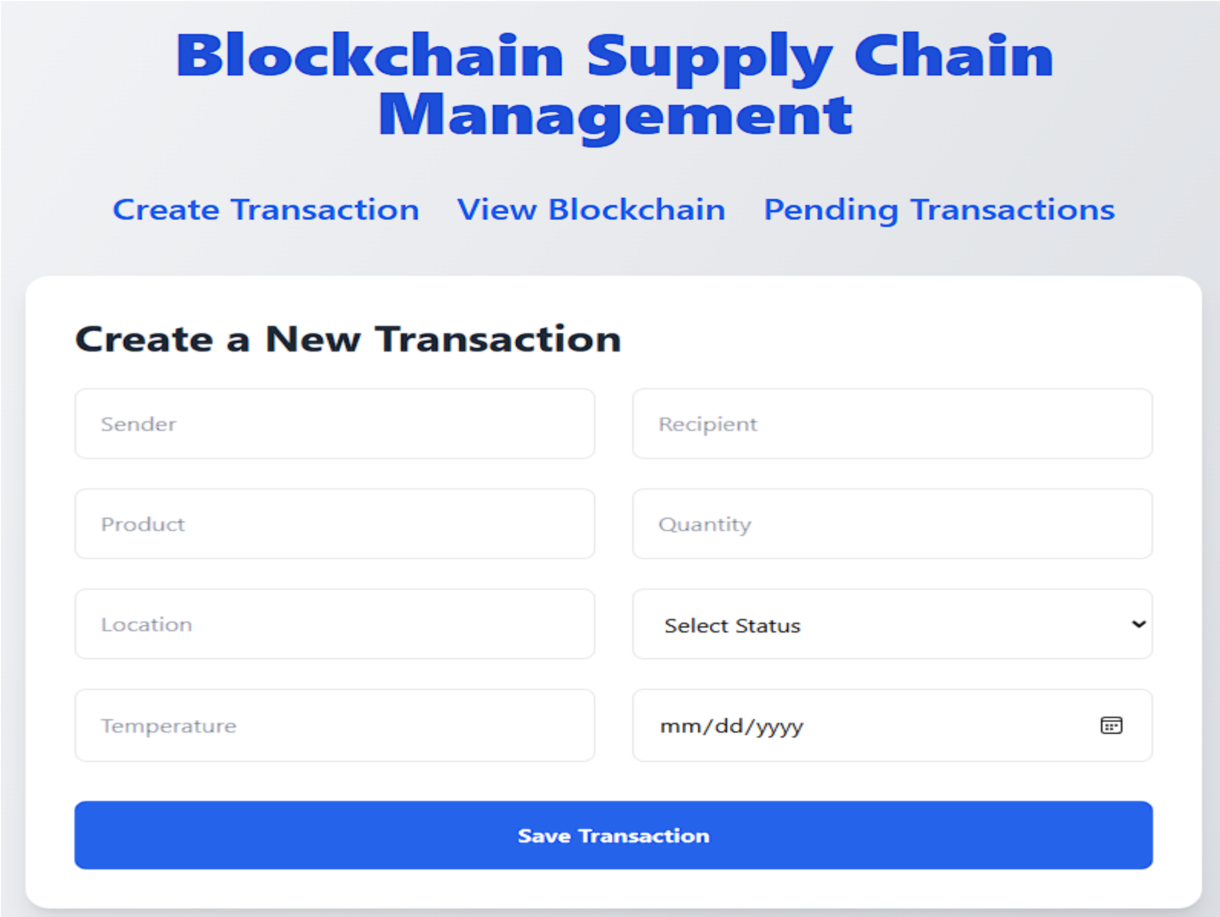

Figure 12. User interface of the blockchain supply chain management system, showcasing the transaction creation form and navigation options

Setting up Trigger Conditions (Administrator Action)

Administrators can set trigger conditions, such as:

- Quantity thresholds
- Temperature limits
- Delivery timelines

To validate these transactions, these conditions are stored in the administrator's interface. Any condition would flag this transaction as invalid.

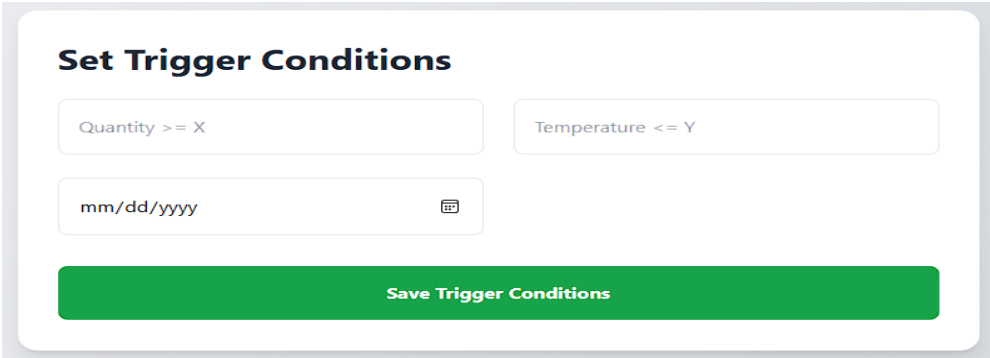

Figure 13. Interface for setting trigger conditions in the blockchain system, enabling automated transaction validation based on predefined thresholds like quantity, temperature, date

Viewing Pending Transactions

Users can likewise view the pending transactions. Administrators can:

- Edit transactions (modify details in the floating form, which appears at the center of the screen).
- Removes transactions from the pending list and database by deleting.

If, for exceptional reason, an incoming transaction is not allowed, then it is denied, and an error message in red text is shown.

Figure 14. Pending transactions interface showing detailed transaction attributes and management options within the blockchain-based supply chain system

Mining Blocks

Once the transactions are validated:

1. **Mining:** It begins from the administrator. The backend processes this request and the transactions are verified according to trigger conditions.

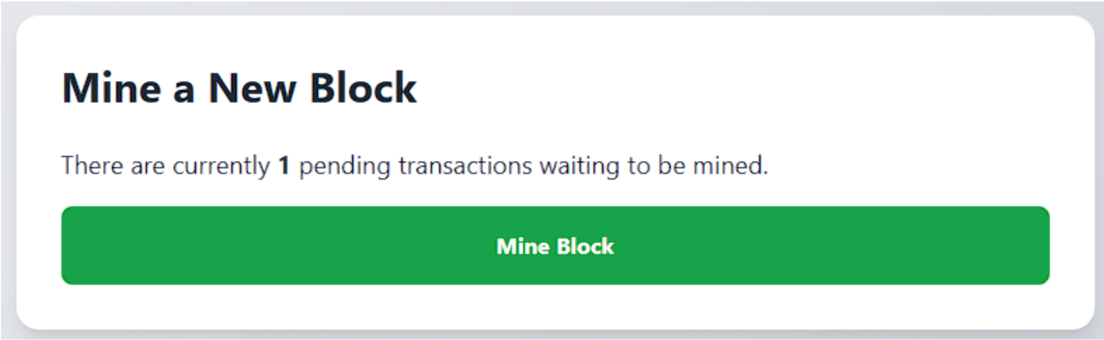

Figure 15. "Mine a New Block" interface enabling the validation and addition of pending transactions to the blockchain

2. **Validation:** Only valid transaction is added to the block.

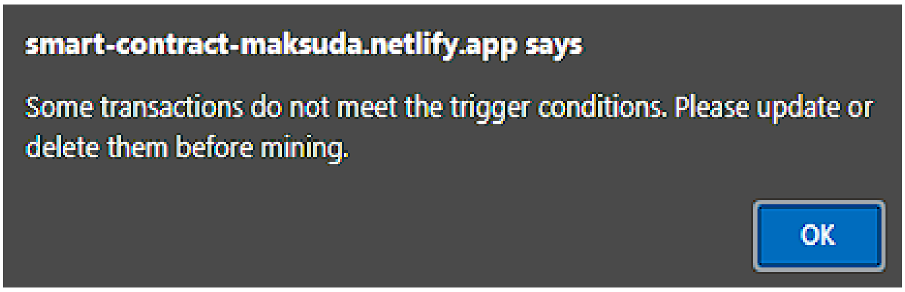

Figure 16. The warning message when Triggered Conditions are not validated

3. **Hashing and Addition**: The block is hashed, and the blockchain is updated with it.

Viewing the Blockchain

Visualization represents blocks as a sequence between them, as a sequence of information flow. The detail that is visible in this is each block has a time stamp, hash of previous block and the transaction data that it has included. This is a feature of added transparency and traceability via an API.

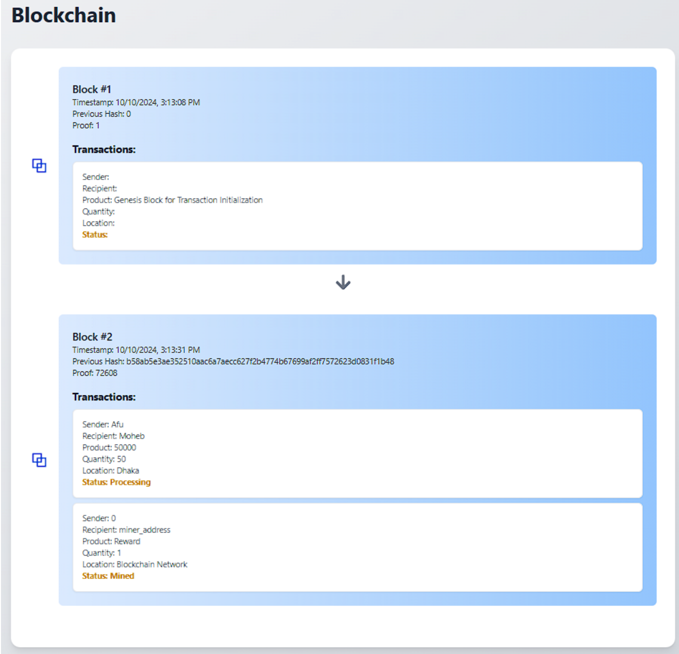

Figure 17. Blockchain interface displaying block metadata and transaction details, illustrating the sequential and immutable storage of information

4.5.3 Smart Contract Execution

Smart contracts automate specific actions, such as:

- **Payment Releases:** It is automatically triggered by successful delivery verification.
- **Compliance Verification:** For example, checking automatically if a product meets the compliance with the temperature conditions.

These contracts eliminate human intervention and, therefore, facilitate a quick and secure completion of actions in the supply chain (Christidis & Devetsikiotis, 2016).

5 Results and Findings

5.1 Analysis of Results

The data collected was gone through and analyzed for how effective the blockchain implementation was in achieving supply chain transparency, security and scalability. Key observations included:

Transaction Validation and Trigger Conditions: The administrative user trigger conditions set depended on transactions validity. These were the conditions that weren't met that got flagged and couldn't be mined until the conditions are updated to prevent errors or fraud entries (Saberi et al., 2019). Block shared with us a bit about how to layer blockchain based validation to add more confidence on other systems which typically have manual checks which are tricky to get right.

Mining and Data Immutability: When texts were verified, they were deposited on the blockchain to become a part of it through the mining process. The blockchain was now impenetrable as every block had the hash of the one before it. I tried to change some historical transactions and discovered the data was immutable, trying to change them would reset the block hashes and invalidate the blockchain (Zheng et al., 2018). Its characteristic of ensuring a time stamp and an immutable record is exactly the opposite of traditional databases in which data is altered or deleted and then there is no trace left, eliminating trust from the system.

User Interaction and Transparency: However, this system allowed the users to easily interact to the system from the web interface, with the real time feedback on the transactions made and also improving the page across systems since the system is almost completely scalable to any size of dataset. Users were able to see pending transactions and what each of them was doing (mining a block to funding a website, for example), and with that knowledge knew when to act. The solution blockchain provided was to solve the visibility problem on the information of supply system, because the traditional supply chain system cannot have the timing and completeness of the flow of information (Treiblmaier, 2018).

Scalability and Performance: The blockchain was populated with every transaction. Difficulty in proof of work and pending transactions at any one time influenced average time to mine a block. While the system could show the scalability of the growth of the blockchain, it actually showed the scalability of the system itself which has to be fixed before using it on a larger scale, but the performance issues have to be resolved (Zheng et al., 2018). However, traditional supply chain systems are not scalable as they have traditional centralized bottlenecks removing potential, however, the solution to being as decentralized with additional computation costs of mining.

5.2 Comparison with Traditional Supply Chain Systems

We can observe several key terms by comparing the Blockchain based system with the traditional supply chain system.

Data Integrity and Security: Today many of the current supply chain systems are dependent on systems whose database of information can be dicked and hacked. After data is in, no one can change it without affecting the entire chain — no unauthorized changes! (Casino et al., 2019b).

Manual Processes vs. Automation: Also, most of these systems suffer from manual processes of transaction validation, which are prone to error and costly in terms of time. A blockchain system using trigger condition for automatic transaction validation was implemented in this study to reduce error risk and increase system efficiency. Other than the cost savings, automation relies fewer on intermediaries as fewer intermediaries save more cost (Francisco & Swanson, 2018b).

Transparency and Trust: On the other hand, traditional supply chain system is unable to manage the stakeholders trust due to a lack of transparency. Once in a blockchain distributed ledger, the information will be available to all participants from the same entry eliminating the number of disputes (Saberi et al., 2019).

Scalability Challenges: On its face blockchain has a lot of upsides and in a way that's another thing. In order to not undermine fast transactions processing, although this is enough to make blockchain secure, we find that the act of implementing proof of work mechanism takes a toll on the scalability of the size of the blockchain. This is computationally less intensive and some of the centralization bottlenecks that have opened up have permitted the more traditional systems to be more effective at processing higher volume transactions.

5.3 Summary of Findings

The implementation demonstrates how blockchain can be applied to supply chain management in order to obtain practical benefits from it. Blockchain was used so that once these transactions were mined, they could not be changed and gave a high data integrity. First, security (Casino et al., 2019b) is one of the characteristics that make blockchain superior to the traditional centralized database. The administrative user had control over validation process, by the means of trigger conditions, i.e. transactions were recorded in the blockchain only if they were valid. This another level of trust, which is one of the important parts of traditional supply chain solutions.

Since the trigger conditions were met, transaction validation was automated which greatly reduced human intervention on the whole transaction process, minimizing errors, and shortening the time that the whole process takes compared to normal processing (Francisco & Swanson, 2018b). This enabled the system overall to run more smoothly, and ensured that data on the blockchain will always be accurate if entered.

As it should have, the blockchain expanded but optimization of the system would be needed if a higher number of transactions can be processed without losing efficiency, especially with the proof-of-work complexity. However, the area of research that this represents is still a key one to continue work on, as in particular to find a compromise between security and scalability (Zheng et al., 2018).

6 Discussion

The supply chain applied on the blockchain could show its ability to significantly increase its transparency, security, and efficiency. Besides being a decentralized ledger of a transaction and an automatic verification of the transaction according to 'trigger conditions', blockchain was at ease with the users without intermediaries. With the new supply chain systems they sent less orders, manually validating orders and sending to the manufacturers for validation, resulting in less errors compared to the old systems.

To manage one's supply chain with a blockchain one can, but the biggest difference on the other end is that everyone else doesn't have that underlying data integrity and security. On traditional system, it was feared by centralized databases under client data tampering hold and unauthorized modification. The reason why this happens because its distributed ledger has immutable and unchangeable data, it is very secured and trusted (Queiroz et al., 2019). Automated supply chain transactions, additionally, were automated with smart contracts in order to remove the manpower that would have been required in traditional systems. Automated such supply chain operations, reduced a risk that was related to human error, transaction cost, and enhanced the efficiency of supply chain operations (Grover et al., 2019; Christidis & Devetsikiotis, 2016).

There were some very cool implementation advantages and challenges inherent in implementation of the blockchain system. The biggest problem we can see with that tech was scalability. As Example Data that is less acceptable was produced from more proof work, and that data shows bottleneck on transaction processing time. And that is the main issue that is the problem to scale the system. The scaling alternatives like proof of stake (Zheng et al., 2018) exist. There is future research. However, the second problem is the energy consumption of the blockchain networks itself. Why the energy required is high in proof of work mechanisms, is because they are intrinsically computationally intensive (except for when using public blockchains). Furthermore, in case of supply chains embracing the blockchain technology to be used, they are going to be figuring out how to manage its effect on the environment with proof of stake (Saleh, 2021, Mougayar, 2016).

Our current implementation, however, has not scaled in terms of system usability and performance. Other consensus processes, such proof of stake, which are proven to scale better and have higher energy efficiency than proof of work, require more research. In light of this, Kathy Kamilaris (2019) proposes integrating artificial intelligence with blockchain to foresee and manage supply chain disruptions, resulting in a more resilient and adaptable supply network (Wang et al., 2021).

It lets us do some last-minute work on making the user more accessible. However, the current blockchain system does not offer sufficient ease of use for customizations; such as applications that require more degrees of ease in access to the blockchain and on the blocks themselves so that non-technical stakeholders can easily adopt the blockchain system (Chang et al., 2020). Although fixing the user interface would help, significantly improve adoption rate for the overall, it can skyrocket potentially for the smaller suppliers or small organizations that lack resources (Tapscott & Tapscott, 2018).

The advantages of blockchain-based supply chain management systems over conventional supply chain systems lies with their ability to observe the entire supply chain as transparent, ensure integrity of its data, and best of all; ensure an efficient supply of their data. The challenges with blockchain are real (scalability and energy consumption – not least), but blockchain has really potential and we can work blockchain and low carbon AI together (both are under assault by many). However, these limitations need to be overcome through future study and technological advancements to fully utilize blockchain technology's potential in supply chain management to be more scalable and sustainable.

7 Conclusion

The objectives of this study were to explore whether or not supply chain management could be restarted with blockchain technology. The Supply Chain system developed and implemented on basis of blockchain was so transparent, traceable and efficient during the operation. This research is about how blockchain's decentralized ledger and automating of the validation of transaction help solve the fundamental problems associated with traditional supply chain management like data integrity, transparency and dependence on centralized intermediaries.

The blockchain technology could offer a lot in terms of integrity and reliability of supply chain data, the study finds. Blockchain is a complete removing supply chain and automation of validation of information that is available for all to use it but only with a minute information, according to Blockchain. This is especially critical in many industries where high supply chain complexity has, historically, tended to engender inefficiencies, distrust, and conflict between stakeholders. It do the reduce error rate in the sys.

And it highlighted obstacles to a blockchain ethos; from prohibitively expensive scaling to the excessive energy expenditure. This consensus proof of work method has a great degree of security and scalability, but it also has a significant energy cost. To address the requirements of large-scale supply chain applications, we want to go over the aforementioned restriction and offer a blockchain solution that makes use of additional consensus techniques, such as proof of stake. Secondly, it shouldn't be forgotten that the use of blockchain can also affect the environment, so the future research should be sustainable.

Yet, the promise on Blockchain for supply chain management is huge. However, integrating Blockchain with artificial intelligence strengthens the supply chain even further by adding analytic prediction and adaptive management of disruption. It also makes the technology more usable and conducive for wider implementation of blockchain-based technologies in industries such as supplying goods, having side effects to other industries like small and medium enterprises that can be technologically illiterate.

Blockchain gives supply chain management a contemporary tool whose value should be harnessed to achieve increased efficiency in data consistency, security and usability. However, this paper shows that blockchain is the building block for a disruptive solution and AI can be the next piece of the puzzle. Future studies will focus on mitigating problems of scale for increased product sustainability and the enabling of user participation. Blockchain is changing almost every industry — from supply chains to if it continues to innovate; it’s increasing the transparency and security of the global supply chain.

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Appendices

Appendix 1. Implementation Details for Blockchain-Based Smart Contracts

This appendix provides consolidated technical details regarding implementation of blockchain based smart contracts for supply chain management. The frontend is built on React.js, backend on Express.js. A live deploy is found on Netlify. It's all publicly available source code on GitHub.

System Overview

- **Frontend:** React.js application with Tailwind CSS for styling, deployed on Netlify.
- **Backend:** Express.js server that manages blockchain and transaction logic.
- **Blockchain Model:** Custom implementation with transaction validation, mining, and proof-of-work using JSON for data persistence.
- **Live Website:** https://smart-contract-maksuda.netlify.app/

Github Repositories

- **Frontend:** https://github.com/maksuda81/smart-contract-frontend
- **Backend:** https://github.com/maksuda81/smart-contract-backend

Frontend Implementation

The frontend enables users to create, view, and validate transactions on the blockchain.

- **Keyfeatures:**
  - Create new transactions with details like sender, recipient, product, and conditions (e.g., temperature).
  - View the blockchain with mined blocks and associated transactions.
  - Validate and mine pending transactions into blocks.
  - Manage trigger conditions for transaction validation.
- **Folder Structure:**

  /public/

  index.html - Main HTML file for the application.

  /src/

components/ - Contains React components for forms, blockchain views, and modals.

App.js - Root component for routing and state management.

index.js - Entry point for the React application.

- **Key Code Snippest:**
- **Transaction Creation:**

```
const saveTransaction = async () => {
    const response = await axios.post(`${SERVER}/api/transactions/new`, newTransaction);
  setMessage(response.data.message);
  setNewTransaction({...defaultTransactionState}); // Reset form
  getPendingTransactions(); // Refresh pending transactions
 };
```

- **Blockchain Display:**

```
{blockchain.map((block, index) => (
 <div key={index}>
  <p>Block #{block.index}</p>
  <p>Timestamp: {new Date(block.timestamp).toLocaleString()}</p>
  <p>Proof: {block.proof}</p>
  <p>Transactions: {block.transactions.length}</p>
 </div>
))}
```

- **Reference**

- **React.js Documentation:** https://reactjs.org/docs
- **Tailwind CSS Documentation:** https://tailwindcss.com/docs

Backend Implementation
The backend is responsible for managing blockchain logic, transaction validation, and data persistence.

- **Key features:**
  - **Blockchain Model:** Includes transaction creation, mining, proof-of-work, and block hashing.
  - **REST API:** Handles requests for adding transactions, viewing the blockchain, and mining blocks.
  - **Data Persistence:** Stores blockchain and pending transactions in JSON files.
- **Folder Structure:**

  /controllers/

  blockchainController.js - Manages blockchain operations like mining and transaction validation.

  /models/

  Blockchain.js - Implements blockchain logic, including proof-of-work and hashing.

  /data/

  blockChainData.json - Stores the blockchain data persistently.

  supplyChainData.json - Stores pending transactions persistently.

  index.js - Main Express.js server entry point.
- **Key Code Snippest:**
  - **Transaction Creation:**

```
createTransaction(sender, recipient, product, quantity, location, status, temperature, deliveryDate) {
    this.pendingTransactions.push({sender, recipient, product, quantity, location, status, temperature, deliveryDate});
  this.savePendingTransactions(); // Save to JSON file
  return this.getLastBlock().index + 1; // Return block index
 }
```

- **Mining Blocks:**

```
createBlock(proof, previousHash) {
  const block = {
    index: this.chain.length + 1,
    timestamp: Date.now(),
    transactions: this.pendingTransactions,
    proof: proof,
    previous_hash: previousHash,
  };
  this.chain.push(block);
  this.pendingTransactions = []; // Clear pending transactions
  this.saveBlockchain(); // Save to JSON file
  return block;
}
```

- **Reference**
  - **Express.js Documentation:** https://expressjs.com
  - **Node.js Documentation:** https://nodejs.org

Blockchain and Supply Chain Example Data

- **Blockchain Data (blockChainData.json):**

```
[
  {
    "index": 1,
```

```
  "timestamp": 1690306600000,
  "transactions": [{"product": "Genesis Block for Transaction Initialization"}],
  "proof": 1,
  "previous_hash": "0"
},
{
  "index": 2,
  "timestamp": 1690324800000,
  "transactions": [
    {
      "sender": "Alice",
      "recipient": "Bob",
      "product": "Apples",
      "quantity": 50,
      "location": "Warehouse A",
      "status": "Completed",
      "temperature": "5",
      "deliveryDate": "2023-12-01"
    }
  ],
  "proof": 101,
  "previous_hash": "abcdef1234567890"
}
```

]

- **Supply Chain Data (supplyChainData.json):**


```
[
  {
    "sender": "Charlie",
    "recipient": "Diana",
    "product": "Oranges",
    "quantity": 100,
    "location": "Warehouse B",
    "status": "Pending",
    "temperature": "7",
    "deliveryDate": "2023-12-15"
  },
  {
    "sender": "Eve",
    "recipient": "Frank",
    "product": "Bananas",
    "quantity": 200,
    "location": "Warehouse C",
    "status": "Processing",
    "temperature": "10",
    "deliveryDate": "2023-12-10"
  }
```

]

System Workflow

- **Frontend Interaction**: The React.js interface is used to create and see transactions by users.
- **API Calls:** RESTful ends points towards the backend are used by frontend.
- **Blockchain Execution:** Proof of work is used for mining blocks, and transactions are validated.
- **Data Persistence:** There are JSON files to store blockchain and pending transactions.

Appendix 2. Structure of thesis

Cover page, abstract, table of contents
Introduction – An introduction to the research topic – Research objectives, research questions and scope – Why the project was justified and why it's relevant to the field. – Knowledge concepts introduced for clarity
Theoretical framework – Review of existing research, theories, and models relevant to the topic. – The overhead calculation key concepts and definitions. – How the theories/models applied actually relate to the research problem.
Empirical part – Description of the research problem, goal, and development task. – Methodology and Research approach. – Describe system design, implementation and data collection – Findings and analysis
Discussion – Critical review of the finding in connection to objectives and theoretical framework. – Reliability and Validity of findings are evaluated. – Ethical considerations – Plans for development or future research in particular.
Conclusion – Summary of key findings – Reflection on research limitations – Implications of the study
Reference – Comprehensive list of references following a consistent citation style
Appendices – Frontend and Backend Source Code Snippets. – Dataset (JSON Data) that is generated by user at the time of interacting with the Web App. – Repository Link and Live Link.