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Use of Blockchain-Based Smart Contracts in Logistics and Supply Chains

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Abstract: Blockchain is a disrupting technology that has the capability to completely alter the design, activities, and product flows in logistics and supply chain networks. It provides assurance of openness, immutability, transparency, security, and neutrality for all supply chain agents and stakeholders. In this paper, we explore the improvements and tradeoffs introduced by using blockchains in logistics management in terms of the sustainability of society, the environment, and economic dimensions of the supply chain. Blockchain technology makes it much more difficult to counterfeit products by providing indisputable and immutable proof of the provenance of the raw materials, products, and sale to the end consumer. This can potentially enhance the trust of the consumer in the product and financially benefit the manufacturer through the protection of their intellectual property rights. This paper explores the benefits, applications, and issues related to the usage of blockchain and smart contracts for logistics and supply-chain management. We focus on the implementation, deployment, audit, and operational aspects of smart contracts in the blockchain applied to terrestrial, maritime, and aerial logistics networks. The paper also discusses opportunities and challenges that arise due to the use of smart contracts in these sectors.

Keywords: blockchain; supply chain; logistics; internet of things

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1. Introduction

Global supply chains are incredibly intricate with many stakeholders, and several intermediaries and regulatory bodies [1]. The challenges faced in modern logistics and supply chains can be resolved through the use of blockchain technology [2]. Blockchain can support significant product and supply chain information through data collection, storage, and operations management. Blockchain technology can streamline the process and reduce the delays involved in a complex supply chain through two significant changes: driving efficiency and introducing new business models [3].

Blockchain can be utilized to keep track of the life cycle of a product and record the transfer of ownership. Modern supply chains are very intricate and are constituted by many levels of decision-making, regulatory bodies, intermediaries, and geographically separated goods and services providers. Moreover, the customers are also geographically spread out throughout the globe [4]. Different territories have varying regulatory policies, and the culture and the society of a distinct region also have an impact on how the operations are planned, managed, and performed. The uncertainty arising from these factors generates a risk that is very difficult to evaluate, assess, and mitigate. These uncertainties and associated risks also raise inefficiencies and increase the opportunities for malicious entities to defraud the legitimate actors and stakeholders that are part of the supply chain.

Consequently, the stakeholders lose mutual trust and are unwilling to share the information without verification and validation. The ability to trace the origin of a product is increasingly becoming an important feature of a product not only for the regulatory bodies but also for the end consumer. In fact, traceability can provide a competitive edge to the producers of high-value goods, such as pharmaceutical products, agricultural inputs, and anything that holds value for counterfeit producers.

The ability to ascertain the manufacturing time, place, and vendor of the product with high certitude is rewarding to both the customer and producer as it provides a guarantee of the quality of the product and the protection of intellectual property rights [5]. Paper-based receipts and certificates can easily be copied or modified by counterfeit agents but digital records protected by cryptographic techniques are secure and cannot be altered. Digital records provide security and restore trust among the intermediaries and primary stakeholders involved in a logistical supply chain.

For example, the loss of trust and financial damage to the respective enterprises caused by outbreaks, such as the Salmonella case related to papayas and E. Coli spread linked to Chipotle Mexican Grill could have been reduced if the customers were able to check the source of these products securely, so as to isolate the actual food product that was causing the disease outbreak.

Although blockchain is being hailed as a panacea for many problems in various domains, there are several organizational, behavioral, policy-related, and technological hurdles and barriers that exist in the implementation and adoption of this technology. The proposed research is focused on exploring the various issues regarding the implementation and application of blockchain to supply chain and overall logistical management framework [6].

Blockchain can be readily customized by choosing new protocols and rules for block generation, incentivization of nodes, consensus rules, cryptographic algorithms, and smart contracts. Multiple actors can participate in a blockchain without undue risk and with minimal trust. Depending upon the application, blockchain can either be public (permissioned) or private (non-permissioned). A private blockchain could be more suitable for a logistics management system as multiple parties know each other, and there is a certain level of trust present among the entities.

A smart contract could be crafted through an agreement and negotiations among the partners and stakeholders of the logistics supply-chain system, and this smart contract could be deployed on the blockchain to guarantee the terms of service required for smooth operations as per the agreed-upon level of the quality of service and product. A smart contract has the capability to automatically update the ledger if the code execution leads to a situation where all the terms of the contract are met by the participating actors.

Blockchain technology has its origins in the digital cryptocurrency introduced by Nakamoto in 2008. Since its inception, blockchain technology has grown tremendously in terms of its applications and underlying procedures. Blockchain is considered to be a revolutionary technology that could disrupt existing processes and facilitate the adoption of new standards and techniques in the organization, management, and operations of logistics supply chains.

Although the most popular implementation of blockchain, i.e., cryptocurrency systems, is open and public with a potentially unlimited number of nodes, the most popular interpretation for its use in supply chain networks is in the form of a permissioned network with a limited number of actors [7]. Limiting access to the blockchain mining process improves the throughput of the blockchain, which might be a requirement for time-sensitive operations in the supply chain network.

The supply chain is considered the most important pillar of a successful manufacturing business since the smooth flow of all commodities and their timely availability is central to the execution of all activities in a manufacturing concern. This is also the most complex activity in a business since it involves the coordination of all the teams with various functions working to complete the industrial process while incurring the minimum possible cost and achieving optimal efficiency. Traditionally, a supply chain is managed through centralized ledgers, e-mails, resource planning software, and excel sheets.

This classical methodology is inefficient and vulnerable and potentially hinders the seamless flow of commodities, limits visibility for decision-makers, and makes them susceptible to attacks. The reason for inefficiency and vulnerability is the centralized nature of the underlying databases that are used to store and retrieve business transactions and activities. These challenges have amplified for modern businesses that depend upon several intermediaries for both supply and distribution of the products with consumers and suppliers spread across the globe.

Moreover, the desire of the consumer to be more informed about the origin of the raw materials and the safety and sustainability of the manufacturing process has made it compulsory to introduce transparency and traceability to the supply chain and logistics for every meaningful manufacturing industry. Apart from the consumer, the traditional supply chain and logistics framework are also inefficient and prone to losses owing to the lack of information sharing between the various stakeholders of an enterprise and the participants, including suppliers and retailers.

In summary, most of the problems in supply chain and logistics today are owing to the lack of visibility of data and due to a lack of trust among the end users, manufacturers, and various intermediaries. Effective sharing of information with trustworthiness among the manufacturer, supplier, dealers, re-sellers, and consumers is critical to the efficient functioning, success, and welfare of all the participating entities. Moreover, the availability and maintenance of information are also vital to the efficient planning of production and logistics activities, demand forecasting, and inventory management.

Typically, this information is spread throughout the organization, and there is no universal ledger that contains the information about all the transactions being performed across different participants of the supply chain. This is particularly true for transactions that involve multiple organizations. Intermediaries are used as guarantors to complete and verify these transactions adding latency and overhead to the process.

The primary difference between conventional databases and blockchain-based data management is that, in the case of the latter, the data are immutable, distributed, and decentralized in nature. For example, for a conventional database, an administrator has the privilege to manipulate the data or control access to it. Furthermore, the centralized nature of the database makes it vulnerable to security threats.

In this paper, we consider the use cases of smart contracts in the domain of logistics and supply chains. Morever, we include discussions related to the advantages and disadvantages of smart contracts in logistics and the factors that influence their adoption in this area.

The rest of the paper is organized as follows. In the next section, we present some related work followed by some basics of blockchain and technical details about smart contracts. In Section 4, the use of smart contracts deployed on the blockchain is proposed for the supply chain and logistics sector. Section 5 presents the discussion and results, while our conclusions are drawn in Section 6.

2. Related Work

In this section, we discuss recent related works that also investigate the application of blockchain and smart contracts in the area of logistics and supply chain. Regarding the search criterion for literature review, we consider both the relevance to the topic of smart contracts and to its application to the general field of logistics and supply chain.

The authors in [8] discuss the application of blockchain in logistics by employing 'Roger's framework of innovation attributes'. The paper adopts a balanced approach by identifying the potential of blockchain and smart contracts as a disrupting technology for the logistics sector as well as outlines the limitations of the approach along with the expected impediments in its adoption.

The authors identify that blockchain offers a natural approach to the decentralized and immutable record of business transactions and agreements, which are the primary entities in a logistics network. The prospective adoption of blockchain in the logistics industry is given as a series of four gradual transformation phases, i.e., single-use, localization, substitution, and transformation. For all these transitions to occur, the authors anticipate that major social, political, and regulatory changes that need to happen.

The authors in the review article [9] emphasize the need to identify useful scenarios for the application of blockchain in the logistics industry that result in cost savings and increase the overall performance of the processes. Blockchain technology was found to be particularly beneficial to the transport of valuable goods whose origin tracing and quality guarantees could yield additional benefits so that it becomes more attractive and acceptable to the customer.

An interesting issue addressed in this article is about information privacy loss due to the placement of agreements or other sensitive data. This vulnerability can be partially addressed through the use of private blockchains. On the flip side, the transparency of information leads to process efficiency and increased trust among various agents in the supply chain. Performance issues can also arise if multiple parallel smart contracts need to be executed on the blockchain. For logistics-related applications, private permissioned blockchains are more suitable compared to public blockchains.

In [10], the authors advocate the adoption of the internet of things (IoT) for supply-chain management of assets in a logistics network. The authors also propose a smart logistics solution that employs smart contracts, logistics scheduling, and conditions monitoring for the management of the supply chain. A prototype of the solution is presented that demonstrates transparency, accountability, and audibility of managerial actions performed by various stakeholders.

The authors in [11] present a blockchain-based simulation of a hyperconnected logistics system to demonstrate that smart-contract-based tracking systems result in performance improvements and transparency as compared to the traditional approaches. One of the important findings of this work is that Ethereum-based solutions limit the transaction rate and, hence, are not scalable for real-world applications. Fortunately, other blockchain networks, such as ETH-IO can be scaled to millions of transactions per second.

The authors in [12] explored the use of blockchains and smart contracts in an extended supply chain network for finding and building collaborations without an established hierarchy. Their developed framework facilitates the interaction of stakeholders through a blockchain-based procurement and distribution unit. An algorithm for distributed verification and validation of smart contracts is also proposed and demonstrated through an Ethereum-based implementation.

A very comprehensive collection of challenges and their proposed solutions for smart contract design and deployment are compiled in [13]. In particular, the authors identify 29 challenges, 60 solutions, and 20 software design patterns for smart-contract-based systems. The proposed solution is considered for three different distributed ledger technologies, i.e., Ethereum, EOSIO, and Hyperledger Fabric.

In [4], the authors build a detailed stochastic simulation model between the manufacturer, wholesale retailer, and other objects and stakeholders in a typical supply-chain scenario to study the benefits of deploying blockchain-based information sharing in terms of a reduction in lead-time, reduction in inventory cost, and increase in average fill rate. The designed solution consists of a software connector that enables interfacing a company's information system with an Ethereum-based blockchain system. The authors demonstrate that information sharing leads to significant improvement in the overall efficiency of the supply chain network by providing trustworthy and reliable demand forecasts.

3. Blockchain Basics

Blockchain has been considered as a groundbreaking technology for the world of transportation and logistics. Maersk has partnered with International Business Machines (IBM) corporation for the application of blockchain technology for their maritime container transportation business. One of the hurdles faced in the implementation of blockchain is the questions surrounding its scalability and sustainability [14]. There is a great deal of recent activity about blockchain and its myriad applications and use cases in the literature, including various aspects of its impact on society, the environment, and the economy.

Blockchain technology consists of a distributed ledger of records or a database of all events that are either executed or shared by participating entities. Blockchain exhibits four properties that distinguish it from its peers:

- Decentralization.
- Security.
- Auditability.
- Smart execution.

On a higher level, a blockchain operates as follows.

- An agent that wishes to record an event, broadcasts a transaction to its peers on the network.
- After verification and audit of the received transaction by a majority of the peers on the network, the transaction is approved as per the agreed regulation followed by the actors on the blockchain.
- A record of the approved transaction is maintained by several peers to ensure the robustness of attacks and for improved reliability in the face of equipment or node failures.
- The transactions are typically grouped in the form of a block, which is tied to the previous block through a hash function of its contents, thus, creating a chain of dependence among the blocks and constituting linked records.
- An arbitrary contract could be deployed in the form of a set of instructions on each node of the network that executes autonomously once the prerequisite conditions are met.

Important characteristics include the immutability of the previous records, consensus protocols among the participating agents, and the security provided by advanced cryptographic protocols. Some of these properties of blockchain are shown in Figure 1.

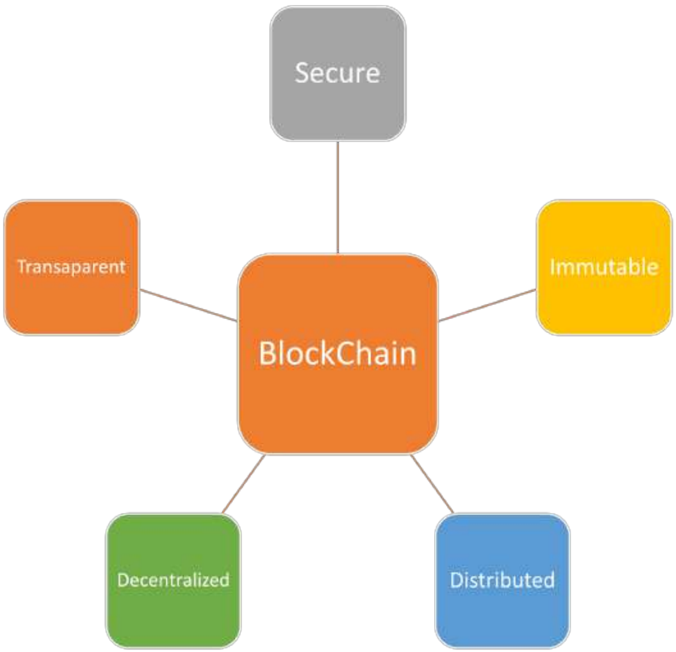

Figure 1. Characteristics of a blockchain system.

Figure 2 shows the interdependency of the blocks in the structure of a blockchain. Each block contains the hash computed from the contents of the previous block. In this way, each block depends upon all previous blocks. Any change in the previous blocks will propagate a change in the hash of the subsequent blocks.

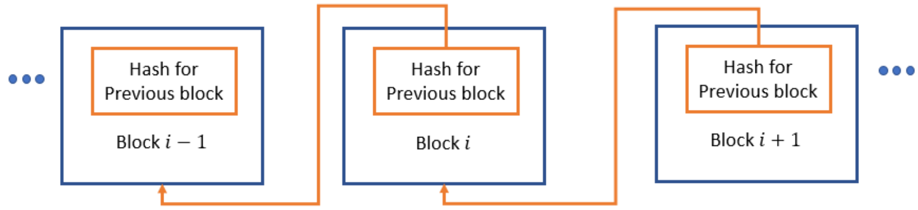

Figure 2. Structure of a blockchain demonstrating the dependency of each block on the previous one.

Similarly, the timestamp information recorded in the blocks ensures the auditability of the transactions. Multiple copies of the transactions distributed over a geographical region create an environment of mutual agreement, trust, and security for the recorded information among the nodes in the network. Decentralization and trustworthiness of the shared information are very important characteristics of a blockchain. Information is available publicly, and it is mutually agreed upon by the stakeholders. Moreover, it cannot be altered once consensus is formed. Blockchain simultaneously provides transparency as well as confidentiality through anonymity.

There are four major participants in a supply-chain-based blockchain network:

- Registrar: provides unique identifiers to all the entities.
- Standardization organizations: defines standards and devises policies for sustainable operation.
- Certifiers: provides certifications to the participating actors.
- Actors: the customers, retailers, and manufacturers.

Access to parts of records can be secured through digital signatures and public-key infrastructure schemes. The records on the blockchain could be about the status, origin, type, and standardization of the product. The product identifier on the blockchain is unique to the physical instance of a product. The transfer of ownership of the product might be governed by a smart contract to authenticate the negotiated requirements. Blockchain technology can emphasize product dimensions, such as the

- Product nature.
- Product quality.
- Product quantity.
- Location.
- Product ownership.

In this way, blockchain can remove the requirements of a centralized authority, and can lend transparency to the overall logistics operations starting from the raw materials, including production, and extending until the sale of the product to the end consumer. All this information is recorded along with timestamps and verifiable transactions. Thus, blockchain facilitates the logistics of materials and information through various stages of the blockchain [15]. This transparency and immutability enhance the trust of the customer in the product and lead to increased customer confidence and perceived value of the product.

4. Smart Contracts

Smart contracts are computer programs that execute automatically when predetermined conditions are satisfied. Smart contracts, by definition, are not necessarily based upon blockchain. However, the term is now used almost exclusively in the context of blockchain-enabled contracts. Smart contracts are computer programs that can be deployed by anyone but cannot be tampered with and are updated on a decentralized ledger maintained as part of a blockchain [16,17]. Smart contracts can contain arbitrary logic and can be used in various applications where the users, events, and other smart contracts can trigger their execution. The benefits and characteristics of a blockchain system are demonstrated in Figure 3.

Figure 3. Important characteristics of a smart contract deployed on a blockchain system.

Currently, the most commonly adopted platform for smart-contract deployment is Ethereum; however, other cryptocurrency blockchains (such as EOS, Polkadot, Tron, and Tezos) provide similar capabilities. The original thought behind smart contracts was to digitize and automate legal contracts [18].

Smart contracts can serve various purposes in a supply chain managed and maintained through a blockchain [19]. For instance, certifier and standardization bodies can verify the digital profiles of entities and products [20]. The digital profiles can be modified by the actors; however, they require subsequent approval from the registrar and certifiers on the network. The rules of the smart contract cannot be modified by individual trading partners, and this would require consensus by the majority of the actors or certifiers.

Similarly, a smart contract deployed on the blockchain can govern the process of procurement of a material or product from the supplier. Both partners provide information regarding the quality, quantity, and status of the product along with the timestamp and geographical location of the request and receipt. Smart contracts also make it possible to improve the efficiency of business processes through continuous quality assessment. The key-performance indicators could be ratified and recorded on the blockchain, and the smart contract can readily evaluate the indicators and check the improvement of quality relative to the historical record.

Thus, smart-contract-enabled blockchain promises solutions beyond simple delivery and governance issues. A key benefit of this approach is that it can remove the dependence on intermediaries for the verification of financial exchanges, such as payments, stocks, and money exchanges. Financial techniques, such as reverse factoring and dynamic discounting, could be implemented in a smart contract to further improve the efficiency of financial flows [21,22].

5. Smart Contracts and Blockchain Enabling Sustainable Supple Chains

Blockchains are databases shared and agreed upon by a community and are characterized by their distributed and transparent nature. An important recent direction of exploration regarding the use of blockchain in supply-chain management is the sustainability of supply-chain operations in the dimensions of society, the environment, and the economy [10]. An application of smart contracts to a supply-chain and logistics scenario is shown in Figure 4.

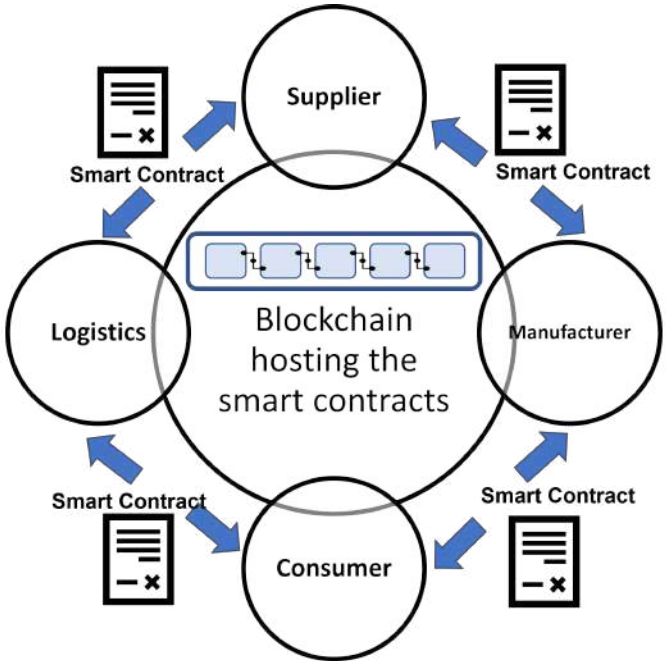

Figure 4. The use of smart contracts in logistics and supply chains.

Blockchain usage in the supply chain may lead to a better assurance of human rights and fair work practices [23,24]. For example, the history of a product recorded on the blockchain might provide assurance regarding its origin and its ethical soundness. Smart contracts can enforce the regulatory policies defined by the governing and standardization bodies [11,25].

Next, we explore the benefits of the blockchain framework and its associated technologies on the logistics and supply chain networks of different product and business categories. We consider the use of blockchain in networks that involve logistics over terrestrial, maritime, and aerial infrastructure [26,27]. The use of these technologies is coupled with various societal, behavioral, and organizational issues that require further research and exploration before these technologies can be deployed in a real-world system with stakeholders belonging to multiple echelons of decision-marking processes [28].

An important use of smart contracts and blockchain technology could be in the food and beverage industry. Using RFIDs and blockchain, a food supply chain can provide traceability of the products to their provenance and document their conduct of operations based on the rules specified by regulatory and governing bodies. Another sector that could benefit from the use of blockchain is the agriculture sector, which could prevent counterfeit and unethical suppliers from operating and restrict supplies to authorized entities.

Similarly, blockchain technology can benefit an organization by improving its economic and fiscal performance through the dis-intermediation and reduction of tiers in the bureaucratic processes. This could reduce the lead times for new products by minimizing human factors and transaction times. Blockchain ensures the safety, security, and reliability of the stored data, thus, enhancing the transparency for all stakeholders, including the governing bodies and the end consumer [29,30].

Currently, logistical supply chains are typically managed by an enterprise resource-management system that is centralized and operates within the confines of an organization [31]. All the stakeholders, which might belong to different organizations, have to rely on this single broker and trust the security as well as trust that they accurately follow of the negotiated and approved processes [32]. Another disadvantage of such a system is the centralized architecture that leads to a single point of failure and makes it vulnerable to external and internal threats and attacks [33].

Another emergent issue in logistics is to certify the sustainability of the overall supply chain in terms of environmental, social, and corporate viability [12]. Several issues and problems related to supply-chain management can be solved by using a decentralized system that is mutually trusted by all the stakeholders and that can prove the provenance of all the goods and services in an undeniable and resilient way. Blockchain technology is a candidate solution to all these problems [34]. Smart contracts can pay an essential role in the management of logistics and supply chains. They can remove hurdles posed by the traditional contract-based system by introducing anonymity, fairness, and traceability to the system [35,36].

One important use case is in managing the supply chain for the pharmaceutical industry. Many raw materials and products need to be checked for their origin and require the maintenance of safe transit conditions. A smart-contract-based system can provide provenance and traceability through various stages of the supply chain. IoT sensors and actuators connected to smart contracts can monitor and control the environmental conditions in transit [37].

This provides auditability and resolution of conflicts without involving an intermediary. As these details and conditions are stored on the blockchain, there is no chance of tampering or editing of the contract once it has been signed and executed by the participating entities. Once the transit conditions are verified and the origin of the materials is confirmed, payments are automatically performed by the smart contract.

6. Discussion and Results

The use of smart contracts deployed on a blockchain enables stakeholders in the logistics supply chain to help with the decentralized tracking of containers and individual goods, i.e., products, raw materials, and their transit. Blockchain solutions are very different from the traditional information systems that are typically deployed within the confines of an organization and provide a very centralized system for storing and managing supply-chain-related transactions.

Blockchain-based smart contracts offer a distributed, decentralized, and traceable system to record, evaluate, and execute transactions. Without involving intermediaries, smart contracts have the potential to reduce the processing and preparation involved in paper-based contracts, help with origin tracking, facilitate in identifying the origin of products, store data, and operate IoT devices on the blockchain. Some supply chains, for example, UbiMS [8] have already adopted blockchain to solve issues related to these conventional systems. UbiMS is a pioneer system that realizes three-dimensional supply-chain processing.

This system is able to interface many suppliers with a global consumer base completely revolutionizing the supply-chain-management process. Enterprises and corporations can access this cloud-based system to gain access to a global e-marketplace for the supply of goods and related communication. UbiMS is the first decentralized global system based upon blockchain technology that can completely alter the supply chain domain.

Since blockchain provides a reliable decentralized way to connect multiple entities with each other, the logistics sector is one of the prime candidates to benefit from this technology. Since blockchain can also interface easily with the internet of things (IoT), it can manage data generated by smart devices in a distributed and efficient way. These IoT devices could be location-based sensors, temperature and humidity sensors, and warehouse actuators installed on logistics and supply-chain infrastructure.

For an instance, Walmart is aiming to achieve last-mile logistics efficiency using a blockchain-based unmanned aerial vehicle (UAV) delivery network [8]. Furthermore, these IoT delivery devices connected to the blockchain are able to perform monetary transactions using cryptocurrencies. Through this feature, for example, they can gain priority access to corridors that require tolls and offer faster and safer passage between destinations.

In a recent paper [38], a blockchain-based radio frequency identification (RFID) traceability system for agricultural products was analyzed to determine its benefits and disadvantages. Such systems, when deployed vertically through a food supply chain, can provide greater surety of food safety by readily providing information related to the storage, origin, processing, distribution, and supplier in the blockchain.

IBM and Samsung have collaborated to mutually develop a platform named ADEPT, which is essentially a distributed internet of things that employs the basic principle of the blockchain network bitcoin. ADEPT uses other well-known protocols, such as Bit Torrent, TeleHash, and Ethereum. Bit Torrent is employed for distributed file sharing, TeleHash for secure peer-to-peer messaging, and the Ethereum blockchain for hosting smart contracts.

Blockchain transactions can be traced and are immutable. Blockchain uses a proof-of-work-based consensus protocol to build a chain of blocks that store information about transactions. Many enterprises in the food business are aspiring to establish a network of global suppliers, manufacturers, and retailers to generate an ecosystem that allows for indisputable traceability and safety assurance of their food products. For example, Walmart and Nestle are collaborating with IBM to employ blockchain to assure transparency, authenticity, and trustworthiness in the food supply chain and associated logistics. This is considered ground-breaking in achieving the dream of food safety and food security for the increasing global population.

Cloud-based blockchains provide a swift, easy, and flexible approach for the quick adoption and deployment of smart-contract-based solutions to an enterprise requiring supply-chain management. Global logistics and supply chain networks can see significant improvements in efficiency by adopting these blockchain-based solutions. In smart contracts, various stakeholders can pre-agree on the compensation and loss assigned to various parties based on contamination or spoilage of goods during transit, storage, or manufacturing.

The stakeholders can also pre-decide in the contract how contamination and spoilage will be assessed. Blockchain provides a unified view of all transactions taking place between multiple parties involved in the supply chain of a product. By adopting blockchain, all parties can achieve improvements in efficiency by reducing paper work, improve warehouse management, reduce delivery costs, reduce latency, make demand and supply predictions, and identify and resolve issues faster. This technology is expected to have a positive impact on the global gross domestic product (GDP) and total trade volume.

The logistics industry has mostly a positive regard for smart contracts and blockchain in terms of barriers and facilitators. However, logistics is a very traditional industry, and it is presumed that the initial adoption of blockchain technology might be slow due to this factor. A clear use-case development and the associated cost–benefit analysis over conventional information technology (IT) solutions must be performed carefully to convince the people working in logistics to adopt these new solutions.

Blockchain adds transparency to the supply chain by providing an option to perform a query related to a transaction. Moreover, there is no single point of failure, and the data are protected by state-of-the-art security and encryption techniques. Initial assessments lead to several benefits of blockchain, such as reduced paperwork, the identification of counterfeit products, help in tracking the origin of products, and easy interfacing with an IoT network. Several authors have found widespread support for blockchain-based smart contracts in the logistics industry, and various business processes can benefit from its adoption.

According to experts in the logistics domain, about 10% of bills of lading contain incorrect data due to human or printing errors, and these can lead to legal disputes. Blockchain can potentially accelerate the digitization of these bills and help improve efficiency in terms of reducing delays in resolving legal disputes. Smart contracts can enable digital transformation and improve business processes. As an example, we consider Shipchain, which is one of the pioneering adopters of blockchain in the maritime logistics industry.

Using blockchain, Shipchain can trace its product from the floor of the factory to the hands of the consumer. A digital cryptocurrency, called ship token, aids with process automation. Execution of a contract and monetary transactions take place on the Shipchain platform using ship tokens. In this business model, data and transactions are saved permanently on the blockchain, thus, providing transparency and traceability to all stakeholders. As with any program, the sequence of instructions in the smart contract is critical for the safe and correct execution of the smart contract. For example, a smart contract that involves payment to a party must first check the pre-conditions of the payment prior to processing the payment.

Blockchain and smart contracts are suitable for decentralized applications that involve problems that involve peer-to-peer transactions operating beyond the boundaries of trust. The contract conditions and individual transactions are visible and executed by all the full participants of the chain. The operation of the blockchain is autonomous and only guided by the rules and stipulations within the contract. Smart contracts are more effective when they are kept simple, auditable, and coherent.

Designing smart contracts such that they involve a single problem and involve minimum data access helps to achieve these objectives. One way to reduce storage for the blockchain is to split data into on-chain and off-chain components. Off-chain data can then be managed by higher-layer applications, while the state variable of the blockchain can store and process the on-chain part of the data. For example, if the smart chain involves a reference to a large legal document, it is recommended to keep only metadata on the chain and a secure hash of the contract.

Similar to many emerging technologies, smart contracts provide several opportunities but also face serious challenges. Blockchain-based systems may also experience threats and vulnerabilities. One common issue identified related to blockchain is the difficulty in scalability and the associated increase in the complexity of the transactions. Since all the nodes in the network have to process the new blocks onto the blockchain, the distributed architecture may not be easily scalable to the global user base in the logistics industry. This problem is particularly serious in proof-of-work-based consensus protocols, e.g., the protocol adopted by bitcoin.

A great deal of computing power and electrical energy is consumed in the process of verifying the transactions and minting coins when the transaction traffic scales. This problem is partially resolved by modern consensus protocol techniques that are more scalable. Another issue with blockchain-based smart contracts might be the issue of privacy. The data and contracts stored on the blockchain are accessible to every node, and all the stakeholders might not be comfortable in sharing their propriety data or even details of a transaction with third parties. This gives rise to serious skepticism about the adoption of blockchain-based smart contracts.

In our opinion, the way forward is to work on permissioned blockchains where only the nodes with the privilege to access a certain piece of information can store this data or access it in the unencrypted form. Another related challenge is that this technology is fairly young and it might take more research efforts to improve blockchain-based solutions to make them more flexible and secure. In short, the opportunities and challenges together make adoption exciting, and the pioneers in the field are already showing a competitive advantage by adopting and customizing the smart contract and blockchain technology according to their respective requirements.

Future regulation and refined consensus mechanisms will further improve the likelihood of universal adoption in various sectors, including logistics and supply chains. Some common blockchain technologies that allow smart-contract implementation are described in Table 1 along with their distinguishing features. Many recent implementations use an Ethereum-based blockchain wallet system to demonstrate the implementation of smart contracts.

Smart contract code is typically written in Solidarity language using a Remix integrated development environment (IDE). Solidity language is specifically designed to write smart contracts and has features derived from Javascript, Java, and C++. Solidity language can be compiled into a bytecode suitable for deployment on an Ethereum virtual machine. The format of a smart contract in Solidity is similar to that of a class definition in an object-oriented language. In other words, a smart contract has a constructor, and it can inherit functions and data from other smart contracts. A solidity function features parameters, visibility and access modifiers, and multiple return values. State changes are automatically returned by the function.

An Ethereum virtual machine is a 32-byte processor optimized for computations that involve integers, and it has a limited set of opcodes. Therefore, using integer arithmetic for computations as much as possible leads to a more efficient code. Remix is a just-in-time compiler commonly used for Solidity language and available with a web IDE.

The Remix environment is very helpful for the design, debugging, validation, and deployment of a smart contract. Remix static analysis warnings are helpful throughout the smart contract development cycle. Remix supports free run-time test environments, such as javascript virtual machines, injected web3, and web3 providers.

Table 1. Blockchain technologies for smart contracts.

Blockchain Technologies and Their Features	Ethereum	Hyperledger Fabric	Quorum
Programming language for smart contracts	Solidity	Golang	Solidity
Currency	Ether	No	No
Permission Mode	Public	Private	Private
Consensus Algorithm	Proof of Stake	Proof of Elapsed Time	RAFT
Developer	DAO	Linux	JP Morgan

As discussed earlier, smart contracts are programs on the blockchain that are executed automatically once the pre-defined conditions are met. If a contract (program) has a fault or vulnerabilities, it could lead to hazardous situations and cause loss of property and fiscal damages or otherwise result in loss of efficiency and subsequent failure of the overall system. In the case of supply-chain and logistics systems, this could result in delayed payments or repeated payments or accepting delivery of a product without first ensuring the agreed quality of the product.

Several formal verification and testing methods, e.g., formal theorem-proving tools, could be used to ascertain that the deployed contract is built according to the specifications of the application and that it is free of faults and vulnerabilities [39,40]. Some common vulnerabilities in smart contracts arise from variable overflow, integer representation, invariant issues, etc. Formal verification of a smart contract for credibility and accuracy using theorem-proving methods is based upon model and mathematical reasoning [41].

7. Conclusions

The logistics and manufacturing industry is always looking for ways to improve efficiency, reduce costs, and increase transparency in transactions. Blockchain technology is purported to be a disruptive technology that possesses the desirable traits of a decentralized record; is mutually trusted by participating peers, is immutable, scalable, secure, and robust; and does not require a centralized authority. Blockchain can help boost the efficiency of the supply-chain process by transforming the paper-based slow and error-prone processes into tamper-proof digital paperless processes. This reduces the burden on bureaucratic procedures while still satisfying the regulatory requirements agreed upon and fulfilled through a smart contract.

Automation helps reduce the number of stakeholders to the bare minimum and speeds up the process. For example, a particular supply-chain process might involve intermediaries and stakeholders, such as insurance companies, legal services, brokerages, and settlement services. Automating the processes makes them more lean, efficient, and robust to variations. We considered various ways in which a smart contract could improve the efficiency of a logistics system by providing financial gains as well as enhancing the trust of the consumer. We also discussed various implementation and security aspects related to smart contracts.

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References

1. Christodoulou, P.; Christodoulou, K.; Andreou, A. A Decentralized Application for Logistics: Using Blockchain in Real-World Applications. *Cyprus Rev.* **2018**, *30*, 181–193.
2. Issaoui, Y.; Khiat, A.; Bahnasse, A.; Ouajji, H. Smart Logistics: Blockchain trends and applications. *J. Ubiquitous Syst. Pervasive Netw.* **2020**, *12*, 9–15. [CrossRef]
3. Pournader, M.; Shi, Y.; Seuring, S.; Koh, S.L. Blockchain applications in supply chains, transport and logistics: A systematic review of the literature. *Int. J. Prod. Res.* **2020**, *58*, 2063–2081. [CrossRef]
4. Longo, F.; Nicoletti, L.; Padovano, A.; d'Atri, G.; Forte, M. Blockchain-Enabled Supply Chain: An Experimental Study. *Comput. Ind. Eng.* **2019**, *136*, 57–69. [CrossRef]
5. Wang, S.; Qu, X. Blockchain Applications in Shipping, Transportation, Logistics, and Supply Chain. In *Proceedings of the Smart Transportation Systems 2019*; Qu, X., Zhen, L., Howlett, R.J., Jain, L.C., Eds.; Springer: Singapore, 2019; pp. 225–231.
6. Álvarez Díaz, N.; Herrera-Joancomartí, J.; Caballero-Gil, P. Smart Contracts Based on Blockchain for Logistics Management. In Proceedings of the First International Conference on Internet of Things and Machine Learning, Liverpool, UK, 17–18 October 2017 ; Association for Computing Machinery: New York, NY, USA, 2017. [CrossRef]
7. Raja Santhi, A.; Muthuswamy, P. Influence of blockchain technology in manufacturing supply chain and logistics. *Logistics* **2022**, *6*, 15. [CrossRef]
8. Dobrovnik, M.; Herold, D.M.; Fürst, E.; Kummer, S. Blockchain for and in Logistics: What to Adopt and Where to Start. *Logistics* **2018**, *2*, 18. [CrossRef]
9. Berneis, M.; Bartsch, D.; Winkler, H. Applications of Blockchain Technology in Logistics and Supply Chain Management—Insights from a Systematic Literature Review. *Logistics* **2021**, *5*, 43. [CrossRef]
10. Arumugam, S.S.; Umashankar, V.; Narendra, N.C.; Badrinath, R.; Mujumdar, A.P.; Holler, J.; Hernandez, A. IOT enabled smart logistics using smart contracts. In Proceedings of the 2018 Eighth International Conference on Logistics, Informatics and Service Sciences (LISS), Toronto, ON, Canada, 3–6 August 2018; pp. 1–6.
11. Betti, Q.; Khoury, R.; Hallé, S.; Montreuil, B. Improving hyperconnected logistics with blockchains and smart contracts. *IT Prof.* **2019**, *21*, 25–32. [CrossRef]
12. Agrawal, T.K.; Angelis, J.; Khilji, W.A.; Kalaiarasan, R.; Wiktorsson, M. Demonstration of a blockchain-based framework using smart contracts for supply chain collaboration. *Int. J. Prod. Res.* **2023**, *61*, 1497–1516. [CrossRef]
13. Kannengießer, N.; Lins, S.; Sander, C.; Winter, K.; Frey, H.; Sunyaev, A. Challenges and common solutions in smart contract development. *IEEE Trans. Softw. Eng.* **2021**, *48*, 4291–4318. [CrossRef]
14. Patel, D.; Britto, B.; Sharma, S.; Gaikwad, K.; Dusing, Y.; Gupta, M. Carbon Credits on Blockchain. In Proceedings of the 2020 International Conference on Innovative Trends in Information Technology (ICITIIT), Kottayam, India, 13–14 February 2020; pp. 1–5. [CrossRef]
15. Li, H.; Han, D.; Tang, M. A Privacy-Preserving Storage Scheme for Logistics Data With Assistance of Blockchain. *IEEE Internet Things J.* **2022**, *9*, 4704–4720. [CrossRef]
16. Ante, L. Smart contracts on the blockchain—A bibliometric analysis and review. *Telemat. Inform.* **2021**, *57*, 101519. [CrossRef]
17. Szabo, N. Formalizing and securing relationships on public networks. *First Monday* **1997**, 2. [CrossRef]
18. Balcerzak, A.P.; Nica, E.; Rogalska, E.; Poliak, M.; KlieÅ¡tik, T.; Sabie, O.M. Blockchain Technology and Smart Contracts in Decentralized Governance Systems. *Adm. Sci.* **2022**, *12*, 96. [CrossRef]

19. Fiorentino, S.; Bartolucci, S. Blockchain-based smart contracts as new governance tools for the sharing economy. *Cities* **2021**, *117*, 103325. [CrossRef]
20. Kumar, A.; Abhishek, K.; Rukunuddin Ghalib, M.; Nerurkar, P.; Bhirud, S.; Alnumay, W.; Ananda Kumar, S.; Chatterjee, P.; Ghosh, U. Securing logistics system and supply chain using Blockchain. *Appl. Stoch. Model. Bus. Ind.* **2021**, *37*, 413–428.
21. Kumar, A.; Abhishek, K.; Nerurkar, P.; Ghalib, M.R.; Shankar, A.; Cheng, X. Secure smart contracts for cloud-based manufacturing using Ethereum blockchain. *Trans. Emerg. Telecommun. Technol.* **2022**, *33*, e4129. [CrossRef]
22. Zou, W.; Lo, D.; Kochhar, P.S.; Le, X.B.D.; Xia, X.; Feng, Y.; Chen, Z.; Xu, B. Smart contract development: Challenges and opportunities. *IEEE Trans. Softw. Eng.* **2019**, *47*, 2084–2106. [CrossRef]
23. Hasan, H.; AlHadhrami, E.; AlDhaheri, A.; Salah, K.; Jayaraman, R. Smart contract-based approach for efficient shipment management. *Comput. Ind. Eng.* **2019**, *136*, 149–159. [CrossRef]
24. Terzi, S.; Zacharaki, A.; Nizamis, A.; Votis, K.; Ioannidis, D.; Tzovaras, D.; Stamelos, I. Transforming the supply-chain management and industry logistics with blockchain smart contracts. In Proceedings of the 23rd Pan-Hellenic Conference on Informatics, Nicosia, Cyprus, 28–29 November 2019; pp. 9–14.
25. Ahmed, M.; Taconet, C.; Ould, M.; Chabridon, S.; Bouzeghoub, A. IoT Data Qualification for a Logistic Chain Traceability Smart Contract. *Sensors* **2021**, *21*, 2239. [CrossRef]
26. Modgil, S.; Sonwaney, V. Planning the application of blockchain technology in identification of counterfeit products: Sectorial prioritization. *IFAC-PapersOnLine* **2019**, *52*, 1–5. [CrossRef]
27. Philipp, R.; Prause, G.; Gerlitz, L. Blockchain and smart contracts for entrepreneurial collaboration in maritime supply chains. *Transp. Telecommun.* **2019**, *20*, 365–378. [CrossRef]
28. Baharmand, H.; Comes, T. Leveraging Partnerships with Logistics Service Providers in Humanitarian Supply Chains by Blockchain-based Smart Contracts. *IFAC-PapersOnLine* **2019**, *52*, 12–17. [CrossRef]
29. Prause, G. Smart Contracts for Smart Supply Chains. *IFAC-PapersOnLine* **2019**, *52*, 2501–2506. . [CrossRef]
30. Casado-Vara, R.; González-Briones, A.; Prieto, J.; Corchado, J.M. Smart contract for monitoring and control of logistics activities: Pharmaceutical utilities case study. In Proceedings of the The 13th International Conference on Soft Computing Models in Industrial and Environmental Applications, Salamanca, Spain, 5–7 September 2018; Springer: Berlin/Heidelberg, Germany, 2018; pp. 509–517.
31. Wang, S.; Ouyang, L.; Yuan, Y.; Ni, X.; Han, X.; Wang, F.Y. Blockchain-enabled smart contracts: Architecture, applications, and future trends. *IEEE Trans. Syst. Man Cybern. Syst.* **2019**, *49*, 2266–2277. [CrossRef]
32. Augusto, L.; Costa, R.; Ferreira, J.; Jardim-Gonçalves, R. An Application of Ethereum smart contracts and IoT to logistics. In Proceedings of the 2019 International Young Engineers Forum (YEF-ECE), Costa da Caparica, Portugal, 10 May 2019; pp. 1–7. [CrossRef]
33. Yuan, Y.; Xie, T. SVChecker: A deep learning-based system for smart contract vulnerability detection. In P*roceedings of the International Conference on Computer Application and Information Security (ICCAIS 2021)*; Lu, Y., Cheng, C., Eds.; International Society for Optics and Photonics, SPIE: Bellingham, WA, USA, 2022; Volume 12260, p. 122600W. [CrossRef]
34. Han, D.; Zhang, C.; Ping, J.; Yan, Z. Smart contract architecture for decentralized energy trading and management based on blockchains. *Energy* **2020**, *199*, 117417. [CrossRef]
35. Prause, G.; Boevsky, I. Smart contracts for smart rural supply chains. *Bulg. J. Agric. Sci.* **2019**, *25*, 454–463.
36. Chang, S.E.; Chen, Y.C.; Lu, M.F. Supply chain re-engineering using blockchain technology: A case of smart contract based tracking process. *Technol. Forecast. Soc. Chang.* **2019**, *144*, 1–11. [CrossRef]
37. Wang, S.; Tang, X.; Zhang, Y.; Chen, J. Auditable Protocols for Fair Payment and Physical Asset Delivery Based on Smart Contracts. *IEEE Access* **2019**, *7*, 109439–109453. [CrossRef]
38. Tian, F. An agri-food supply chain traceability system for China based on RFID & blockchain technology. In Proceedings of the 2016 13th International Conference on Service Systems and Service Management (ICSSSM), Kunming, China, 24–26 June 2016; pp. 1–6.
39. Krichen, M.; Lahami, M.; Al–Haija, Q.A. Formal Methods for the Verification of Smart Contracts: A Review. In Proceedings of the 2022 15th International Conference on Security of Information and Networks (SIN), Sousse, Tunisia, 11–13 November 2022; pp. 1–8. [CrossRef]
40. Liu, J.; Liu, Z. A survey on security verification of blockchain smart contracts. *IEEE Access* **2019**, *7*, 77894–77904. [CrossRef]
41. Sun, T.; Yu, W. A formal verification framework for security issues of blockchain smart contracts. *Electronics* **2020**, *9*, 255. [CrossRef]