Decentralized Information System for Supply Chain Management Using Blockchain

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Abstract
Development of international and domestic trade, globalization, creation of longer and more complex supply chains, increase in sales of goods and similar trends lead to an increase in requirements and load on information systems that manage and monitor the shipments of goods, resources and products. The aim of this paper is to make improvements to the existing approaches of building and designing logistics information systems. The paper proposes usage of blockchain technology in order to simplify and make more transparent the processes of monitoring and managing the movement of products between different equal participants in logistics supply chain information systems. A prototype of the supply chain information system based on the use of blockchain technology and smart-contracts using a decentralized Ethereum virtual machine was developed and studied in comparison with traditional approaches.

Keywords
Supply chain, blockchain, decentralized system, logistics, smart-contract, Ethereum, information system.

1. Introduction

Nowadays international trading is increasing significantly, and that means cooperation between different companies from all over the globe increases as well in order to create and develop new products and transfer them to final customers. Companies are moving shipments of goods and products between different continents, countries and companies around the whole world. These movements create a complicated process of product tracking and management, which a big number of different companies are involved in at the same time.

These logistics processes consist of many actions and transfers between suppliers and companies in different locations. And the more of them, the more complicated it becomes to manage supply chains and the overall process becomes less transparent for suppliers, customers and final consumers of products and goods as well.

The world is faced with supply chain crisis and many companies are struggling with optimization of the whole process of tracking and managing shipments [1], orders and product movements from one location to another one. Modern supply management information systems, which are used for this purpose, have a list of disadvantages they deal with.

The main problem is complicated communication between various participants in supply chain systems. These information systems are usually working only inside of one company, managing shipments and other logistic events only within their company only. When a company needs to receive goods and products from another company, it doesn't receive all the previous data and metadata about delivered items. Even if companies agree on sharing this information with each other without any

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automatization, here a technical problem comes with different data structures used in different companies and their adaptation for one of them. And this problem becomes even more complicated when there are more than 2-3 companies involved.

This problem could be solved by using one specific information system for the supply chain. But here the second problem comes, when this system becomes centralized, and the information system is fully controlled by one of the participants of the supply chain. This means one specific participant would have the whole access to the editing and deleting data from the database. In some cases, it's not acceptable for other participants of logistic processes because it gives too much power over the system to a participant or a mediator, which could not be trustworthy as well.

These problems cause a non-transparent and complicated process of interaction between different participants of supply chains in logistics. This leads to delays and difficulties in shipments management, product tracking and overall logistics. Final customers, in turn, can face insufficient or inaccurate information about the origin of products, the complexity of verification of origin and originality of goods. Also, such systems can face problems with analyzing their working processes and introducing innovations to the system.

In this paper in order to solve these problems, blockchain is proposed to be used in the development of supply chain information systems.

Blockchain is a distributed data structure that is replicated and distributed between network members. Every piece of data in a blockchain is wrapped inside a block and appended into the data structure as a separate transaction to it using cryptography mechanisms. Every new block consists of data itself and specific metadata, such as a hash of the previous block in the blockchain, which creates this chain, date of transaction, information about sender, etc. And special validators are verifying every transaction to the blockchain according to the validation method of the blockchain. After a transaction is validated, a new block is received by all the participants running the blockchain, which makes it distributed [2].

The first blockchain specification was proposed together with the digital currency Bitcoin in 2008 by a person under a pseudonym Satoshi Nakamoto to solve the problem of financial centralization around banks. Nowadays it's known as the most famous blockchain and digital currency in the world.

Today, blockchains are used mainly in the field of decentralized finance (DeFi) in the form of cryptocurrencies and instruments to them in the form of exchangers, auctions, exchanges. Also, in recent years blockchains are used for creating special "non-fungible tokens" (NFT) which are represented as a unique record into blockchain for proving ownership over digital and physical arts and items [3].

2. Related Works

In publications there are papers which review the possibility of blockchain usage in sustainable logistics and supply chain management.

According to the review of blockchain technology implementation in logistics paper, blockchain technology can improve logistics information systems via registering every single shipment item which is moving through the supply chain participants, that allows to track all the data related to supply chain items and any documents related to these items as well in unified way in information systems. Approaches which adopt blockchain technology could be used for passing several challenges which exist in modern supply chain information systems, such as, for example, delivery delays, documentation and items source loss, any kind of mistakes error and any other problem with logistics [4]. Magnus in his paper [5] researched production circles in the Norwegian fishing industry and how blockchain can affect on quality, speed and sustainability of the whole aquaculture industry, using blockchain for forecasting information, production planning, suppliers management, etc.

In the paper "An agri-food supply chain traceability system for China based on RFID & blockchain technology" [6] authors proposed a supply chain traceability system for food safety based on HACCP (Hazard Analysis Critical Control Point) and also discussed the advantages and disadvantages of RFID (Radio Frequency IDentification) for automatic collection and storage of information to improve information transparency and enhance food safety.

In the [7] authors also research a topic of combining blockchain technology with radio frequency identification in the meat producing & consuming industry. Using radio frequency identification helps to improve the level of automatization in supply chains, combining it with a blockchain which provides an efficient traceability system without the involvement of subjects who are external to the supply chain and who act as a trusted third party.

The review of the scientific literature and existing solutions shows the interest in blockchain technology not only in the field of decentralized finance, but in supply chains, logistics and sustainability as well. Applying these techniques can vary in different industries and depends on structure of management, shipments, quantity of participants, type of products, etc. Also, proposed systems are different in their implementations and use different types and structures of blockchains and other decentralized schemas. The final design and implementation depend on a specific problem which the information system should solve.

3. Proposed technique

The use of blockchain technologies in building modern information systems has become more popular. But many of these systems which rely on blockchain violate some core principles of Web3 approach. Web3 is a concept of the net of information systems which fully relies on a decentralized working process using a bunch of machines, not on a single server, and operates with a blockchain as a single source of data. Core principle of the Web3 concept is full decentralization of a system [8].

There are flaws in existing systems which are using blockchains, such as using private blockchains for managing data records about properties, tracking product movements in logistics and using them in finance and trading. For example, a NASDAQ LINQ platform which is designed as a private blockchain which stores information on current shareholdings, the prices of shares in investment rounds and information on available stock changes.

Private blockchains have the same problems as centralized data structures because this type of blockchain has an owner, who controls it within his organization. This approach could lead to unauthorized data changes and deletion despite using blockchain. In this case, usage of a private blockchain could create an illusion of safe and trustworthy storage, which could be exposed by desire of its owners.

Information systems which rely on open-accessed blockchain there is a common flaw when the system is not fully decentralized itself. It uses a blockchain as a part of the system, but it saves most of control over the system in the hands of one organization, which runs this information system despite being open.

In systems with a big number of participants with equal rights it’s important to save trust between each participant of the business process. That means the concept of Web3 could be used for designing this kind of information system.

In this paper it is proposed to use smart-contracts as a server itself which logic is executed directly on blockchain.

The information system for monitoring the movement of goods in this work is based on the specifications of the blockchain network Ethereum and Ethereum Virtual Machine (EVM). Also, a designed in this paper system could be implemented for working inside most of existing blockchains, such as NEAR, Cardano and others which support the execution of smart-contracts inside of their blockchains and state machines.

Ethereum is a single blockchain-based decentralized virtual machine platform based on smart contracts. That means, Ethereum is a blockchain network with the ability to program transaction behavior using code of smart contracts.

A smart contract is a program that is stored and executed in the blockchain. It allows to implement business logic with data stored on the blockchain using programming code. Each smart contract is assigned a 20-byte address, which is its unique identifier. For writing contracts in the Ethereum blockchain virtual machine uses the Solidity programming language, fully Turing complete language. That means smart-contracts could be used as a server for an information system for handling and manipulating data [9].

New entries in the blockchain and work with smart contracts are carried out through the creation and signing of transactions by members of the blockchain network.

To call a smart-contract for doing some business logic, it's required to create a transaction with the necessary parameters for the Ethereum network, such as "to" (address to which data is sent, for example some specific smart-contract), "gasPrice", "gasLimit" - a kind of "energy", ie commissions in Ether for transactions (it is used as a reward for validators who validate and add a transaction to the blockchain), "nonce" is current the transaction number from an account, "data" is the data within the transaction, "value" is the amount of Ether to send. Other blockchain systems could have different parameters inside transaction and data blocks inside blockchain, this means parameters needed for performing transactions in other networks can vary. A transaction with all needed data is signed with the cryptographic private key of the account holder and sent to the blockchain for the next processing. After validating, code of a smart-contract is executed with input parameters, which were set by the transaction creator. Blockchains also can vary on different consensus algorithms, such as Proof-of-Work, which requires members of a network to expend effort solving arbitrary mathematical tasks in order to validate transactions for adding new blocks to blockchain and defend the network from illegal data adding, Proof-of-Stake, which allow network members to validate block transactions based on the number of coins they as a validator stakes in the network, Proof-of-Authority, where there are chosen members who can validate transactions etc. [10].

There are many different consensus mechanisms used in various blockchain networks. For example, Bitcoin and Ethereum use Proof-of-Work mechanism, but Ethereum is going to change it to Proof-of-Stake in the future. Proof-of-Stake is used by suck networks such as Cardano and NEAR.

The main disadvantage of the Proof-of-Work mechanism is that it's not ecologically friendly. This method consumes much of the electricity of network members, producing a huge amount of heat instead. Other mechanisms, such as Proof-of-Stake are counted as more eco-friendly for usage in information systems [11].

In order to develop an information system for supply chains that can interact with different entities, an agreed specification is also needed, according to which each member of the logistics network will know what features and actions are available to them and how to properly access smart contracts which are used as a server. The classic approach for designing logistics information systems include several independent servers which belong to each company for managing their information system for logistics operations. In this case, companies share information with each other about logistics transactions to provide all the needed information as it's shown on Figure 1. This paper investigates a prototype of a simple logistics system based on blockchain and fully decentralized, without using any third-party mediators and central servers for any actions. The supply chain system has four different roles which are used in most logistics systems – manufacturer, supplier, transporter and distributor as it's shown on Figure 2. The approach from Figure 1 has several disadvantages in the comparison with the approach from Figure 2 such as extra complexity in data sharing between participants, lack of trust between participant without a way of verifying data.

Supplier creates a resource and transfers its ownership to the manufacturer which needs the resource for creating a good. The manufacturer creates its product using the resource, after that the manufacturer transfers ownership over the product to the distributor. The resource and the product are physically transported between supplier, manufacturer and distributing via transport companies tied to resources and products. Every physical movement of the products and resources are tracked by the blockchain as ownership and transport companies changes as well. All this logic is executed by smart-contracts inside of blockchain data structure, without the need in the central operator server.

Each participant of the supply chain inside of the logistics information system described in this paper is represented as an Ethereum-account (wallet) with its own address, to which and from which goods will be moved inside the system. Each smart contract also has its own address on the network to which transactions are sent to execute the code and add new data to the blockchain.

Important note is that the data model with all data fields for each item stored in the blockchain should be specified and agreed on with all supply chain participants. It's a specification which participants rely on for communication with each other within the decentralized system.

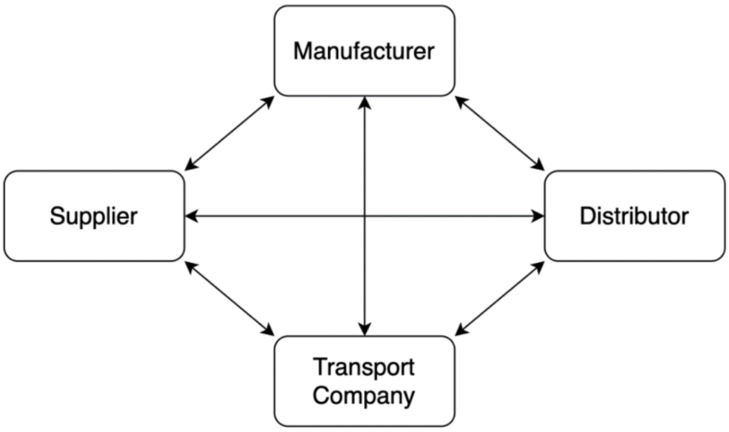

Figure 1: Scheme of classical approach in data sharing between participant in logistics information systems

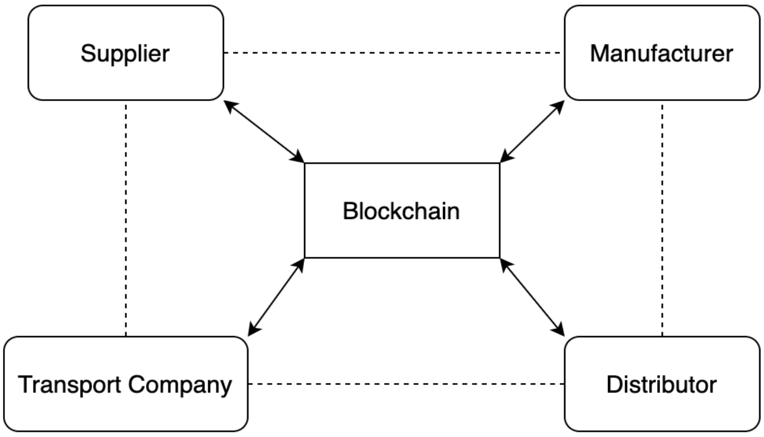

Figure 2: Scheme of data sharing approach with participants in logistics information systems using blockchain

In this paper data models are resources and products. Resource data model consists of its supplier Ethereum-address, serial number, title and creation date. Product data model consists of its manufacturer Ethereum-address, serial number, title, creation date and additionally a blockchain hash of a resource used for manufacturing this product. This last parameter will also help to fetch and track resources info used for creating a product during working with product assets in the blockchain. Proposed data models could be different for various information systems and should be specified by participants for more accurate usage.

The system described in this paper consists of two smart-contracts, one for managing products and another for managing movements. The smart-contract for managing products (ProductManager) has hashmaps for storing information about registered resources and products in the blockchain. Suppliers and manufacturers are able to register their resources and products via calling dmethods of this smart-contract. This action adds information about these items to the blockchain.

The second smart-contract for managing movements (MovementManager) has hashmap arrays for storing information about owners of resources and products (separate hashmap for each type), their transport companies tied to them and history of locations. After registering a product in the first smart-contract, the manufacturer should add his ownership rights to it. After that the manufacturer is able to transfer ownership rights to the next participant (distributor in the example) and define a transport company which will transport it. The transport company can change location history for the product or resource. Every action also supports callback events for informing participants about movements in the supply chain.

The ProductManager smart-contract which is responsible for registering resources and products in the blockchain described in this paper has the following signatures and interfaces:

- products() function, it takes the productHash and returns the product data with the manufacturer's data, serial number, product type and date of manufacture (manufacturer, serial_number, product_type, creation_date);
- resource() function, it takes resHash, and returns the resource data with information about the manufacturer, serial number, resource type and date of manufacture (manufacturer, serial_number, res_type, creation_date);
- registerRes() function, it takes the structure of the part (serial_number, res_type, creation_date), and registers the resource in the blockchain;
- registerProduct() function, it takes the structure of the product together with a resource for manufacturing (serial_number, product_type, creation_date, resource), and registers the product in the blockchain.

The MovementManager smart-contract has more complicated structure, if the ProductManager is only responsible for registering resources and products, the MovementManager smart-contract is responsible for managing ownership rights over resources and products, also it tracks location changes of goods and transport companies responsible for transportation of certain products and resources. This smart-contract has the following signatures and interfaces:

- currentResOwner() function, it takes resource hash, and returns the blockchain address of the resource owner in the blockchain;
- currentProductOwner() function, it takes product hash, and returns the blockchain address of the product owner in the blockchain;
- The constructor of the smart-contract, it takes the blockchain address of the ProductManager smart-contract used for checking the existence of products and resources before changing their owners;
- addOwnership() function, which accepts the type and hash of a resource or product, adds the original owner to the product or resource if the owner has not previously registered for this item;
- changeOwnership() function, it takes the type and hash of a part or resource, performs a change of owner to a product or resource, can only be performed by the current owner;
- Callback functions (event listeners) TransferResOwnership() and TransferProductOwnership(), which is performed when the owner of a resource/product changes, and notifies participants of the supply chain about this event with a hash of the resource/product;
- currentResourceTransporter() function, it takes resource hash, and returns the blockchain address of the resource transport company in the blockchain responsible for transportations;
- currentProductTransporter() function, it takes product hash, and returns the blockchain address of the product transport company in the blockchain responsible for transportations;
- addTransporter() and changeTransporter() functions, which take item’s type and hash, and transport company for assigning it for transportations;
- addLocation() function, which takes resource/product hash, place, transport company ,date and coordinates for managing location changes for goods;
- Callback functions (event listeners) TransferPartTransporter() and TransferProductTransporter(), which is performed when the transport companies for product/resource are changed for notifying the supply chain participants;
- ChangeLocation callback function (event listener), which is performed when the location of product/resource is refreshed and for notifying the supply chain participants.

Certain functions inside of smart-contracts are allowed only to specific participants. This logic and checks are written inside of smart-contracts methods, which are called by participants, and cannot be overcome with well-designed smart-contracts without backdoors. That means, in the system nobody will be able to register first ownership over the product except for its manufacturer, which is written inside the blockchain during first registering in the system. Nobody can transform ownership rights over the product to another participant except for the current owner of the product or resource.

Also, only the current owner can appoint a transport company for the product for its delivery. And only the current transport company is able to change locations of their items. All history of these actions is also stored inside of blockchain, without an ability to overwrite or delete it, for example, for the illegal benefit of one of the participants. In combination with well-designed smart-contracts, which allow certain actions only for the responsible parties, it creates a well-organized and trustworthy information system for managing supply chains.

The sequence scheme of ownership rights changes for resources and products within the logistics system on blockchain described in this paper is shown on Figure 3. Every step with full information on this scheme is recorded into the blockchain as well.

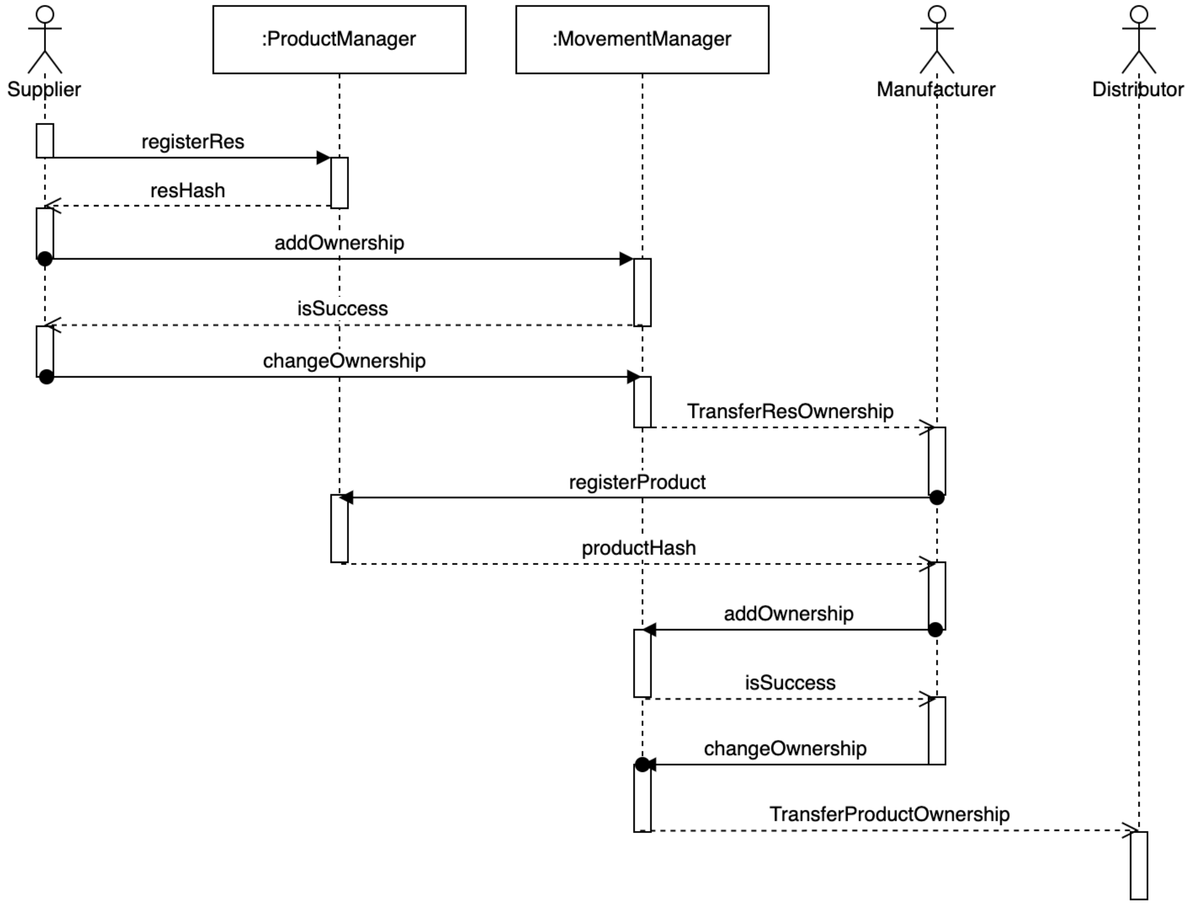

Figure 3: Sequence diagram of ownership rights changes for resources and products within supply chain system on blockchain

The supply chain system described in this paper is responsible for handling both ownership rights and physical transporting and location changes of resources and products. In order to transfer a product or resource physically from one participant to another, manufacturer or current owner of the item should assign a transport company responsible for transportation (also, manufacturer could be a transporter of the products itself as well, if it's required by the system) and this transport company is able to inform and make records in the blockchain about new physical location of items. Final destination receives updates about these location changes.

Inside of smart-contracts suppliers or manufacturers are responsible for setting transportation companies and assigning them to the specific resources or products. Assigned transporter is able to add new locations for products and resources. This action is also notified to other members. The scheme of transporting items is shown on Figure 4.

That's the way how a fully decentralized supply chain information system described in this paper is able to handle tasks about both transferring ownership rights between different equal participants of the supply chain and physical shipments between these participants from one location to another by assigned transport companies with the support of transit locations for products and resource as well.

Supposed blockchain database and state machine is going to be open and fully distributed across multiple machines. This kind of systems is designed to be fully trustworthy among multiple users, where transactions couldn't be fabricated due to decentralization where there is no one specific person or organization which could edit or delete data in illegal way and making new records into blockchain is backed with cryptography. Private blockchains don't fulfil this requirement due to the strong centralization of blockchain network inside one organization, what can lead to possible manipulations with data inside blockchain without proper mode examination and control. Benefits of using blockchains in this situation is questionable.

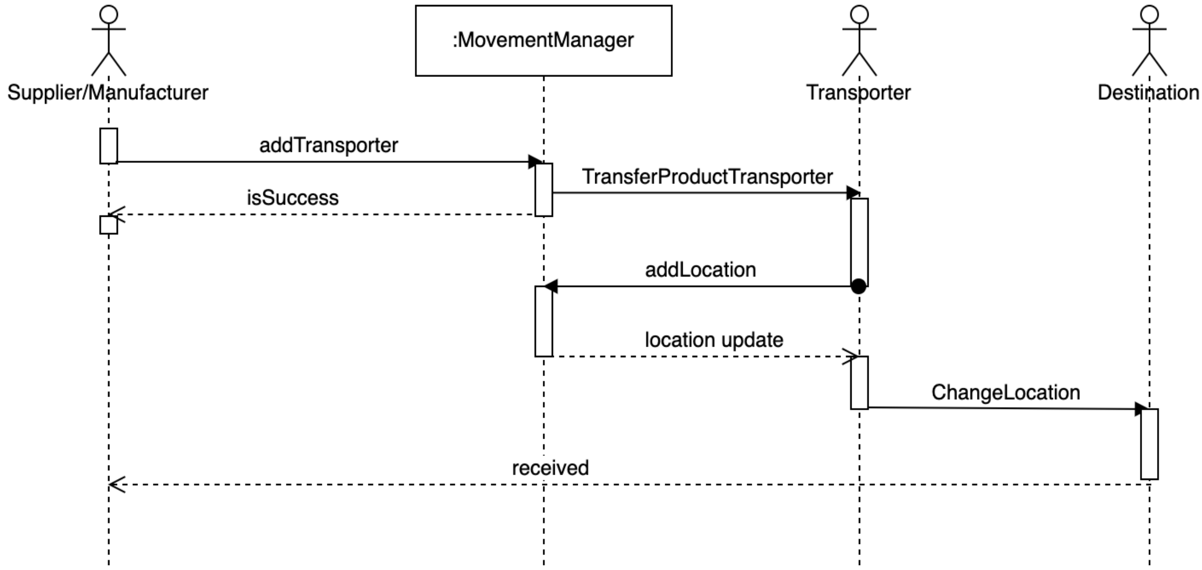

Figure 4: Sequence diagram of transportations of resources and products within supply chain system on blockchain

Usage of partly-open blockchain still needs additional studies. This kind of systems can be built as a trustworthy information system, where the blockchain is controlled by and only by all participants of the supply chain. In this case blockchain is held by all the participants without any third-party users, as it is on open public blockchains. This approach can ensure truthfulness among of all supply chain nodes without participation of other network members. It could be useful in situations, when it's important to manipulate with information with restricted access, which should be available only to participants of the network without sharing it with other people, organizations and companies outside of the information system.

Described in this paper, the system is fully decentralized, which means it doesn't use a central server and doesn't belong to one particular owner who can manipulate data without proper permissions. The system is designed and built with use of blockchain technology, using a mechanism of smart-contracts which play a role of software responsible for all business logic.

4. Results and Discussions

In this paper the simple fully decentralized logistics supply chain information system based on blockchain technology without any central server was described. Similar supply chain system could be built using a traditional approach using a central server with a relational database. But in a deeper comparison a supply chain information system based on blockchain could have several benefits over traditional approach.

On Figure 5 transactions for creating & setting owner for resource could be seen. These transactions add this data into blockchain for future storing and management.

On Figure 6 it could be seen the location for the resource is applied and current owner is moved to another address in the blockchain for further supply chain manipulations in the information system.

These transactions are performed via using Ethereum protocol using blockchain wallets which are belong to information system participant. Smart contracts within the information system based on blockchain create an interface which can be applied and used with user-friendly interfaces, including web-sites, mobile app, robotics connected to the Internet and etc. All records are saved to the blockchain, they are non-editable and non-deletable, they could be verified via smart contracts functions within the information system.

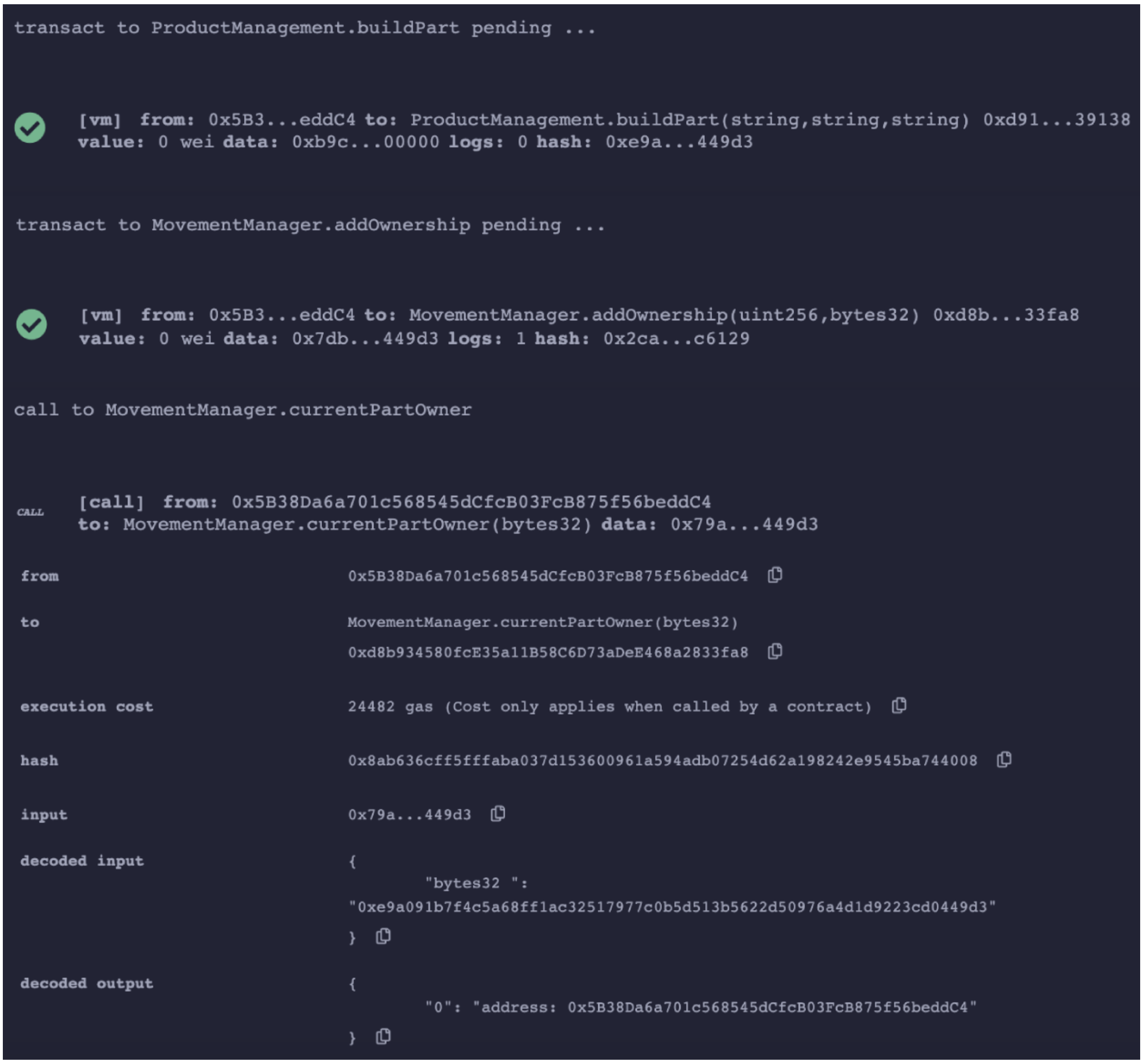

Figure 5: Experiment with creating a resource and applying ownership for it in logistics information system prototype with blockchain

Using developed smart contracts, we can access to the history of locations with all the needed meta-data of specific resources and products which is stored inside of blockchain and can be retrieved, as it's shown on Figure 7. The proposed approach for building a logistics information system using blockchain is decentralized and doesn't belong to any particular authority or chain participant, which could have any kind of not allowed benefits from owning this kind of system in order to change or delete information illegally. This could play a huge role for systems where it's important to keep equality between all participants of the system for providing a trustworthy environment.

This system also could simplify tracking of data flow about movements of products due to using blockchain data structure, which save data sequentially in the chain of data blocks, with ability to implement business logic on a transaction applied to blockchain using smart-contracts, which are compiled hosted on the blockchain itself as well with an ability to fire events of certain action on blockchain. Also, the supply chain information system based on blockchain benefits on reliability in comparison with a central server approach. An information system based on a central server could be shut down due to many reasons, such as problems with electricity, Internet-connection, such events as fires, earthquakes, etc. These events could interfere with the work process of the system which can lead to operation delays which are able to take a significant amount of time to fix.

Decentralized system doesn't operate with one machine or a cluster of machines and could resume operation when there are active nodes which serve blockchain. If there are many nodes, there is a very small possibility of shutting down the blockchain system. But there are a few cons of using a decentralized supply chain information system on blockchain in comparison with a classical centralized server solution. To begin with, not all types of blockchains will suit the supply chain information system. Proof-of-Work blockchains are not ecologically healthy due to consuming much electricity and generating heat, which doesn't correlate with sustainable development ideas. Also, this type of blockchains need to pay extra commissions for every transaction, which can lead to extra expenses on making the information system work. If a logistics supply chain information system requires a lot of transactions for proper work, it would become too expensive for most possible clients and participants of the system in the blockchain network with big prices for transactions, which are often found in networks which are based on Proof-of-Work, such as Bitcoin. Ethereum is also a Proof-of-Work blockchain network, but it's on the road of migration to another consensus mechanism.

Also, there are programmable blockchains with smart-contract support which don't have these problems, blockchains with different consensus mechanisms, such as Proof-of-Stake, Proof-of-Authority and others which could be used for building supply chain information systems. It could be studied in the future to see which consensus mechanism suits logistics systems better.

In the case of a centralized system, it's only required to maintain and pay for a single server or a bunch of centralized servers tied to one cluster.

The next note is blockchains are divided to 3 groups by their availability to members and third-party groups of people: open public blockchains, where all the data and transactions inside them are available to everybody and can be checked, private blockchains, where all the records of the database are available only to one particular organization which hosts this blockchain system and partly-open blockchains, where blockchain records are accessed by particular number of participants among each other without fully publicity. The most trustfulness information system for supply chains with multiple independent participants can be designed with using open public blockchains, as it was described in this paper. Private blockchain can negate the benefits of blockchain due to trust issues to blockchain-holder from other participants of the network. What's about part-open blockchains, they can be an option in situations, when some data inside of blockchain which is used by supply chain participants should have access restrictions. This kind of blockchains usage in logistics information systems needs to be studied in the next papers and future studies.

The other con of the fully decentralized system based on blockchain is a problem of software upgrading, applying updates to smart-contracts for modifying business logic and possible bug fixes. The thing is once a smart-contract deployed to blockchain, it could not be reverted or changed. It can create certain difficulties in possible software upgrades and bug fixes of the information system. These actions would require new smart-contract deployments on blockchain and getting new network addresses for communication with it. In many cases it can create several problems and delays in the working process of information systems and updating of smart-contracts addresses could lead to lack of trust in the system in some cases. This con will be analyzed in the future studies of information systems based on blockchain. The centralized information system in its turn, doesn't have this kind of problems, its software could be upgraded by the main administrator of the server in a short term without a need to change endpoints which are used for communication with the system.

1. Conclusion

In this paper a fully decentralized logistics supply chain information system based on blockchain and smart-contracts was described and prototyped.

The intermediate results of the prototype of the information system based on the blockchain of the Ethereum virtual machine with Solidity smart-contracts usage, designed to manage a simple supply chain, were obtained. It was analyzed and studied in comparison with traditional centralized information systems for supply chains.

It is concluded that the transparency of the tracking, trustworthy and automation process in the supply chain has been improved. But also, there are several cons facing the decentralized system, such as the software upgrading problem and the right choice of type and consensus algorithm for the blockchain network on which the system will operate. These problems could lead to slow adoption of new technologies and approaches based on blockchain in information systems or even the impossibility of its adoption. These problems and possible ways of handling them will be studied in the following works. This work is useful for designing and creating more detailed and sophisticated information systems in a decentralized way using blockchain technology for monitoring and managing the shipments of resources, goods and products and other supplies with the participation of a large number of participants of logistics supply chain processes.

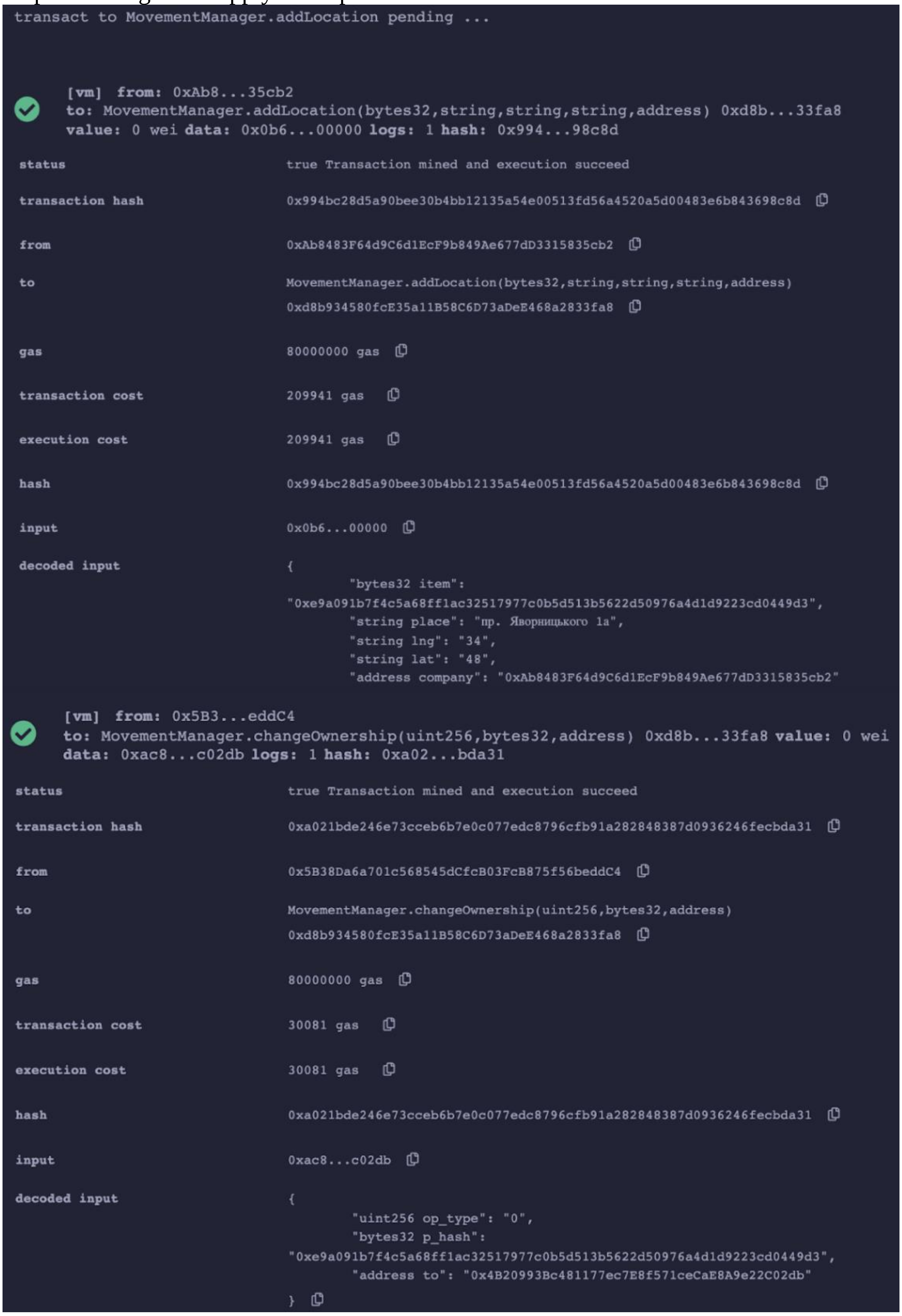

Figure 6: Applying location and moving resource ownership to the next participant of the logistics information system

Figure 7: Retrieving location history for the specific resource via its hash inside of blockchain in the logistics information system

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