Enhanced Vendor-managed Inventory through Blockchain

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***Abstract*—Vendor-managed inventory (VMI) is a commonly used collaborative inventory management policy in which manufacturers/vendors manage the inventory of retailers and take responsibility for making decisions related to the timing and extent of inventory replenishment. Several prerequisites exist for successfully implementing a VMI strategy like information sharing, trust, systems integration and long-term collaboration. However, in nowadays supply chain networks are becoming more complex, highly disjointed and geographically spread. As a consequence, the implementation of a VMI strategy may be a difficult task. In this paper, we propose a new interaction mechanism between retailers and vendors, which aims to improve their supply chain strategy and inventory policies based on a trustless and distributed mechanism. In particular, we use an autonomous trustless framework based on smart contracts and blockchain technology for governing the relationship between multiple vendors and multiple retailers. Finally, a use-case VMI scenario is presented along with several functional smart contracts. Tests performed using a local private blockchain illustrate the applicability of the proposed architecture along with the significant benefits for each participant.**

Keywords*—Vendor Management Inventory, Supply Chain management, Blockchain, Smart Contracts

I. Introduction

Vendor-managed inventory (VMI) is a very common supply chain (SC) management approach for improving multi-firm SC performance while establishing a mutual beneficial relationship between a vendor and a retailer. The main idea behind VMI is that the vendor is authorized to oversee product inventory for the retailer, therefore, the vendor is responsible for tracking, monitoring and replenishing the retailer's agreed-upon inventory. VMI is a streamlined approach to inventory management and order fulfillment in which both the retailer and the vendor may smoothly and accurately control the availability and flow of goods across the SC. VMI was first introduced as a fundamental element in the partnership between Wal-Mart and Procter & Gamble and since then has been widely adopted by many industries. VMI is considered an example of virtual integration across the SC in which no merge is required like in vertical integration [1].

The adoption of VMI approaches may have significant benefits for all the participants within a SC network (retailers, vendors etc) [2]. For vendors, VMI offers the necessary visibility for better demand forecasting and, therefore, more accurate inventory management. For retailers, VMI provides a more efficient framework for order processing while reducing operating and administrative costs. From a sales perspective, VMI may increase sales by ensuring that products are always in stock and also may act as an enabler for increased inventory turn over. VMI may also provide upstream SC members with significant benefits. For instance, manufacturers are able to predict more accurately how much to produce (based on actual retailer sales data) and, therefore, achieve more accurate ordering and fulfillment. For the overall SC VMI offers reduced inventory overstocks and stock shortages, stronger retailer relationships and improved end-customer experience.

Although VMI has become a widely used tool for SC performance improvement, not all VMI implementations are successful. Several challenges and prerequisites exist for successfully implementing a VMI model. In Figure 1 a comparative analysis is provided at both strategic and operational level regarding key prerequisites for successfully implementing a benefiting VMI approach [3]–[6]. Of particular interest are SC complexity and the difficulty in information sharing and opportunistic behavior among key SC participants (which participant will reap the most benefits from VMI implementation). Other important challenges for VMI implementation may relate to security issues attributed to systems integration (lack of effective data management with increased level of protection of sensitive customer's information) and inherent costs involved in managing SC intermediaries and relevant VMI processes.

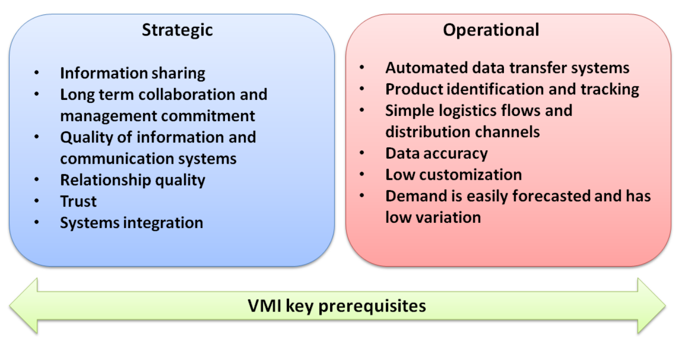

Figure 1. Key prerequisites and success factors for VMI implementation.

A. *Motivation and contribution*

VMI-related literature within the SC domain is abundant [7], [8]. However, several barriers/limitations related to its successful implementation, as described above, still exist.

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Moreover, VMI implementation has been so far seen through the lens of operations management perspective whereas issues of trust, visibility and security across SC networks have been poorly studied. In addition, very few publications study the use of blockchain in VMI applications [9], [10]. It is worth noting that both studies take into account a single pair of SC participants (a buyer and a vendor), whereas real-life VMI applications require multiple buyers to interact with multiple vendors.

The paper addresses the aforementioned gaps in the literature and further extends the approach presented in [10] by providing a distributed trustless and secure architecture for VMI implementation based on blockchain technology. In particular, an autonomous and effective back-end data sharing architecture based on smart contracts and blockchain technology for governing the relationship between vendors and buyers is used. A use-case VMI scenario is presented illustrating the applicability of the proposed architecture along with the significant benefits for each participant. Finally, some limitations of the developed architecture are discussed and several fruitful areas for future research are proposed.

B. Structure of the paper

The rest of the paper is organized as follows. In Section II we provide an overview of blockchain technology, Internet of Things (IoT) applications, and their interface with SC management. In Section III, we briefly review the available VMI literature and its main characteristics. In Section IV, the proposed blockchain-enabled VMI architecture is presented and we detail our proof of concept implementation. Then, in Section V we discuss a possible application scenario. The paper ends in Section VI with some concluding remarks.

II. Background

The convergence of various disruptive technologies such as IoT, artificial intelligence and blockchain are characterizing the Fourth Industrial Revolution. Such technologies transform modern SC networks into complete digital ecosystems, and they also bring together business solutions that are inclusive, trustworthy, interconnected and sustainable [11], [12]. In the sequence, two disruptive technologies currently transforming the way SC operate, namely IoT and blockchain technologies, are presented.

A. Blockchain technology

Blockchain is mainly a distributed append-only time-stamped data structure where non-trusting members can interact with each other in a verifiable manner without the need of a trusted authority [13]. Therefore, blockchain, as a data structure, is an ordered list of blocks containing and storing transactions in a distributed manner through consensus mechanisms. Blockchain is resistant to any data modification (immutability) which means that all information registered cannot be altered or modified. According to the literature [14], there are three types of blockchain networks: a) public blockchains, b) private blockchains and c) consortium blockchains.

A relatively recent aspect of the blockchain technology is the notion of smart contracts [15] (with a full Turing complete Language) which provide the ability to perform computations within the blockchain, thus operating as a decentralized virtual machine. In essence, smart contracts are actual programs written in specific programming languages, e.g. Script in Bitcoin or Solidity in Ethereum. Smart contracts can be considered agreements between mutually distrusting participants, which are automatically enforced by the consensus mechanism of the blockchain without relying on a trusted third party.

Blockchain technology is set to revolutionize SC management in several ways [14]. The aforementioned features of blockchain and smart contracts could be extensively used for solving several problems in SC management. For instance, blockchain-enabled applications will enhance traceability in SC operations, particularly in safety-sensitive sectors like pharmaceuticals and food supply [16], [17]. Significant benefits from the adoption of blockchain-enabled applications in SC management may relate to cost reduction, sustainability and risk management [18]. In general, blockchain technology will enhance SC management by providing transparency, auditability, integrity, authenticity, security and privacy among other features. Moreover, blockchain-enabled SC architectures coupled with IoT will improve communication and selective export of data, offering several additional benefits to the logistics sector regarding data management and data analytics [19], [20].

B. Internet of Things (IoT)

The revolution of IoT is reshaping modern SC networks with far-reaching implications and promising business prospects. IoT is considered a possible disruptive technology in the field of logistics and SC management because it bridges the gap among miscellaneous features of modern SC networks such as the complexity of big data, massive amounts of information, the concurrency of operation and application, and real-time services [21]. IoT-enabled architectures can connect any item through the Internet, thus facilitating the exchange of information among numerous devices [22]. From a technical standpoint, IoT is based on key technologies like RFID (Radio Frequency Identification), WSN (Wireless Sensor Network), cloud computing, IPv6, nanotechnology, GPS, laser scanners and other information sensing devices and intelligent embedded technologies [23]. Most IoT architectures are made up of three layers, perception layer, network layer and application layer [24]. IoT-based application systems have been widely used in several industrial settings. During the last decade, IoT applications have been extensively used for locating, identifying, monitoring and tracking products and/or services across the entire SC [25]. Such systems may capture real-time information for monitoring and recording purposes related to logistics processes such as production, transportation, warehouse management and customer service.

III. Literature review

VMI-related literature is abundant within the SC domain [1], [7], [8], [26]–[28] and various VMI-related frameworks have been developed across a wide variety of sectors, like automotive industry [29], groceries industry [30], healthcare [31] and e-commerce [32]. Several studies address issues of critical success factors and their importance for actually implementing VMI strategies [3]–[6] along with the value of information

[33] and information exchange [34] in VMI implementation. VMI in SC literature has been used for optimizing market strategies within SC networks [35], for reducing the bullwhip effect [36], for measuring performance [37], for establishing better pricing strategies [38], [39], for managing backorders [40], for better retailer services provision [41] and, finally, for improving environmental performance [42]. Some authors have also used VMI as a driver for suppliers' selection [43] and better SC coordination [44]. An important aspect of VMI strategy relates to determining the significant benefits the various SC members enjoy for actually implementing VMI strategies [45], particularly in terms of cost [46], [47] and inventory reduction [48]. Various decision support systems have also been developed related to VMI implementation [49], [50].

Very few publications study the use of blockchain in VMI applications. For example, in [9] a blockchain-based approach is applied for defining the requirements and information flows of a VMI system. In [10], a new interaction framework based on smart contracts and blockchain for governing the relationship between a vendor and a buyer is proposed. A use-case VMI scenario is presented along with a functional smart contract. It is worth noting that both studies take into account a single pair of SC participants (a buyer and a vendor), whereas real-life VMI applications include multiple buyers to interact with multiple vendors. Based on the limitations described above, this paper proposes a blockchain-enabled framework for VMI implementation in which multiple vendors interact with multiple buyers through functional smart contracts.

IV. Our Framework

Among the main limitations for successfully implementing a VMI strategy, we should highlight the opportunistic behavior of the various SC stakeholders. The main impediment lies on the fact that the retailer has higher benefits than the vendor, particularly in terms of cost reduction. Such an affirmation is based on the fact that a VMI partnership implies that the vendor will take over the inventory responsibility and decide how much inventory the next member downstream the SC should maintain. The power of decision gives the vendor the responsibility of assuming the cost involved with risks of shortages or overstocking. This concept is one that vendors are concerned with, and it represents a primary reason why they avoid entering such a VMI partnership [8]. Nevertheless, VMI encourages information sharing and allows an upstream supplier to access demand information and make replenishment decisions for the retailer. Such decisions are based on agreed upon limits of inventories at the retailer location, which guarantee that the retailer service levels are maintained [1].

In this context, blockchain enables a full set of features and configurations to enhance VMI. Moreover, smart contracts and IoT technologies provide a secure and verifiable replenishment policy, which helps to avoid typical problems of VMI such as the bullwhip effect [51], delays, traceability, quality assurance issues and above all orders cost allocation. In addition, transparent communication between vendor and retailer enhances client satisfaction, quality of service and efficiency in SC operations. Another underlying benefit is that information stored in the blockchain may be studied with machine learning and data analytics, thus offering additional benefits. Taking into consideration the aforementioned prerequisites, we propose a novel multiple-vendors-to-multiple-retailers blockchain-based VMI architecture.

Figure 2 shows the overview of the VMI-based process. The main actors of the system are the following:

- **Vendors:** Act as inventory managers and can propose replacement orders as well as deploy smart contracts in the blockchain.
- **Retailers:** Place orders and let vendors manage their resources. They establish interactions with the rest of actors via blockchain and smart contracts.
- **Distributors:** Provide quality delivery according to some parameters (established in the smart contract or defined by quality policies). In addition, they can interact with blockchain to update information about products. For safeguarding the quality of the transported products, IoT technologies may be used (for example, monitoring temperature and continuous tracking of the location of the products).

We assume that each actor has its pair of keys and access to the corresponding transactions, depending on their role. In this regard, each function/operation implemented in the smart contract will be accessed by the required actor verifiably and securely.

Therefore, a standard procedure in the case of direct vendor-retailer connection is described as follows:

1) The inventory of a retailer is updated by means of internal management or by means of a vendor. Therefore, the retailer may rely on off-chain storage such as the InterPlanetary File System (IPFS) [52] to enable scalability, while having backups of the inventory in a local database.
2) The vendor checks the inventory of the retailer via blockchain or directly accessing the local retailer repository (according to predefined permissions, depending on the VMI model). These options are compatible with the retailer requesting an order to the vendor, as in traditional VMI scenarios.
3) The vendor determines the needs of the retailer and deploys a smart contract with a new order to refill the retailer, according to specific conditions, periods and additional information. Other participants (declared in the smart contract) such as distributors may participate with specific permissions to update and change the status of products.
4) The retailer checks the smart contract's contents and accepts it, confirming the order.
5) The products are distributed to the retailer. The status of the products (e.g. location, transportation conditions, delivery times, temperatures) will be updated throughout the SC to keep track of events and relevant processes.

The transaction is completed when the products reach their final destination and are verified by the retailer. The conditions of the smart contract can be adapted to be compliant with some directives, and thus, efficient and on-site auditability may be provided. For instance, in the case of food supply, risk management systems that identify, evaluate, and control hazards related to food safety could be easily embedded within the smart contract.

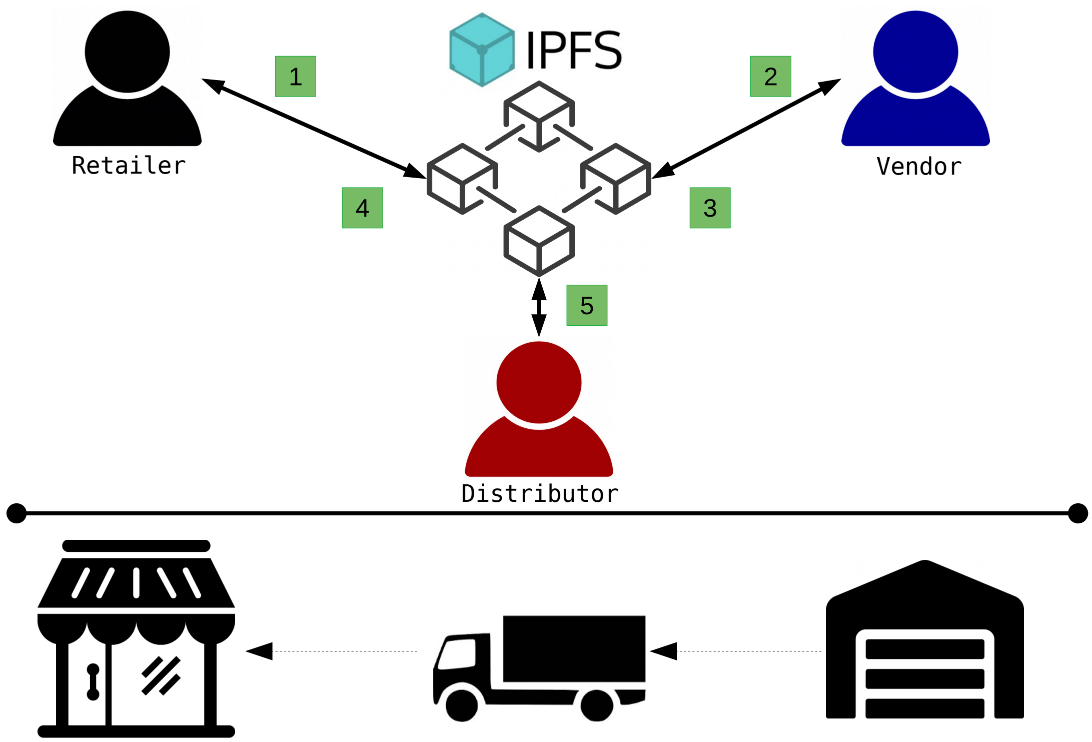

Figure 2. Blockchain-based VMI overview. The digital transactions are represented above (managed through smart contracts and off-chain storage), whilst the physical SC operations are depicted below.

A. *Integration Details*

To showcase the efficacy of the proposed architecture, we provide experiments using a local private blockchain to show the feasibility of the proposed architecture. More concretely, we have created an ethereum-based blockchain using `node`[1] and `ganache-cli`[2], and we used `truffle`[3] to implement and deploy a set of fully functional smart contracts.

Our smart contracts enables several operations. Nevertheless, one of our major concerns is to guarantee the privacy of the transactions and the involved actors. Therefore, their contents can be retrieved and/or modified only by participants with specific roles (each function is implemented with concrete permissions, e.g. using the *require* clause of solidity and variables such as *msg:sender* to check account authenticity). For example, public users will be able to check the hash of the information committed in the smart contract to publicly check their integrity but they will not be able to retrieve specific information about products, orders, prices and so on. We also included a set of private functions to retrieve traceability information (e.g. the set of locations of a particular product) in the case of an audit or to perform data analytics, improving the efficacy of the system. For the sake of clarity, Table I describes all the available functions and their characteristics.

Our framework consists of four smart contracts (see Figure 4. The first one keeps track of the vendors. The second, manages the list of possible retailers. The delivery/transportation actors are registered in the third smart contract. Finally, the fourth smart contract stores all interactions related to the VMI between a vendor and a retailer. In this context, the vendor will deploy a VMI smart contract with an order by using the *constructor* function, containing a set of products with different characteristics. Such smart contract stores a set of information structures that contain the details of each product as well as traceability information such as temperatures and locations over time based on IoT applications. This information will be updated by the vendor or the distributor accordingly, using the proper *update* function (e.g. distributors can update the list of locations of a product at any time using the *addTrace()* function). Moreover, every time the information of the smart contract is updated a *trigger()* function is called, which can be used as an alert. Therefore, the retailer will be able to check in real time the information about the contents of the order using the *get/retrieve* functions implemented in the smart contract for verification purposes.

The transactions tested in our private blockchain (e.g. update the location of a product or use the functions to retrieve information about the order) are performed in the order of milliseconds, so that our approach enables real-time VMI interactions. The code implementation is available on GitHub[4].

[1]https://nodejs.org/
[2]https://github.com/trufflesuite/ganache-cli
[3]http://truffleframework.com
[4]https://github.com/francasino/NtoN_VMI

V. Discussion

The inherent features of blockchain enables a set of SC stakeholders to maintain a safe, permanent, and tamper-proof

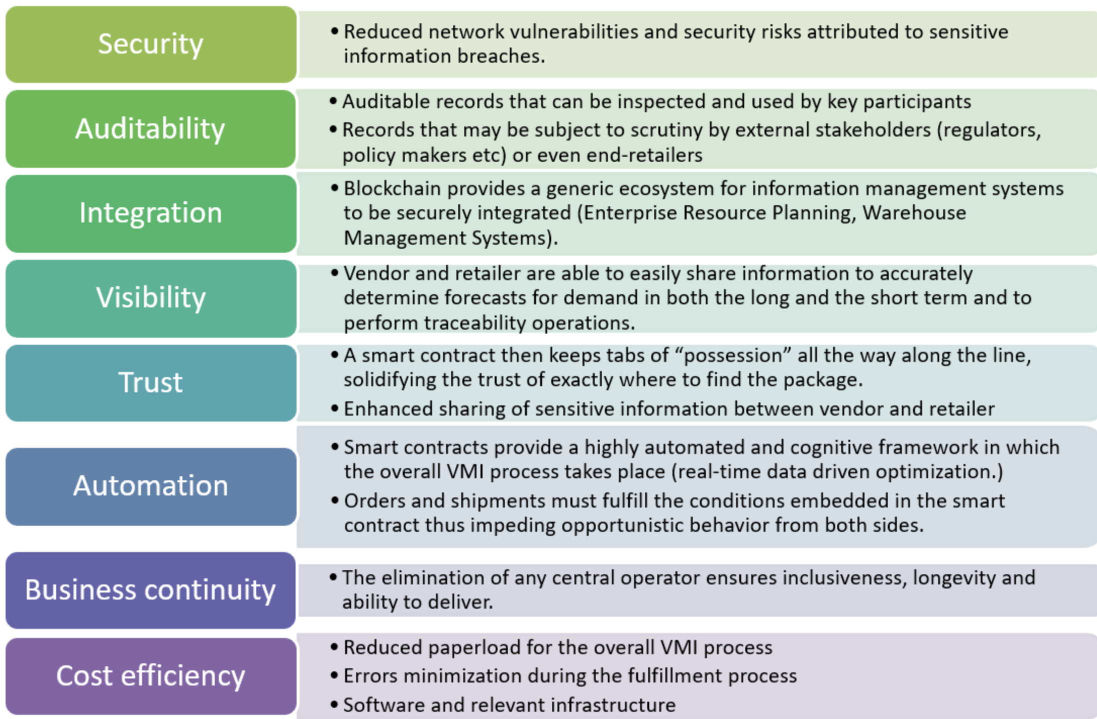

Figure 3. Main benefits the proposed blockchain-enabled VMI architecture.

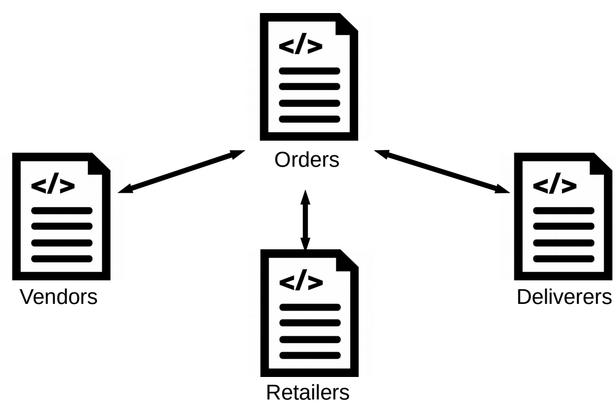

Figure 4. Interactions between the different smart contracts. Note that the Order smart contract manages the information and retrieves data from the other smart contracts.

digital record of transactions, without the interference of a central trusted authority. Moreover, due to its distributed nature, blockchain may simultaneously assure the availability and resilience of the SC management system efficiently.

The framework presented in this paper overcomes several limitations of previous works [10] while enabling a myriad of new possibilities. More concretely, it avoids the "hall of mirrors" effect, since each actor is managed by a different smart contract and operations are only accessible to determined actors. This also enhances data management, auditability and data analytics, since all operations can be related to specific participants. Although a single-vendor-single-retailer approach yields less privacy and management challenges than a multiple-vendors-multiple-retailers approach (as presented in this paper), the inherent security of blockchain and a proper permission management (paired with off-chain storage and encrypted transactions data) minimizes the risk of data disclosure and monetary losses [53]. In addition, the proposed framework presents several benefits for all SC participants and has far-reaching managerial implications, most of them summarized in Figure 3. For instance, auditability (in terms of scrutiny by external stakeholders) or cost reduction (by automating the overall VMI process) are two of the main benefits of our framework. In this regard, we also identify benefits such as a lower overhead for handling transactions and improved order fulfillment (since human errors are minimized). In terms of security and visibility, the proposed framework is safe not only because it has its roots in cryptography but also because of its decentralized nature. In regard to visibility, it improves and strengthens the overall SC by making data readily available to all stakeholders. Moreover, the framework presents other benefits, such as efficient storage management, verifiability and reduced interaction and communication between vendor and retailer, features that are translated into a notable cost reduction. Finally, other important features may relate to safeguarding business continuity and also to offering better integration among the various SC stakeholders.

Although the proposed methodological framework presents several benefits to VMI implementation, some limitations should be kept in mind. Despite the improvements of the blockchain technology and its heterogeneous applications [14], scalability is one of the main challenges to solve. Scalability issues mainly stem from the time required to confirm/verify transactions which may take several minutes for popular cryptocurrencies. Therefore, private permissioned blockchains need to be used, so that scalability issues of public blockchains

Table I. MAIN CHARACTERISTICS AND PERMISSIONS OF THE FUNCTIONS IMPLEMENTED IN OUR SMART CONTRACTS. V STANDS FOR VENDOR, D FOR DISTRIBUTOR AND R FOR RETAILER. NOTE THAT THE PERMISSIONS MAY VARY DEPENDING ON THE PURPOSE OF THE CONTRACT AS WELL AS THE CONTENTS OF THE HASH FUNCTION. THE TRIGGER FUNCTIONS ARE EXECUTED AFTER CONCRETE EVENTS (SUCH AS ORDER UPDATES).

Function	Input	Output	Permissions	Description
constructor	-	True/False	V	Initializes and stores information about the order
addProduct	productName, productQuantity, description	True/False	V	Adds a product to the order list
getNumberOfProducts	-	Integer	V, D, R	Returns the number of products of the order
updateProduct	productId, description	True/False	V, D	Updates description of the product
getProduct	productId	Object	R	Returns the information about a product. For auditing / accepting order
addTrace	productId, location, timestamp	True/False	V, D	Updates the location of a product
addTemperature	productId, temperature, timestamp	True/False	V, D	Updates the temperature of a product
getNumberOfTraces	-	Integer	V, D, R	Returns the number of traces of the order. For statistics.
getNumberOfTemperatures	-	Integer	V, D, R	Returns the number of temperatures of the order. For statistics.
getTrace	traceId	Object	R	Returns detailed information about a trace
getTemperature	temperatureId	Object	R	Returns detailed information about a temperature
getNumberOfTracesProduct	productId	Integer	V, D, R	The number of different locations of a product. For statistics
getNumberOfTemperaturesProduct	productId	Integer	V, D, R	The number of different temperatures of a product. For statistics
getTracesProduct	productId	Object[]	R	The array of trace objects of a product. For auditing
getTemperaturesProduct	productId	Object[]	R	The array of temperature objects of a product. For auditing
updateNumOfVendors	address	Integer	-	External update to avoid non-existing ids
updateNumOfRetailers	address	Integer	-	External update to avoid non-existing ids
updateNumOfDeliverers	address	Integer	-	External update to avoid non-existing ids
retrieveHash	productId	Hash	Public	The hash of the information of a product. For auditing
triggerFunctions	-	Alert	-	A set of functions called after specific operations

are overcome. Finally, although our framework is generic, more specific solutions could be provided according to the possible application scenarios. For instance, in terms of food supply chain [54], [55] the quality control of some products is critical and requires detailed pedigree structures [56] as well as more sophisticated data management by means of token-based systems [57], [58]. In other fields such as health, VMI could be used between pharmaceutical companies and hospitals. In this regard, IoT devices [59] and sensors could keep track of the medicines and medical supplies, increasing the efficiency and reliability of the healthcare ecosystem [60], [61].

VI. CONCLUSIONS

Blockchain technology is able to overcome certain impediments traditional VMI approaches present like lack of security, integration difficulties and opportunistic behavior. In this work, we have proposed a novel VMI architecture based on blockchain and smart contracts for improving inventory policies between multiple vendors and retailers. Moreover, we provide a functional implementation through the use of a local private blockchain and various smart contracts, which implement a set of functions that enable different characteristics/benefits of VMI implementation. Therefore, we have presented a use case VMI scenario in which multiple vendors and multiple retailers may interact with each other based on a trustless and distributed mechanism. This solution enables several benefits like cost reduction, increased visibility, security and operations' automation. Future work will focus on the interaction of VMI with external auditors such as insurance companies, to provide enhanced functionalities. Finally, other promising topics for future research include the usage of blockchain technology and smart contracts for the establishment of an automated pricing control mechanism between vendors and retailers as well as the use of blockchain tokens for establishing a more detailed VMI approach.

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