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Modeling food supply chain traceability based on blockchain technology

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Abstract: Traceability has become a critical element in supply chain management, particularly in safety-sensitive sectors like food, pharmaceuticals, etc. Upstream (manufacturers, producers, etc.) and downstream (distributors, wholesalers, etc.) supply chain members need to store and handle traceability-related information for providing proof of regulatory compliance to both state authorities and more demanding customers. More specifically, European Union regulations mandate food producers to trace all raw materials/ingredients used throughout their supply chain operations. Consumers also place high expectations on food supply chains (FSC) with specific emphasis on facets related to safety. However, the complexity of modern FSC networks and their fragmentation act as barriers for the development of sound traceability mechanisms. This paper aims to develop a distributed functional model to provide decentralized and automated FSC traceability based on blockchain technology and smart contracts. For assessing the feasibility of the proposed modeling approach, a food traceability use-case scenario is presented. The applicability of the model is further illustrated by the development of a fully functional smart contract and a local private blockchain. The overall benefits of the proposed model are assessed based on a set of predefined Key Performance Indicators (KPIs). The results are of significant value to both practitioners and researchers.

Keywords: Supply chains and networks; Supply Chain Management; Industry 4.0

1. INTRODUCTION

Food Supply Chain (FSC) networks are getting increasingly more complex and fragmented nowadays. This complexity makes the identification and tracking of products and processes along globalized FSC networks extremely difficult. In this context, traceability has become a requirement for ensuring not only safety in FSC but also regulatory compliance, better understanding of the products' life cycle and conscientious consumption. In particular, traceability is considered as a new quality index in the food industry, according to Bosona and Gebresenbet (2013). Storing and handling sensitive case information for tracing in FSC becomes mandatory worldwide. Regulations are imposed in order to enable tracking and identification of all raw materials used in food products as claimed by Dabbene et al. (2014). For example, the pork supply chain is actively regulated in terms of traceability. In this case, apart from tracing the raw materials used in pig feed and treatments and the final destination of the pork, the transportation of the animals between factories must also be registered by law. These requirements tangle many FSC participants, some of them still depending on non-automated information managing methods, as mentioned by Rabah (2018); Gromovs and Lammi (2017).

Traceability-driven FSC management is based on novel technologies like the Internet of Things (IoT) that provide real-time information about products as well as contamination information throughout production and distribution. Such technologies address practical problems/monetary constraints and (re)design/optimize food supply networks, as stated by Zhu et al. (2018). IoT-enabled applications and relevant technologies (RFID, etc.) could revolutionize the industry by digitizing information to be queried and controlled in real time. However, the reliability of such information is still a key challenge. This is particularly true for globalized FSC networks with numerous suppliers, different regulators and millions of clients, in which traceability data needs to be in digital format and accessible by the various stakeholders and its processing to be automated to comply with different regulations. These digital technologies are creating significant opportunities for the food industry, reshaping the FSC in terms of business and operational processes and requiring revisions of existing analytic models in this domain to accommodate the changes (Figure 1). Nevertheless, some of the key players still depend on non-automated information managing methods, as observed by Saikouk and Spalanzani (2016). Missing or unreachable information can induce food insecurity and consumer health issues. In fact, food contamination is still a significant health problem in

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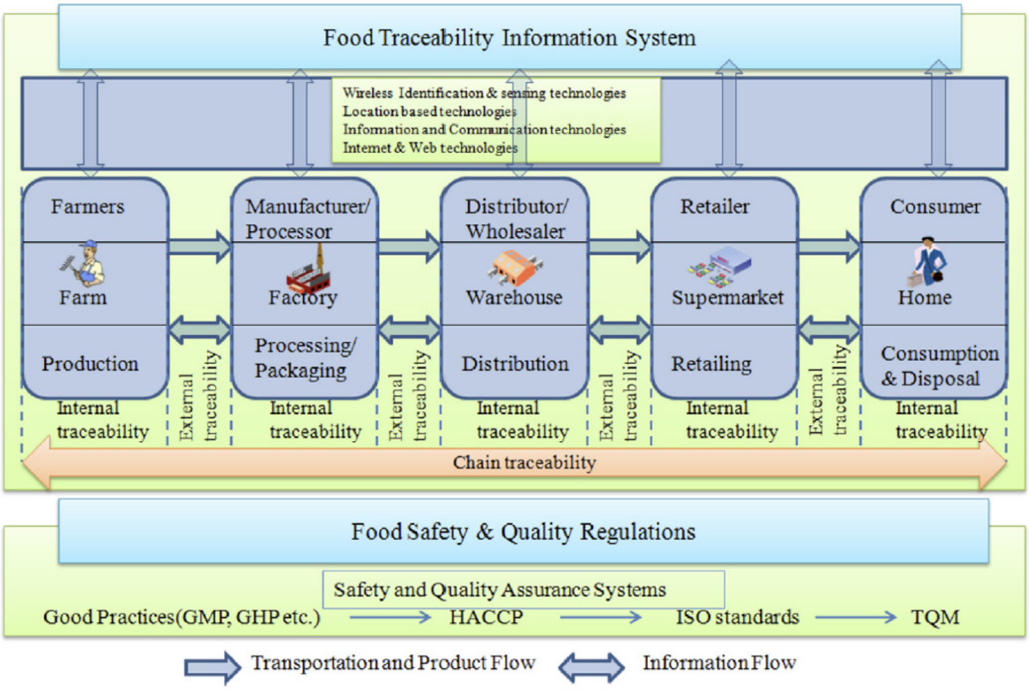

Fig. 1. Conceptual framework of food traceability system Aung and Chang (2014).

several countries (according to the World Health Organization, every year around 600 million people worldwide endure illnesses from eating contaminated food, out of which 420,000 die) and results to public suspicion and a substantial reduction in demand, as stated in Trebar et al. (2013). In addition, traceability-related information is not shared between participants, since each of them has its traceability mechanism and inevitably stores its unique traceability records. This information sharing impediment poses significant risks for the core participants in terms of food safety and quality and also hinders external stakeholders from checking for regulatory compliance.

Blockchain technology, a decentralized database that allows transparent, secure and auditable append-only transactions, can be used in FSC networks, according to Casino et al. (2018); Dasaklis et al. (2019); Zhang and Wen (2017). However, blockchain-related literature within the FSC domain is scarce and several limitations related to its successful implementation still exist. The paper addresses this gap by providing a distributed trustless and secure architecture for the establishment of a sound FSC traceability mechanism. The aim is to develop an interoperable, autonomous, functional and back-end data sharing model which provides decentralized and automated FSC traceability. A blockchain based implementation is provided, using not only transaction information but smart contracts as well. A use-case FSC traceability scenario is presented illustrating the applicability of the proposed model along with the significant benefits for all FSC participants. Finally, some limitations of the developed architecture are discussed and several fruitful areas for future research are proposed.

The remainder of the paper is organized as follows: In Section 2 an overview of food traceability is provided, along with an introduction to blockchain technology and its main characteristics. In Section 3 a brief review of the available relevant literature is presented. In Section 4 the proposed model is described in detail and a use case scenario is presented. Section 5 analyses the model performance according to a set of key performance indicators. Finally, the paper ends with some concluding remarks.

2. BACKGROUND

Food Traceability

Food traceability captures, stores and transmits adequate information about a food, feed, food-producing animal or substance at all stages in the FSC so that the product can be checked for safety and quality control, traced upward and tracked downward at any time, as claimed by Aung and Chang (2014). It includes product, process, genetic, inputs, disease and pest and measurement traceability, as suggested by Zhu et al. (2018). There are three essential characteristics for traceability systems: i) identification of units/batches of all ingredients and products, ii) information on when and where they are moved and transformed, and iii) a system linking these data, as stated by Aung and Chang (2014).

The food industry uses traceability systems for the improvement of FSC and the facilitation of the traceback for food safety and quality. Traceability is viewed as a strategic tool to improve food safety systems, the quality of raw materials, inventory management and as a source of competitive advantages, according to Aung and Chang (2014); Dasaklis et al. (2019); Dasaklis and Casino (2019). Traceability systems help firms identify the cause and extent and resolve safety or quality control problems.

Blockchain technology

Blockchain, a structured and decentralized ledger, was initially developed to provide a practical solution to reaching an agreement in an untrusted decentralized distributed environment, as defined by Nakamoto (2008). In blockchain, information is structured in a chain of blocks, where each block keeps a set of transactions executed at a given time. Blocks are connected by a reference to the previous block, forming a chain. Blockchain incorporates cryptography, mathematics, complex algorithms and economic models, using together peer-to-peer networks and unanimous distributed algorithms to solve traditional distributed database synchronization problems and therefore it is an integrated multi-stage tool. The blockchain is resistant to any data modification (immutability), which means that once information is registered it cannot be altered or modified. Moreover, blockchain technology is evolving to be the most significant technology revolution since the invention of the Internet and its adoption is a reality in many fields, as claimed by Rabah (2018); Gromovs and Lammi (2017); Garay et al. (2015); Saha et al. (2018); Casino et al. (2018).

A relatively recent aspect of the blockchain technology is the notion of smart contracts, introduced by Szabo (1997) (with a full Turing complete Language), which provide the ability to perform computations within the blockchain, thus operating as a decentralized virtual machine. Generally, a smart contract pertains to the computer protocols or programs that permit an agreement to be automatically executed/enforced taking into account a set of predefined conditions. Today smart contracts have been included in the majority of existing blockchain executions. A typical example is the Hyperledger [1], which is a blockchain created for companies that allows components to be developed according to the needs of users, supported by large companies such as IBM, JP Morgan, Intel and BBVA.

The above mentioned features of blockchain and smart contracts could be extensively used for solving several problems in current FSC traceability approaches. The blockchain is a technological advance that has the potential to change services by providing trust in distributed environments such as FSC. It can provide backward control from the end consumer to the factory or farm, bypass traditional authorities and ensure faster and secure transactions. For instance, blockchain-enabled applications enhance the sharing of information among disparate partners across FSC networks without compromising privacy and security. Significant benefits from the adoption of blockchain-enabled applications in FSC traceability may relate to data interoperability, cost reduction, transparency, auditability, integrity and authenticity. It is worth noting that blockchain-enabled FSC approaches 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, according to Banafa (2017); Huh et al. (2017).

3. LITERATURE REVIEW

Although several published research papers have discussed traceability applications in FSC management, as suggested by Badia-Melis et al. (2015); Dabbene et al. (2014); Bosona and Gebresenbet (2013); Yan et al. (2018), the utilization of blockchain and the capability to track and trace items in real-time at item-level has not been examined in depth. Most of the blockchain-enabled FSC approaches, although significant, are limited in scope and applicability.

Casado-Vara et al. (2018) propose a new tracking model that involves blockchain, smart contracts and a system to coordinate the tracking of food in the agriculture supply chain. Tian (2018) developed a FSC traceability system by using IoT and blockchain technologies and it is compared with the linear centralized system widely used in FSC. The new system uses blockchain for guaranteeing that the information shared and published in this traceability system is reliable and authentic. Bettín-Díaz et al. (2018) integrate blockchain in the food industry supply chain to allow traceability along the process and provide end customer with adequate information about the origin of the product to make an informed purchase decision, thus enhancing supply chain provenance. Finally, Caro et al. (2018) presented a fully decentralized, blockchain-based traceability solution for agrifood supply chain management, which integrates IoT and blockchain in a "from-farm-to-fork" approach.

4. THE MODEL

An effective traceability system should enhance the collection and handling of the related information and promote its exchange among all FSC members like farmers, producers, distributors, and consumers, according to Aung and Chang (2014). The novelty of the proposed approach lies in the method of keeping vital records for each member in the FSC. In particular, information is stored in a table of content (TOC) using IoT technology regarding products' key characteristics. Therefore, records for each FSC member are stored locally (using decentralized storage approaches such as IPFS [2]). This method avoids storing a pile of data in central repositories and, consequently, the transaction process is faster due to the small volume of data. Moreover, the backward traceability will be easier, since the only information necessary for tracking a product is the corresponding TOC from each FSC member.

With the aim to develop an architecture that enables all the previously stated requirements, a two-step procedure is implemented, differentiating upstream members (like farmers, food producers, manufacturers) from downstream members (wholesalers, distributors, retailers). First, the upstream data is stored in a centralized server. This is a typical procedure that is not affected by the adoption of the blockchain, since, for example, the manufacturer needs to store data about its products, pedigree, quality inspections, etc. Nevertheless, a system is required that provides verifiability, auditability and integrity among others. Therefore, data generated by IoT as well as manual entries provided by qualified staff are optimized and filtered to create a TOC file. As previously stated, such data are stored both in the central server and in a decentralized database such as IPFS. The use of smart contracts is not needed nor recommended here, since using blockchain only for data storage is not efficient. On the other hand, downstream FSC operations like distribution procedures require smart contracts to enable their full potential in terms of better customer service and quality assurance.

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[1] Hyperledger project.https://www.hyperledger.org/

[2] https://ipfs.io/

A set of functions is implemented to enable supply chain operations management with high tracking detail (the objects and data involved can be uniquely identified and data stored are precise for each operation). In addition, a smart contract enables permission-based access to its information and thus only allowed users have access to specific information (e.g., using the *require()* clause in solidity). The proposed approach includes hash transaction verification as well as product specification, tracking/location history, etc. Additional features such as QoS and policy compliance can also be enabled. Finally, several state-of-the-art blockchain-based approaches based on transaction-only models, as described by Casado-Vara et al. (2018); Tian (2018); Bettín-Díaz et al. (2018); Caro et al. (2018), offer only a small amount of information (see Figure 2(left)), compared to our proposed smart contract architecture, as depicted in Figure 2 (right). Thus, the proposed method includes the benefits of transaction-based approaches as well as a rich set of new operations. Note that we consider manufacturing information and pedigree of products to enable a holistic supply chain traceability system, although manufacturers don't directly interact with the rest of FSC members through the smart contract. It should be noted, however, that manufacturing-related info is taken into account through the usage of the IPFS approach and decentralized storage. In Figure 2 the various interrelationships among the FSC members are presented.

The smart contract developed takes into account the information provided by upstream and downstream members of the FSC, like manufacturers, wholesalers, distributors and retailers. Therefore, the smart contract stores the information and interactions between them in a verifiable way. This enables efficient auditing to discover, for instance, product quality issues and at what point of the supply chain they occurred. This information can be retrieved by any of the actors and shared accordingly as well as supervised by third parties or law enforcers.

In order to link the upstream and downstream procedures, two fields are added in the product object of the smart contract. The field *globalId* identifies uniquely a product (using the same identifier as the manufacturer). The *hashIPFS* field is the hash where the information about the product is stored (TOC records) in the decentralized database. Therefore, all data can be retrieved (from the creation of a product until its consumption) using the functions implemented in the smart contract. A description of the proposed data storage management is depicted in Figure 3. Note that all products (pedigree and final) have their associated data and that the pedigree of the products is linked with their corresponding IPFS hashes so that all the information can be holistically retrieved for an individual product.

4.1 Integration Details

To assess the feasibility of the proposed approach an ethereum-based blockchain was created using node[3] and ganache-cli[4], and truffle[5] was used as the smart contract framework. It is assumed that all involved actors (e.g., wholesaler, distributor) are registered in the blockchain and they have an address with their respective pair of public/private keys. Thereafter a smart contract is deployed, which includes a set of operations and stores required data to enable FSC traceability, as claimed by Casino (2018). The contract stores product characteristics and implements a set of functions to add or retrieve information only by specific users. Permissionless functions such as consulting the hash of a product are implemented, so that all users of the platform can check for integrity. A thorough list of the implemented functions and a brief description is provided in Table 1. The experiments performed in the local blockchain show that the average cost of a transaction is of the magnitude of milliseconds (e.g., contract deployment and constructor) and thus the proposed solution could enable real-time FSC traceability.

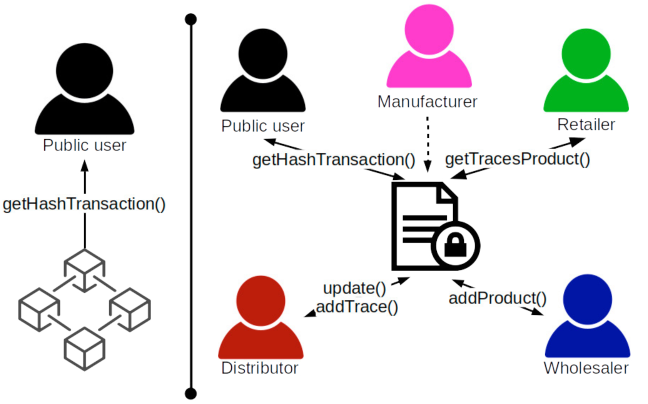

Fig. 2. Case scenarios using only the information of a transaction in blockchain (left) and using a smart contract (right).

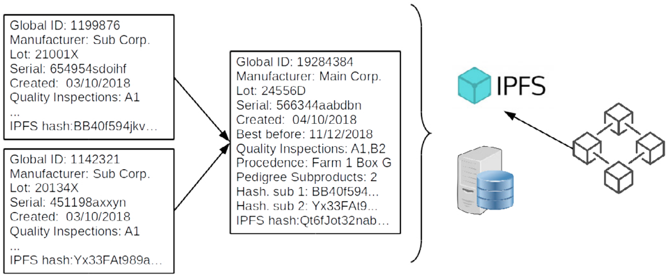

Fig. 3. Overview of the architecture's storage management.

5. MODEL PERFORMANCE

For assessing the performance of the proposed FSC model a hybrid qualitative approach is used based on: a) the conceptual approach for integrated supply chain performance measurement model proposed by Aramyan et al. (2007) and b) the suitability of the blockchain-based applications framework as described by Casino et al. (2018). The performance of the proposed model is measured using a group of Key Performance Indicators (KPIs) like efficiency, responsiveness, required trust assumptions, context requirements, required consensus mechanisms and food quality of the proposed blockchain-enabled model, which is also compared against traditional FSC traceability mechanisms. An intuitive three-level scale (i.e., low, medium and

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[3] https://nodejs.org/
[4] https://github.com/trufflesuite/ganache-cli
[5] http://truffleframework.com

Table 1. Summary of the functions implemented in the smart contract and their characteristics, as well as permission management. Permissions vary depending on the purpose of the contract.

Function	**Input**	**Output**	**Permissions**	**Description**
constructor	-	True/False	W[1]	Initializes and stores information about the order
addProduct	productName, productQuantity, description	True/False	W	Adds a product to the order list
getNumberOfProducts	-	Integer	W, D[2], R[3]	Returns the number of products of the order
updateProduct	productId, description	True/False	W, D	Updates description of a product
getProduct	productId	Object	W, R	Returns the characteristics of a product.
getProductGlobalID	productId	string	W, D , R	Returns the global ID of a product.
getProductHistoric	productId	Hash	W, D , R	Returns the historic/manufacturing information of a product
addTrace	productId, location, timestamp	True/False	W, D	Updates the location of a product
addTemperature	productId, temperature, timestamp	True/False	W, D	Updates the temperature of a product
getNumberOfTraces	-	Integer	W, D, R	Returns the number of traces of the order.
getNumberOfTemperatures	-	Integer	W, D, R	Returns the number of temperatures of the order.
getTrace	traceId	Object	R	Returns information about a trace
getTemperature	temperatureId	Object	R	Returns information about a temperature
getNumberOfTracesProduct	productId	Integer	W, D, R	The number of different locations of a product.
getNumberOfTemperaturesProduct	productId	Integer	W, D, R	The number of different temperatures of a product.
getTracesProduct	productId	Object[]	R	The array of trace objects of a product.
getTemperaturesProduct	productId	Object[]	R	The array of temperature objects of a product.
retrieveHash	productId	Hash	Public	The hash of the information of a product.
triggerFunctions[4]	-	Alert	-	A set of functions called after specific operations

[1] wholesaler, [2] distributor, [3] retailer, [4] Trigger functions are executed after relevant events such as product updates

Table 2. Performance of the proposed blockchain-enabled FSC traceability model.

Performance metric		Estimate
Efficiency	Cost	High
	Automation	High
Responsiveness	Customer complaints	Medium
	Response times	Medium
Food quality	Process quality	High
	Product quality	High
Trust	Accountability	High
	Immutability	High
	Verifiability	High
Context	Data transparency	High
	Security	High
	Privacy	High
Consensus	Autonomous and dynamic interactions between transactions of different writers	High
Resiliency	Business	High
	Continuity	High

high) is used to measure the relevance of each indicator. As seen in Table 2, the proposed model offers several benefits in terms of efficiency since its automated nature removes hidden costs and paperload from the FSC traceability process. Apart from the inherent security of the blockchain architecture, the proposed model also offers excellent benefits in terms of auditability and trust (auditable records that can be inspected and used by key participants or by external stakeholders like regulators, policy makers, etc). It should also be noted that the proposed modeling approach offers significant benefits in terms of quality and resilience. An immutable and distributed traceability mechanism safeguards quality since any tampering with food data can be immediately identified and prevented. As a direct consequence, the high quality of food products offered to end-customers reinforces the business continuity of the FSC participants. The decentralized nature of blockchain also avoids denial of service attacks, contrary to centralized systems. The latter prevents possible loss of information, which could entail monetary losses as well as health risks for the customers.

6. CONCLUSIONS

In this paper, a novel FSC traceability modeling approach based on blockchain and smart contracts is presented. The purpose of using blockchain is to overcome certain impediments of traditional FSC traceability mechanisms, like lack of security, information sharing, and systems integration difficulties. To showcase the feasibility of the proposed architecture, a local private blockchain and a smart contract are used, which implement a set of functions that enable different characteristics/benefits. In addition, the benefits of the architecture mentioned above like increased visibility, security and operations' automation are discussed.

Some limitations of the proposed FSC traceability model should be kept in mind. For example, the model addresses a relatively simple FSC network (manufacturer, wholesaler and distributor). Therefore, it would be interesting to explore FSC scenarios in which multiple and disparate FSC members interact. In this case, it is expected that features of trust and visibility would be further exemplified by the use of smart contracts and blockchain. Regarding the KPI's developed, future validation of the proposed model will provide concrete evidence regarding its performance in advanced business settings. Some limitation of the blockchain technology itself should also be mentioned. For instance, blockchains are not suitable for storage of vast amounts of data and many recognize that scalability is one of the main challenges to solve. In addition, a multi-tier FSC network would require the processing of a large number of transactions in a relatively short period; therefore, scalability issues could also arise. It should be noted that scalability issues mainly stem from the time required to confirm/verify transactions. Apart from the implementation of traceability in a multi-tier FSC network, further research will focus on the use of the proposed modeling approach in conjunction with supply chain optimization approaches.

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