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A decentralized model to ensure traceability and sustainability of the food supply chain by combining blockchain, IoT, and machine learning

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Many food contamination incidents have occurred during the last decade which has proven the failure of the food supply chain management system to track the food, money, and information movement within the food supply chain. Many models have been established. This paper presents the design and implementation of the new model providing real-time data acquisition, monitoring, and storing on a tamper-proof blockchain of the main food supply movement. This system is using smart contracts that are deployed on the Ethereum blockchain to allow every participant to transact securely with other FSC players. IoT networks are implemented in different workplaces to gather multiple data about food status without human involvement to ensure transparency by different sensors. Machine learning models are established to ensure the correctness of the collected data and help drive decision making within the application or businesses.

Keywords: *blockchain; food supply chain; IoT; traceability; smart contracts; machine learning.*

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1. Introduction

Providing food of the right quality and at an appropriate time to an increasing world population which is expected to reach 8.5 billion by 2030 and 9.7 billion by 2050 [1], is the prime goal of the food supply chain. However, multiple obstacles are challenging the sustainability of FSC such as price volatility, food safety, and food quality, in addition to the food origin traceability and FSC transparency.

The Horse meat scandal in 2013, in which horse DNA was discovered in frozen beefburgers sold in several Irish and British supermarkets [2] or the Chinese milk scandal in 2008, in which sixteen infants in China's Gansu province were diagnosed with kidney stones (all of them had been fed on milk powder that was later found to be adulterated with a toxic industrial compound called melamine [3]), these incidents were caused by food fraud and have proven that the traditional food supply chain management fails to ensure transparency and traceability.

The International Organization for Standardization (ISO) has defined traceability in the agri-food sector as the ability to follow the movement of food through specified stages of production, processing, and distribution. Traceability allows organizations to locate products through the stages of the food supply chain from farm to fork [4]. Instead of traditional tracking systems, the European Commission has highlighted the importance of developing advanced traceability systems as a major strategic competitive advantage, especially regarding privacy control and process transparency.

A mysterious individual or possibly, a group, known as Satoshi Nakamoto has published in a white paper a blockchain-based solution to the double-spending problem called bitcoin. Bitcoin uses blockchain to secure financial transactions without the need for a trusted third party or a central authority like a bank or financial institution. Blockchain is a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network. An asset can be tangible (a house, car, cash, land) or intangible (intellectual property, patents, copyrights, branding).

In recent years, many sectors have adopted blockchain as a basic approach to bring transparency and traceability such as agriculture, health care, environment, energy, and banking.

From an economic and business perceptive, blockchain-based systems offer a secure way to manage data and information when multiple parties are involved to record and share data. As a result, many sectors have adopted these systems, such as the food supply chain, in which researchers have proposed innovative models to secure food, money, and data transactions. The development of the second blockchain generation has given birth to smart contracts. Smart contracts, as a technology implemented on top of a blockchain, have allowed securely interacting with any blockchain-based system. Furthermore, the Internet of Things as an emerging technology has enabled to interconnect of heterogeneous devices and objects to create a physical network in which sensing, processing, and communication processes are automatically controlled and managed without human intervention [5].

Combining IoT and blockchain to bring transparency and traceability to the food supply chain has attracted huge interest from academics, researchers, and entrepreneurs thanks to their capacity to offer the possibility of designing a decentralized, autonomous, and time-stamped proof system over the food supply chain to restorer confidence between stakeholders and to fight food fraud, in addition, to solve financial issues not only by cost reduction but also by maintaining clear financial policy between all FSC participants.

2. Related works

In recent years, many researchers and academics have tried to take advantage of combining blockchain and IoT or combining blockchain and machine learning to secure data over some parts of the food supply chain. However, none of them has tried to address the impact of those combinations to manage and secure main movements (money, food, and information) over the entire food supply chain due to its complexity and the number of mutual relationships that can be existed in the real world. Moreover, many solutions have been established using permissioned blockchains that are not really decentralized applications due to the control that has to be established to well manage the network. This control kills any essence of decentralization.

Authors in this paper have highlighted the importance of combining blockchain and IoT to store and secure data in permissioned blockchain (Hyperledger Fabric (HF)) of hem production without discussing the impact of this use case to bring transparency and track data over the entire supply chain [6]. Without mentioning that permissioned blockchain-based systems are not really decentralized applications. On the other hand, many other researchers have established models to solve other issues related to the food supply chains such as food waste, reverse digital food supply chain [7], and finance supply chain [8].

Hence, this study seeks to propose a model by combining blockchain, IoT, and machine learning that can secure food, money, and information transactions over the food supply chain despite its complexity and multiple players involved in it. This paper will try to answer a research question: What is the best solution to ensure traceability over any food supply chain by using blockchain combined with both machine learning and IoT?

3. Brief overview of the technology

3.1. Food supply chain

Food supply chain refers to the processes that describe how food from a farm ends up on our tables. As shown in Figure 1), it includes organizations, people, information, products, and resources that move from one point to the next until it reaches the hands of the consumer. The process includes the procurement of raw materials, production, packaging, storing or warehousing, shipping, delivery, and retail.

In the food supply chain, tow main processes are identified, pull processes and push processes. Under pull processes, the food and information are pushed from providers up to retailers through

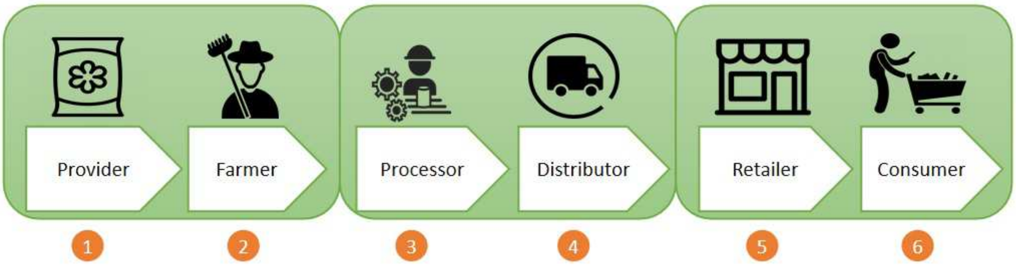

Fig. 1. Food supply chain.

the channel based on demand forecast. This strategy relies on predictions instead of responding to actual customer demand. In the opposite of this strategy, pull processes are driven by actual customer demand. They are related to just-in-time school inventory management, which aims to reduce stock and focus on last second deliveries in spite of unforeseen factors such as climate change, geopolitical conflicts, rising demands. It is difficult to eliminate stocks and wait until the customers place their orders. That is why, in real life all a mixture of both strategies (pull and push) is applied to meet customer requirements. The domino-like fashion is best way to illustrate this mixture.

According to the domino-like fashion representation (see Figure 2), food moves from provider to consumer through the processes of production, distribution, retailing, and consumption in a domino-like fashion. On the other hand, money that consumers pay for food, moves from consumer to provider in the opposite direction, from consumer to retailer to distributor to processor to farmer to provider, between tow successive participants(dominoes). Main food supply chain movements must be regulated by choosing the best process (pull or push) in order to keep all dominoes up and avoid any domino effect that can put the entire chain in risk.

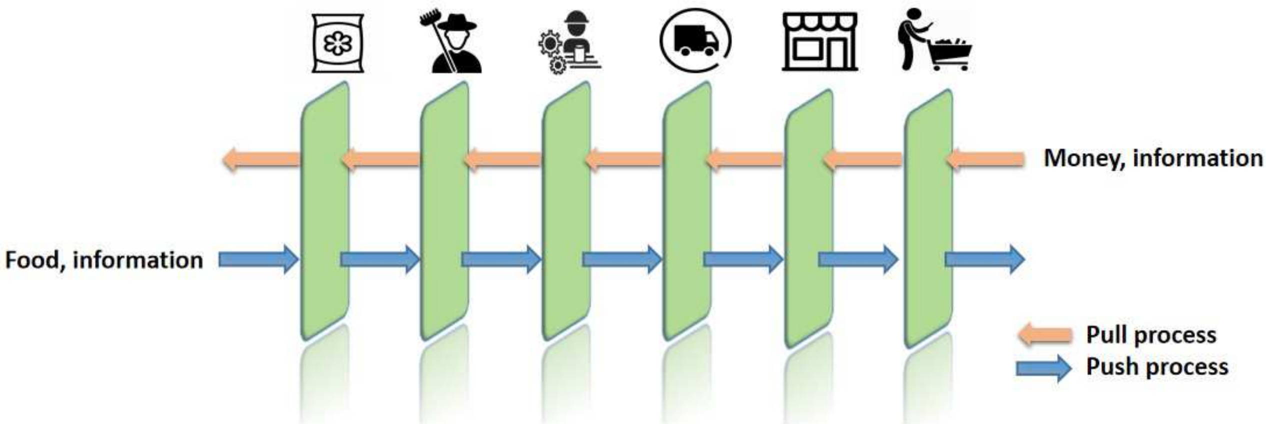

Fig. 2. Domino-like fashion representation.

3.2. Blockchain technology

Blockchain is a shared, immutable, and distributed ledger of information that keeps a record of transactions. It is a peer-to-peer network in which nodes from different networks are connected but do not trust each other [9]. The ledger of each node keeps a track of transactions and ensures that they are always synchronized. A blockchain is made up of blocks put together in the form of a chain. Data from each of the participants in the network is stored in these blocks, this is done in a block format, called a set of transactions, Following their formation, these transactions are grouped into blocks and connected to one another in chains along with the time stamp, an additional layer of security is provided by this chain mechanism, even the smallest modifications invalidate subsequent blocks. Furthermore, if only the hash of the last block is verified, the validity of the entire chain can be ascertained, the content of each block is presented in the following table(see Table 1).

Data integrity, decentralization, and high reliability are the prime features of blockchain. The main advantage of blockchain is that it does not rely on a third party for communication and transaction between nodes. Regarding the blockchain structure (see Figure 3), it may be permessionless or permissioned. While permessionless blockchain is public, anyone can join its network and participate to add a new block to the ledger according to the consensus mechanism or simply set a transaction. Permissioned one has two types private blockchain and federated blockchain.

Table 1. Block header.

Name	Description
Version	Block version number
Hash	The block's hash value
Parent hash	The previous block's hash value
Difficulty	The proof-of-work target difficulty
Timestamp	Creation time of the block
Merkle root	The root of Merkle Tree of transactions
Nonce	A random counter for proof-of-work

In a private blockchain, only particular entities can take part in the consensus mechanism for adding a new block and has the authority to send transactions. It is a centralized implementation of blockchain that anyone wanting to join the network must be approved by a specific organization. On the other hand, federated blockchain is private for a specific group of business such as financial organizations.

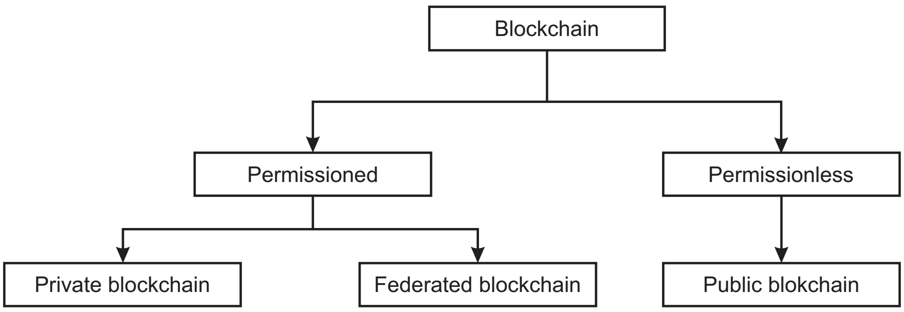

Fig. 3. Blockchain types.

3.3. IoT technology

The IoT concept was introduced by a member of the Radio Frequency Identification (RFID) development community in 1999. It refers to a type of network to connect anything with the Internet based on stipulated protocols through information sensing equipment to conduct information exchange and communications to achieve smart recognitions, positioning, tracing, monitoring, and administration. It refers also to everyday objects that are readable, recognizable, locatable, addressable through information sensing devices, and/or controllable via the Internet, irrespective of the communication means (whether via RFID, wireless LAN, wide area networks, or other means) [5]. Everyday objects include not only the electronic devices. We encounter the products of higher technological development such as vehicles and equipment but things that we do not ordinarily think of as electronic at all such as food, clothing, chair, animal, tree, and water.

3.4. Smart contracts

The term smart contracts was introduced for the first time in the 1990s by Nick Szabo, a computer scientist and cryptographer. Smart contracts are simply a written codes stored on a blockchain that run when some conditions are verified. They are used to execute automatically an agreement so that all participants can be immediately certain of the outcome. Without any third-party involvement or time loss, they can also automate a workflow, triggering the next action when conditions are met. They are also immutable, secure and encrypted records. They live forever in the blockchain generally in the form 'if/when . . . then'.

3.5. Machine learning

Machine learning is a branch of computer science, it is an important component of the data science field. By using statistical methods and algorithms trained to make classifications or predictions, machine learning helps find insights that are used generally to drive decision-making within applications and used cases. In machine learning science, three primary categories are identified. Those categories are supervised machine learning, unsupervised machines, and reinforcement learning. While supervised machine learning uses labeled datasets to train algorithms and models to classify data or make predictions, unsupervised machine learning uses algorithms to cluster datasets in order to find similarities and differences in information. In addition to that, reinforcement machine learning does not use sample data to train models. Instead of that, models learn as they go. Successive outcomes will reinforce these models to make the best recommendation.

4. Proposed model

4.1. General model architecture

Having given enough details about the basics of blockchain, IoT technology, and the global structure of the food supply chain in addition to some facts about machine learning and its benefits, it is possible to address the goal of this paper, which is the design of a new model based on combining blockchain, IoT and machine learning to secure and sustain food supply chain main movements (food, money, and information). The said proposed model proposes that every stakeholder in the food supply chain must have at least one electronic wallet in the Ehtereum blockchain network (see Figure 4), by which he can interact with other nodes and share data that is collected automatically by an IoT network implemented in his workplace. For example, the farmer IoT network gathers information about food status in his farm such as ambient temperature, soil moisture, humidity. In addition to a web form dedicated to gather information related to the use of pesticides, fertilizes and other information that cannot be collected automatically, all this collected data will be transferred to the Ehtereum blockchain via cloud server. This information can be visualized by any authorized entity connected to the network by its graphical end front.

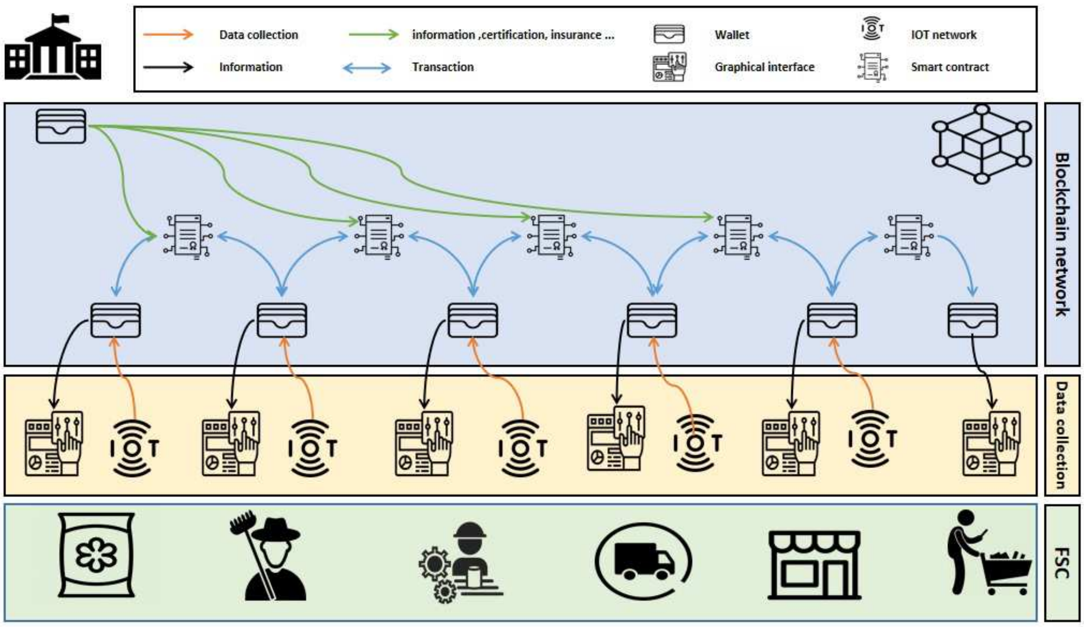

Fig. 4. General model architecture.

On the other hand, at least one smart contract must be deployed in the Ehtereum blockchain between two stakeholders in the food supply chain to manage the relationship between them. For example, let us assume that the processor has released a purchase order in the Ehtereum blockchain via smart contract. In the moment of the delivery, the smart contract must verify all the predetermined conditions via the two IoT networks: farmer IoT network – to be sure that all climatic and biologic conditions are met. In addition, to state agencies certification if it is needed. And processor IoT network – to verify the concreteness of delivered quantities and other parameters if it is needed. At this moment, the smart contract can release the farmer payment procedure. In this way, the model can manage both flows: physical flow, and financial flow within the food supply chain and store all those transactions forever in the Ehtereum blockchain.

Table 2. Model features.

Feature	Tool
Decentralization	Public blockchain (Ethereum)
Data privacy	Asymmetric cryptography
Data integrity	Hash function and Merkle Tree
Data quality	Machine learning and data analysis
Heterogeneity	IoT
General solution	Modularity

This model architecture allows the following features (see Table 2).

Decentralization: in order to bring transparency and security, decentralization is a powerful tool to store and share data over a network. Without the need for a central entity to manage data storage, any authorized entity can access to specific data via public or/and private key. Blockchain as a peer-to-peer distributed network connecting multiples nodes that they do not trust each other have showed its benefits as the best solution for decentralized systems. Furthermore, public blockchains, such as Ethereum which is an open-source decentralized blockchain platform that securely executes and verifies smart contracts, allow the participants' nodes to transact with each other without the need for any central entity; allow participants to interact between them securely by sending and receiving transaction without sharing any personal data. These transactions are immutable and verifiable records that allow for restoring transparency and traceability.

Data privacy and data integrity: it is required to build a model that protects the data privacy of every participant who is taking part of the system against any hack or any suspicious participant, thanks to asymmetric cryptography as a tool of data encryption/decryption via public and private key generation. An electronic signature is required to send any transaction or interact with the smart contracts which allow tracking and identifying data senders. Hash function like SHA and merkle tree help also to verify any transaction source and detect any small data modification.

Heterogeneity: in the food supply chain, multiples devices are implemented to collect data. Every FSC player has his own devices and his own network, thanks to IoT technology that enables heterogeneous devices based on different hardware platforms and networks to interact with other devices or service platforms through different networks.

Data quality: sending corrupted data to blockchain is west of time and money, therefore, the model must be able to ensure the quality of collected data, thanks to machine learning which can help detect any misleading or corrupted data sent by defective sensor, by establishing an appropriate models and data analysis.

General solution: the supply chain food is a complex network connecting different actors (see Figure 1) illustrates it basic standard model, nevertheless, multiple combinations of the six main players of the supply chain exist in the real life, for example, provider, farmer, distributor, and consumer can form a possible supply chain without processor or retailer. Moreover, a processor may have different farmers as suppliers for the same product. As a result, the proposed model must take into consideration those possible combinations. However, it is not practical to build a model for any one them all. That is why the proposed model is modular solution (see Figure 5). Modularity means that every two successive player of the food supply chain form an independent unit, each unit is managed with the same tools and techniques since the ultimate goal of the overall supply chain is managing the same parameters (money, food, and information) from farm to fork. Indeed, modularity allows to build a general solution for any food supply chain by assembling blocks formed by tow successive participants of the chain.

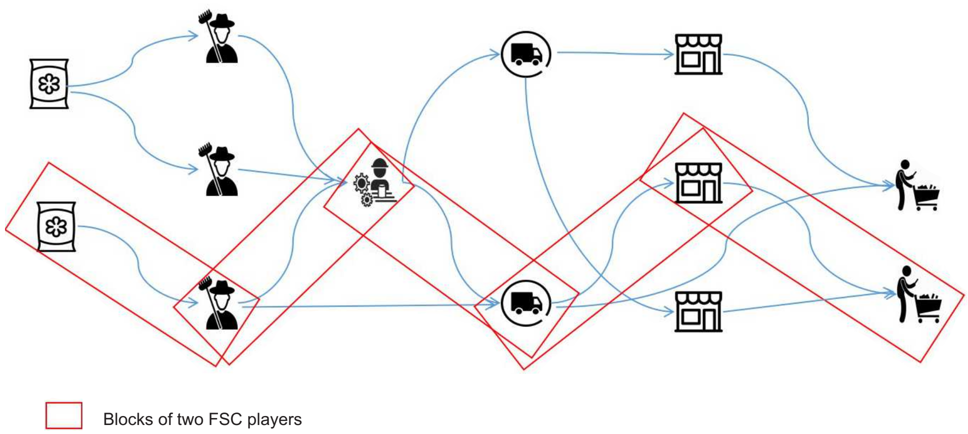

Fig. 5. Complexity of FSC and modular solution.

4.2. Detailed model architecture

Modularity of the proposed model allows dealing with any food supply chain. In this perspective, our focus will be concentrated on how this model will manage the relationship between two food supply chain factors as a solution that can be generalized within the entire chain, and how it can fight food fraud and bring transparency. The relationship between processor and farmer has been chosen to be a subject of our study in which the model must restore transparency and sustain permanently this relationship.

The model proposes (see Figure 6) that a main smart contract must be deployed in the Ethereum blockchain by which the processor can place the purchase order via his graphical interface under predetermined conditions (food temperature, humidity, soil moisture, pesticides used, ...). By the same smart contract the farmer can accept or deny the purchase order via his graphical interface.

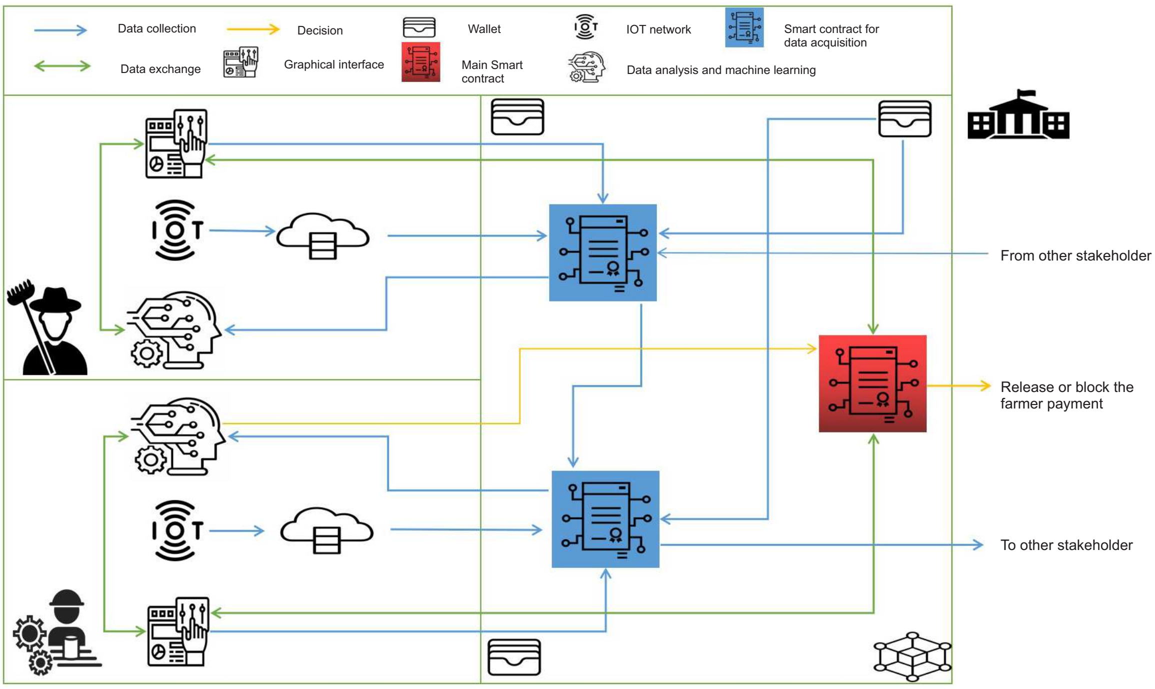

Fig. 6. Detailed model architecture diagram between farmer and processor.

Two other smart contracts must be deployed to collect and store different data in the Ethereum blockchain. The first one will be deployed by the farmer. The main role of this smart contract is collecting data about food status via the farmer IoT network implemented in his farm and all other data that cannot be delivered by sensors such information about the type of crops or the type of pesticides used to treat plants. All this data (collected by sensors or by web forms) will be transferred to the Ethereum blockchain through farmer electronic wallet. In this way, the model can be sure that the delivered information is electronically signed by the farmer via his private key. This smart contract must gather also other data that state agencies and other organizations such as bank and insurance companies must deliver via another electronic wallet designated for this purpose.

The second smart contract must be deployed by the processor. The main role of this second one is gathering data about food status in the processor's workplace through the IoT network implemented for this purpose and other data that cannot be processed by sensors. All these information must be transferred to the blockchain via processor electronic wallet to guarantee that all this data are signed in addition to other information that state agencies and other organization such as bank and insurance companies must deliver through another electronic wallet designated for this purpose. The collected data are stored in the Ethereum blockchain forever. However, every authorized stakeholder in the food supply chain can access this data via those two smart contracts.

The model proposes also that the data collected by the farmer smart contract will be processed by a suitable machine learning model and methods to ensure data quality delivered by the farmer IoT network and detect any system failure such as corrupted data delivered by a defective sensor. Machine learning helps also to monitor and control all farming parameters and performances by detecting any possible food contamination. On the other hand, the data collected by processor smart contract will be also processed by suitable machine learning model and methods to ensure data quality delivered by processor IoT network and help also processor to make a final decision whether the farmer payment must be released or blocked based on data analysis and prediction models.

5. The experimental model implementation

The designed model requires the following steps to be implemented.

5.1. IoT implementation

To monitor and supervise the food status in the farmer's workplace the following sensors are required to gather different information:

— a temperature sensor is needed to measure the ambient temperature of the area where the food is located (warehouses, farms, trucks, ...). It is also used to measure the food temperature inside those areas. DHT11 has been chosen as a temperature and humidity sensor;
— a humidity sensor is used to measure the air humidity of the area where the food is located all over the supply chain (warehouses, farms, trucks, ...). DHT11 has been chosen as a temperature and humidity sensor.

To collect data from different sensors, NodeMCU ESP8266 which is an open-source development board specially targeted for IoT based applications, will be connected to a gateway via a WIFI network is installed in the farm where the food is planted. NodeMCU ESP8266 will be programmed to collect different data using Arduino IDE software (see Figure 8), according to the following flow chart (see Figure 7).

The use of the temperature and humidity sensor and NodeMCU ESP8266 have been chosen for experimental purposes. Nevertheless, other sensor may be included such as soil moisture sensors. Moreover, electronic cards may be used with other networks such as LORA, ZIGBEE, ...; these modules use less energy.

To store the collected data, a cloud server is needed. ThingSpeaks has been chosen as a cloud server for experimental purposes. It is an IoT analytic platform service from MathWorks. It allows users to create and update ThingSpeak channels by using REST API calls (GET, PUT, DELETE and CLEAR). Users can also visualize and analyze data in the cloud. Using different sensors, the collected data will be transferred to the Ehtereum blockchain in two steps:

1) data will be sent automatically without any human involvement and in real-time from sensors (temperature, humidity and soil moisture sensors) to ThingSpeaks cloud server using GET REST API call every 30 minutes;
2) data stored in the cloud server will be transferred also to Ethereum blockchain by GET REST API call and through farmer or processor METAMASK acount. Both farmer and processor have to own an electronic wallet in the Ethereum blockchain by creating an account using METAMASK in order to be sure that every transaction is signed.

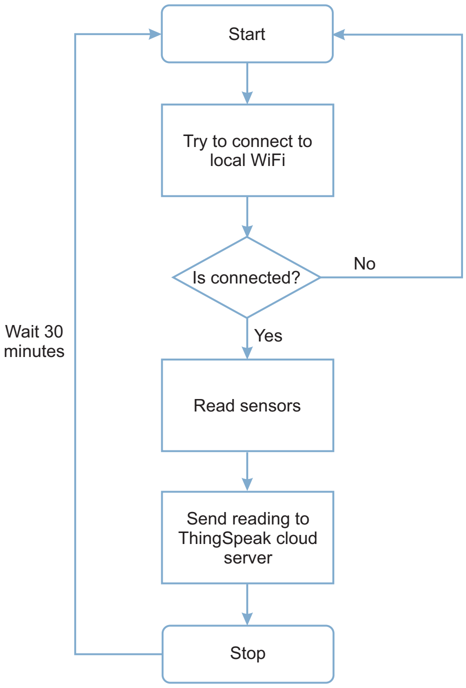

Fig. 7. Flow chart of collecting and sending data to ThingSpeak.

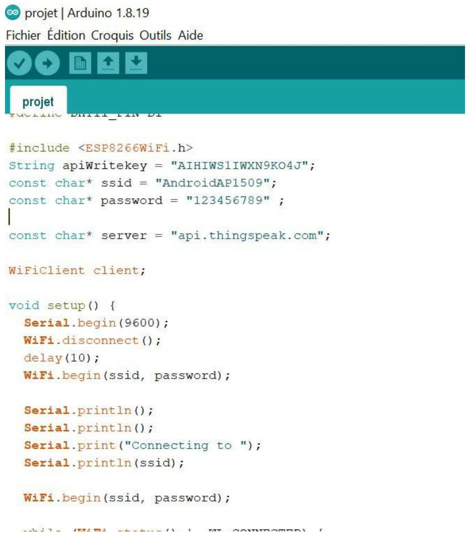

Fig. 8. IDE software.

5.2. Blockchain implementation

As it is illustrated in Figure 4, every stakeholder in the food supply chain must be considered as a node connected to the Ethereum blockchain. In our case: farmer, processor, and other external organizations must be connected to this blockchain via their electronic wallet. Ethereum platform is an open-source public blockchain that empowers not only cryptocurrency (ether) but also focuses on running any decentralized application (dapp) that establishes a peer-to-peer network. To interact with the Ethereum network, Metamask wallet must be installed. Metamask is a google chrome extension used to create accounts in the Ethereum blockchain by generating randomly both a private key and a public key; in our case, three accounts must be generated (see Figure 10). As mentioned in the model detailed architecture diagram between farmer and processor Figure 4, between farmer and processor three smart contracts are deployed in the Ethereum blockchain. The main smart contract manages and sets rules and conditions that must be fulfilled to authorize any financial movement (payments) and accountability transfer (who is responsible for food safety). The two other smart contracts are used to gather data from different IoT networks and web forms, all those smart contracts will be deployed via RIMEX ID which is a plat-

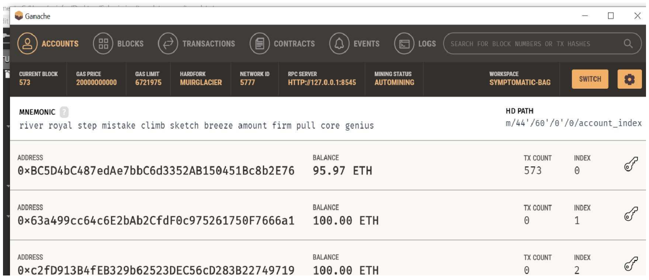

Fig. 9. Ganache local network.

form dedicated to write and deploy smart contracts in the Ethereum blockchain using the Solidity programming language. Solidity was developed by Christian Reitwiessner, Alex Beregszaszi, and other Ethereum core contributors. It is an object-oriented programming language dedicated to implementing smart contracts on various blockchains notably Ethereum, programs written by solidity are run over Ethereum Virtual Machine. Ethereum blockchain is an open-source peer-to-peer network but it is not free. Every transaction cost gas (ether) to pay miners how spending enormous energy to solve the blockchain enigma. In our case ganache will be dedicated to emulating the Ethereum blockchain so that helps to interact with smart contracts in a local private blockchain. Using 10 accounts with fake gas ganache offer, the possibility to simulate real blockchain with some additional advantages such as time of mining block is nearly 0 s, which can help saving time during the testing phase (see Figure 9).

In our case and for experimental purposes, the following setups will be followed to write and test programs and different interactions between different accounts: Jupyter notebook code will be used as a code editor to write most of pieces of the project; Python will be implemented; thanks to Web3.py which is a Python library for interacting with Ethereum. It helps with sending transactions and interacting with smart contracts, thank also to solcx which helps in compiling solidity files. In addition to that, Python will be used to write and execute machine learning models.

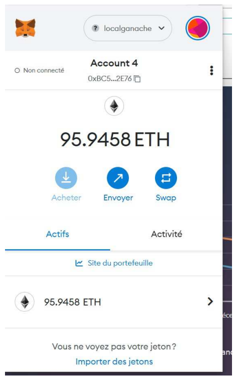

Fig. 10. Metamask account.

After writing and deploying farmer smart contract (see Figure 11) by using Python (see Figure 12) and ganache as local blockchain, a hash function of the deployed contract is generated. A combination of these hash and contract ABI will be used to interact with it in two ways:

— sending data to the Ethereum blockchain by sensors via Python script that prepare, sign and send data to the blockchain or via web form by an other script that prepare and sign and send data collected by web form;

— reading and downloading data by any authorized entity in the food supply chain by using contract function that allow making this operation.

```
//SPDX-License-Identifier:MIT
 pragma solidity ^0.8.17;

 contract farmer_contract {

      struct farmer_data {
        int _ambiant_tep;
        int _sol_mois;
        int _food_temp;
      }
      struct farmer_data_m {
        string _pesticide;
        string _Fertilizer;
        string _crop_name;
        int time;
      }

      farmer_data[] collected;
      farmer_data store;
      farmer_data_m[] collected_m;
      farmer_data store_m;

      function setPoint(int value1, int value2,int value3) external returns (farmer_data[] memory){
              collected.push(farmer_data(value1,value2,value3));
              return collected;
      }

      function getData() public view returns (farmer_data[] memory) {
```

Fig. 11. Farmer smart contract.

Graphical interfaces (see Figure 13) are needed for both farmer and processor to interact with the deployed the smart contracts by visualizing collected data and uploading data that cannot be collected by sensors. It helps also to display errors in case some corrupted data is uploaded to blockchain by any defected sensor.

```
In [ ]: ABI = compiled_file['contracts']['your file name.sol']['farmer_contract']['abi']
        Bytecode = compiled_file['contracts']['your file name.sol']['farmer_contract']["evm"]["bytecode"]["object"]

In [8]: w3 = Web3(Web3.HTTPProvider("HTTP://127.0.0.1:8545"))

In [9]: nonceA = w3.eth.getTransactionCount(my_address)
        gasPrice = w3.eth.gas_price
        Contract = w3.eth.contract(abi=ABI, bytecode=Bytecode)

In [12]: # Build a transaction
         transaction = Contract.constructor().buildTransaction(
                              {"gasPrice":gasPrice ,
                               "chainId": 1337,
                               "from": my_address,
                               "nonce": nonceA})
         # Sign a transaction
         signedTransaction = w3.eth.account.sign_transaction(
         transaction, private_key=private_key)
         # Send a transaction
         transactionHash = w3.eth.send_raw_transaction(signedTransaction.rawTransaction)
         # Wait for the pending and confirmed transaction response
         transactionReceipt9 =  w3.eth.wait_for_transaction_receipt(transactionHash)
```

Fig. 12. Deploying smart contract.

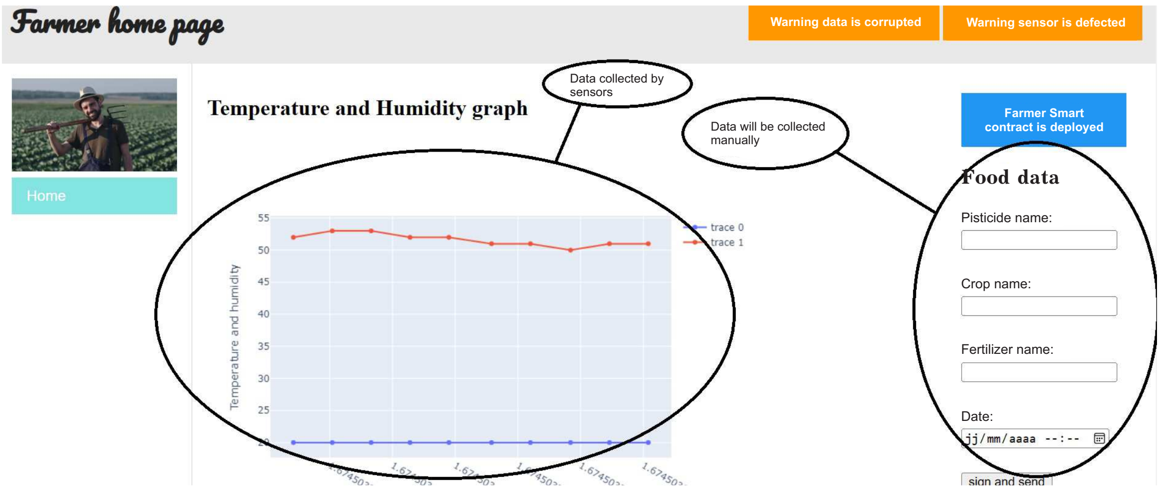

Fig. 13. Farmer graphical front end.

5.3. Machine learning implementation

The proposed model needs machine learning to build a model able to ensure that all collected data is correct by analyzing the different correlations between features and sending warnings to the concerned entity to carry out all necessary corrections because it is useless to store incorrect data in the blockchain that participants pay money for its transactions, the following steps explain how such machine learning models are established.

In our case, there is no available dataset to build a model that can predict if the collected data is correct or not. However, it is clear that there is a strong relationship between physical features such as temperature and humidity which depend on time, season and location. In this perspective, it has been chosen to build models that predict temperature and humidity in region of Casablanca, Morocco, by using climatic data collected by a local agency, the dataset is a record of humidity and temperature every hour during of last 5 years.

Three models are established: the first one predicts temperature based on the time of year of given humidity; the second model is predicting humidity based on the time of year of given temperature; and the last one is predicting temperature and humidity of a given time of years. The model verifies the data correctness as the following flow chart (see Figure 14).

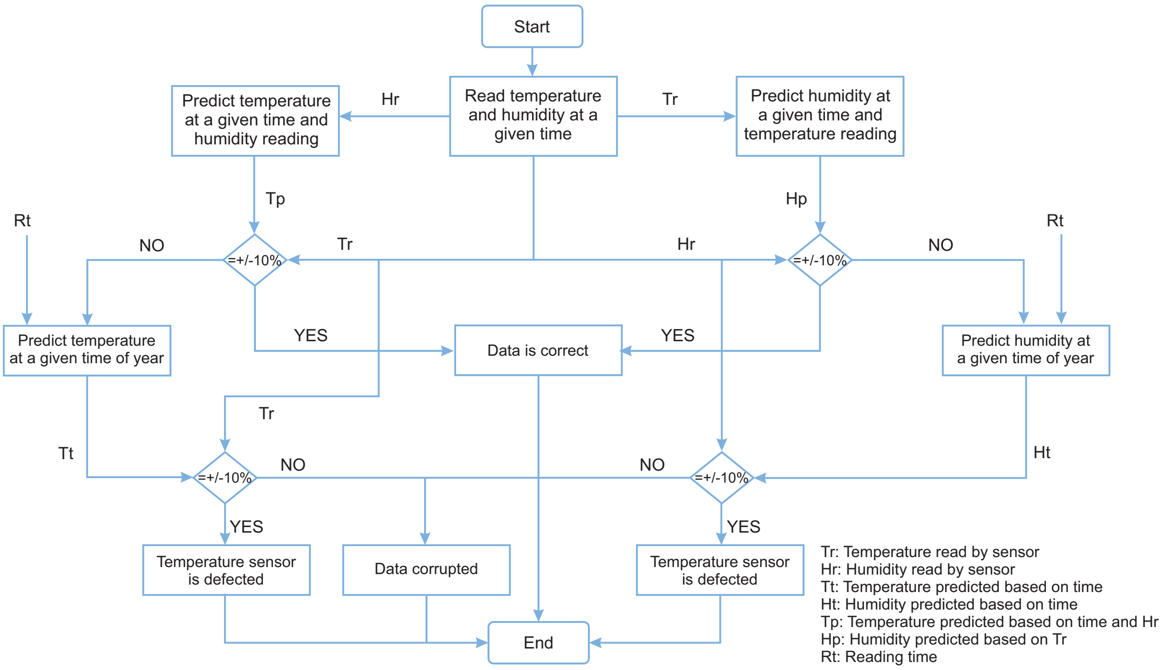

Fig. 14. Flow chart.

6. Conclusion

In this paper, it has been shown by developing and implementing a new model to track and record food, money, and information transaction within the food supply chain to ensure traceability and sustainability using a tamper-proof public blockchain. Even with the complexity of the food supply chain regarding the number of possible combinations of its participants, the modularity of the model as it has been shown allows to deal with any possible FSC by implementing this model between two successive participants, and therefore, build a general solution for the entire food supply chain. However, multiples challenges and limitations must be discussed for any future development of these models:

— the lack of historical records about food parameters and food contamination incidents makes it difficult to build machine learning models to predict food fraud, this lack can be solved by conducting an investigation into the matter or using a new technique of machine learning that can help the model to learn as it goes, and therefore, built a dataset of record based on the data collected by it;

— in this paper, it has been discussed mostly humidity and temperature as parameters to prove the validity of the model, nevertheless, other parameters can be included such as the geographical position of the food delivered by GPS, the quantity of food delivered by scales, radio frequency lectures, ..., these parameters will be included easily in the model with the same methods and techniques.

— the model enables to build of a decentralized system that enables participants in the food supply chain to exchange data and make transactions without the need for any central entity. However, the use of the cloud server, as an intermediate between IoT networks and the blockchain is the neck of the bottle that can put the system at risk, researchers and entrepreneurs are discussing this point in order to find a solution that can enable to transfer of the data directly to the blockchain without the need of any cloud server.

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Децентралізована модель для забезпечення відстежуваності та стабільності ланцюга постачання харчових продуктів шляхом поєднання блокчейну, Інтернету речей і машинного навчання

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Протягом останнього десятиліття відбулося багато інцидентів із зараженням харчових продуктів, які довели неспроможність системи керування ланцюгом постачання харчових продуктів відстежувати рух харчових продуктів, грошей та інформації в ланцюзі постачання харчових продуктів. Було створено багато моделей, у цьому документі представлено дизайн та реалізацію нової моделі, яка забезпечує збір даних у режимі реального часу, моніторинг та зберігання в блокчейні, захищеному від несанкціонованого втручання, основного руху ланцюга постачання продуктів харчування, використовуючи смарт-контракти, які розгортаються в блокчейні Ethereum, щоб дозволити кожному учаснику безпечно здійснювати транзакції з іншими FSC гравцями. Мережі IoT впроваджуються на різних робочих місцях для збору багатьох даних про стан харчових продуктів без участі людини, щоб забезпечити прозорість, за допомогою різних датчиків. Моделі машинного навчання встановлюються для забезпечення правильності зібраних даних і сприяють ухваленню рішень у програмі чи бізнесі.

Keywords: *блокчейн; ланцюг поставок харчових продуктів; IoT; простежуваність; розумні контракти; машинне навчання.*