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Agricultural traceability model based on IoT and Blockchain: Application in industrial hemp production

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ABSTRACT

Facilities based on the Internet of Things and embedded systems along with the application of ambient intelligence paradigms offer new scenarios for optimization services in agronomic processes, specifically in the hemp industry. The traceability of products and activities demonstrates the scope of these technologies. However, the technologies themselves introduce integration-related problems that can affect the planned benefits. This article proposes a model that balances agricultural expert knowledge (user-centered design), value chain planning (through blockchain implementation), and digital technology (Internet of Things protocols) for providing tamper proof, transparent, and secure traceability in this agricultural sector. The proposed approach is backed by a proof-of-concept implementation in a realist scenario, using embedded devices and a permissioned blockchain. The model and its deployment fully integrate a set of services that other proposals only partially integrate. On one hand, the design creates a permissioned blockchain that contemplates the different actors in the value chain, and on the other hand, it develops services that use applications with human–machine interfaces. Finally, it deploys a network of embedded devices with Internet of Things protocols and control algorithms with automated access to the blockchain for traceability services. Combining digital systems with interoperable human tasks it has been possible to deploy a model that provides a new approach for the development of value-added services.

1. Introduction

As agriculture intensifies and international product trade expands, agricultural products from remote areas of the world can be found in various markets located far away from their origins. In recent years, consumers have become generally unsure about the safety, quality, and origin of products. Information technologies and the latest digital paradigms can be integrated to advance new digital traceability services. This article proposes incorporating different technologies to achieve traceability in agricultural production processes, taking the cultivation of hemp as a proof-of-concept. The remainder of this paper is organized as follows. Section 2 reviews related works on information technologies. Section 3 presents the proposed model and leading technologies that allow the development of traceability solutions. Section 4 introduces the proposed blockchain platform and designed services. In Section 5, the integration of blockchain and Internet of Things (IoT) in a hemp crop experiment is reported. The results and discussion are presented in Section 6. Finally, Section 7 concludes the paper.

2. Literature review

The International Trade Centre, an agency that belongs to United Nations and World Trade Organization, and the International Organization for Standardization (ISO) define traceability in the agri-food sector as the ability to follow the movement of food through a specified stages of production, processing, and distribution [1]. Traceability allows an organization to document and locate a product through the stages involved in the manufacture, processing, distribution and handling of feed and food, from primary production to consumption [2]. The European Commission has highlighted the importance of developing advanced traceability systems as a major strategic competitive advantage versus traditional tracking systems, particularly regarding information storage, privacy control, and process transparency [3]. The UK Food Standard Agency has identified three aspects that are relevant for developing traceability systems: (a) identification of all ingredients and raw materials used to make the final product, (b) information about where and when they were transformed and moved, and (c) a system linking these data [4]. Therefore, an effective traceability system must collect the relevant data, define information owners at

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every stage of the supply chain, and establish sensors, IoT devices, and communication protocols. Finally, the information must be clearly and effectively managed and presented to all actors involved (e.g., customers, producers, retailers, governmental agencies) [5]. Further, the system must guarantee quality and safety control throughout the supply chain management [6]. Advances in technology can help to address the proposed challenges in the precision agriculture and food sectors. The first approaches to use technology in this context were based on barcodes, radio-frequency identification (RFID) devices [7], and wireless sensor networks (WSNs) [8]. The integration of all these technological resources constitutes an ecosystem called the IoT. Different wireless technologies and protocols connect smart devices to Internet protocols (IPv6). Bluetooth Low Energy (BLE), Z-Wave, Zigbee, LoRa, and LoRaWAN are examples of communication technologies integrated into precision agriculture facilities. [9] proposed a BLE sensor node for greenhouses in precision agriculture; their experimental results showed that the developed sensor node lifetime was approximately eight years. In [10] a WSN solution for precision agriculture based on ZigBee technology was proposed. LoRa and LoRaWAN have also been employed in different proposals [11–13]. Proofs of concept have already successfully demonstrated the applicability and benefits of applying technologies and embedded systems to precision agriculture [14–16]. Technological support at the edge and fog computing systems have also been proposed and tested with success [17–19]. In this regard, it can be concluded that there is sufficient hardware and communication support to address new advances. One of the most anticipated and challenging aspects of incorporating technology into the life cycle of agri-food products is robustness against fraud regarding the product origin or processing, control of the phytosanitary treatments used, conservation chain maintenance, and intermediary agent corruption. In this sense, the blockchain paradigm can help achieve traceability and transparency in the value chain of agricultural products, from planting and monitoring the crop until the product reaches the consumer through logistics and conservation. These aspects are of utmost importance for quickly identifying consignments of products in poor condition that have triggered food alerts or those that require strict supervision by authorities [20], as is the case with crops destined for the pharmaceutical industry [21]. State-of-the-art blockchain technology in the agro-food sector shows us that it is still in its embryonic state. In recent years, proposals of this technology have been presented alongside proofs of concept. Some authors have used blockchain technology for the digitalization and traceability of the supply chain, connecting it with RFID devices [22]. The integration of IoT with blockchain was proposed as part of a framework called AgriBlockIoT [23]. [24] proposed the use of blockchain and IoT devices to eliminate manual data manipulation and verification. The authors of [25] used the Ethereum platform for smart contracts in agri-food transactions.

However, no studies have considered the integration of communication protocols in the monitoring and control of production together with the business model (with human and digital tasks) in a permissioned blockchain, which would increase the security in terms of traceability and reliability. Generally, public versions of blockchain technology are used, without permission from the general ledger, which results in higher power consumption, less control over data, lower performance, and less scalability as they aim for more decentralization. These aspects of security, reliability in the business model, transaction monitoring, and maintenance of data privacy according to the profile of the stakeholder involved are fundamental to our work.

3. Proposed model

Supply chains in agriculture are complex, which often leads to a lack of transparency and traceability. The design and development of technological models that introduce a holistic approach can mitigate these problems from different perspectives. Based on the analysis of the state-of-the-art, the following challenges must be resolved for the adoption of a new technological model:

- For the technology to be effective, agricultural experts must be involved in both the design and development of the model.
- The technological solution must develop tools that facilitate the tasks of farmers, technicians, and users.
- Technological systems must be easy to integrate into real scenarios.
- Maintenance, updates, and improvement must have costs that are acceptable to the sector; otherwise, the technology will become unsustainable.
- The integration of different technologies that provide solutions to the defined objectives increase the performance of the solution.
- It is important to employ the useful aspects of each selected technology.

Considering the above aspects, this paper proposes a model based on the following paradigms:

1. System based in user-centered design (UCD) with agricultural expert participation.
2. Embedded control, communication protocols, and interfaces are adapted (IoT scenarios).
3. Business model to provide tamper proof, transparent, and secure traceability services (blockchain paradigm).

As a result of the previous analysis, the model presents an ecosystem that integrates different actors and processes, coordinated by a digital platform that allows all contributions to be integrated, centered in the *blockchain farmer plant manager (BCFPM)* concept. The BCFPM is the set of digital services and utilities installed both locally and in the cloud, adapting to the needs defined by the type of crop and decisions of the agronomic expert. It is a tool that offers traceability services to all actors involved.

This ecosystem is based on the adaptation of production technologies to different digitization tools. Fig. 1 shows the scenario and main integrated technologies with their relationships.

The participation of **agricultural experts**, the analysis and selection of **suitable technologies**, and the design of a **business model** that provides specialized services to develop process and product traceability are the core of model design for traceability in agriculture. The development of the model, based on these three main elements, is described in the following subsections. Its application is exemplified for a type of crop that requires high levels of traceability for its development.

3.1. User-centered design for adaptation and selection of digital services

Within the UCD methodology, farmers and technicians focus on the real needs in each phase of the model design process. In UCD, design teams involve all actors throughout the design process to create highly usable and accessible systems [26].

- Farmers have the agronomic knowledge, which must be transferred to the interfaces, control algorithms, and services that solve the usual problems of the processes.
- Digital technology technicians receive the opinions of farmers and decide the technologies and tools that are most suited to solving the imposed requirements.
- Other actors in the value chain (e.g., suppliers, clients, logistics, agencies) also contribute their experience to improve the services designed in the model.

3.2. IoT technologies for BCFPM development

An effective system must be able to collect relevant data to define the sources of information at each stage of the supply chain, establish the sensors and communication protocols necessary to facilitate transmission, and manage them appropriately. Furthermore,

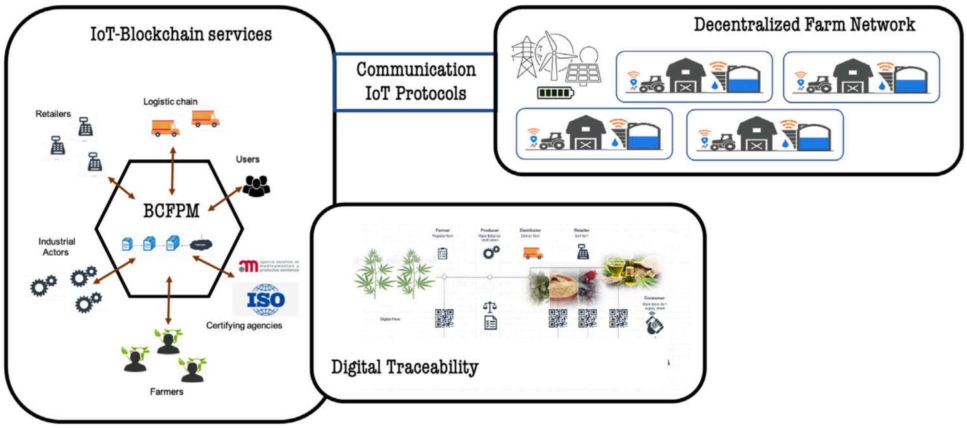

Fig. 1. Model scenario and main technologies that allow the development of traceability solutions. The *BCFPM operator* concept is introduced as a digital management tool. This virtual operator can be used by different actors to manage, audit, and certify the supply chain.

the system must guarantee quality and safety control through supply chain management. Advances in digital technology can help address the challenges posed in precision agriculture sectors. Approaches such as marking technology for traceability based on codes (barcodes, QR), RFID sensors, and wireless sensor networks (WSN) are examples of the incorporation of these advances.

BCFPM is a concept employed in the model to define an organization that manages a distributed network of facilities from cloud resources. In turn, each installation integrates local technologies that connect with the cloud technologies of the parent organization. Therefore, three types of levels are established in the IoT model design (Fig. 2): cloud network management services, local facilities management services, and connection services.

- Cloud network management. For the cloud level, certain data management, storage, and processing services have been developed by platforms such as Azure [27], IBM [28] and Amazon Web Services (AWS) [29]. Others at a smaller but much more flexible level also offer resources, such as UBIDOTS [30]. The proposed model benefits from both developing and integrating the design specifications within its services.
- Local facilities. The integration of different technological resources for action and sensorization is grouped into ecosystems based on IoT, using different wireless protocols and technologies. BLE, WiFi and LoRaWAN are communication technologies installed using current paradigms and communication protocols.
- Connection services. For the connection between the cloud platform and local facilities, a distributed network based on a type of permissioned blockchain is designed and implemented, where different organizations can act at different levels and conduct transactions of their activities in a secure manner. The blockchain technologies used are based on Hyperledger Fabric.

3.3. Blockchain for traceability

With the IoT deployed, there are facilities capable of using technologies to capture, process, and filter data locally or in the cloud, store and analyze data to optimize processes, and develop user-friendly interfaces and various utilities adapted to the needs of installation and processes. Despite all this, security, transparency, and traceability are not sufficiently assured due to the interaction of multiple agents and devices that are not always trustworthy and whose data must be tamper-proof. Systems based on blockchain have been developed exactly to resolve this issue. The basic advantages of blockchain technology are decentralization, immutability, security, and transparency. In this sense, the permissioned blockchain integration in the agricultural model aims to create an information chain accessible to different actors: government agencies, suppliers, clients, users, and associations, who must have permissions to access certain types of data in the chain.

The issues considered in each agricultural production facility include what types of data are accessible, who the authorized external actors are, what data are published, how are the processes for receiving raw materials and sending finished products designed, how data transactions are presented in the chain, and how scalability is achieved. This model provides the basis for the development of an appropriate solution. However, there may be certain variations and adaptations depending on the type of crop or industry and it is the role of the expert to provide the solution to these.

Our proposed model has a layered architecture (Fig. 2), in which the services and functionalities of the platform are integrated. At an agricultural facility (newly built or already in operation), monitoring and actuation devices are installed and connected to the processing and control layer. The following is a brief description of each of these layers.

In the **physical layer**, human–machine interfaces (HMIs) are also installed, where the farmer or technicians can act by entering data and requests. The processing layer filters data, executes control actions, and communicates with the upper layer (IoT).

The **edge layer** also receives data from the upper layer to manage the different processes and conduct control and maintenance actions. The IoT installation can be different in each design based on the type of industry, cultivation, or conditions. In any case, it must provide the necessary support to communicate the data to the installed blockchain. The interest of the integrated use of blockchain and IoT is to achieve the immutability of data obtained through secure IoT communication protocols.

The **service layer** integrates a blockchain connected to the IoT solution deployed in each facility. This layer is where the management tasks of the different local and cloud networks are performed, communicating the data from each facility (in the case of managing different facilities), as well as sending and receiving data to/from the different applications of the top layer.

In the **application layer**, applications are designed and developed on different platforms (mobile phones, business networks, computers, etc.) through the use of chaincodes to interact the blockchain. These chaincodes are the link of each application with the blockchain. In each of them, a relationship is defined between the user and type of access allowed. Chaincodes can be automated and activated when the established conditions occur; for example, if environmental conditions occur, the execution of a chaincode is activated, and an alert is sent, or other types of defined control actions are performed.

The functionality and architecture were described above. The following defines the blockchain and how it is integrated with the IoT, how it is implemented at a general level, and how it combines the

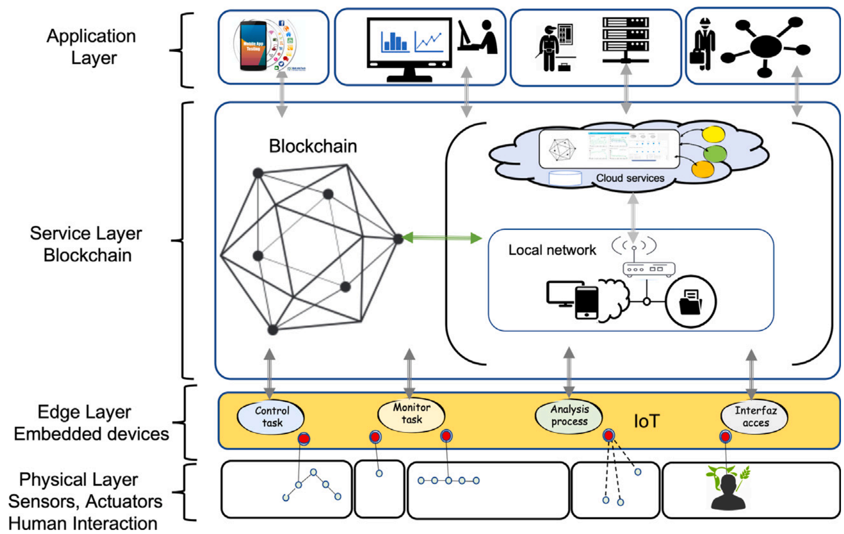

Fig. 2. BCFPM architecture. Layer-based IoT-blockchain platform.

singularities of the crop. As with selection of the appropriate IoT technologies, blockchain has various alternatives and types.

For the implementation of the traceability model connected to agricultural IoT, we selected the **Hyperledger Fabric (HF)** blockchain as the most effective technology to achieve the defined objectives. HF implements a distributed ledger technology (DLT) in a permissioned blockchain, where inserting and monitoring data using chaincodes requires entities to be previously authenticated.

IoT solutions depend on the type of agricultural facility and crops. Different communication protocols, embedded systems, and sensors are chosen for each situation. However, in all situations, the IoT must cover the following functionalities:

- Capture the data of the physical variables necessary for managing the processes (sensors).
- Install the actuators to allow manual or automatic control (actuators) using the access interfaces.
- Develop the necessary HMI interfaces so that data, actions, events, or tasks are accessible (mobile, web).
- Deploy data sensorization, control, and storage networks both locally and shared in the cloud and integrated and connected to the blockchain.
- Offer maintenance, storage, operation, upgrade, and testing services.
- Provide the necessary documentation and operating manuals.

IoT facilities are enhanced by blockchain networks, increasing the functionalities. They provide data veracity, unalterable digital records, and the potential to develop algorithms that define relationship models (business models) between different actors in the supply chain. These algorithms, called smart contracts, provide a very powerful tool to produce previously defined benefits. As for the IoT part, the facility can make the type of blockchain design change. However, it must provide the following functionalities in all installations:

- The blockchain technology allows for verification without being dependent on third parties.
- The data structure in a blockchain is append-only. Since the transactions stored in each block are recorded in an unalterable way using hash functions and, in addition, each block contains the digest of the previous one, the data cannot be deleted or altered.
- It uses protected cryptography.
- All transactions and data are attached to a block after the process of verification.
- Transactions are recorded in chronological order. Thus, all blocks in the blockchain are time-stamped.
- It is distributed across every node participating in the blockchain.
- The transactions stored in the blocks are contained in different computers participating in the chain. Hence, it is decentralized. It also ensures that lost data, if any, can be recovered.
- It reduces the risk of duplicate entry or fraud.
- With smart contracts, businesses can pre-set conditions. Automatic transactions are triggered only when the conditions produce use software algorithms.

Considering the scope of application, as the model advances, it appreciates that both technologies (IoT and blockchain) can connect and generate more robust solutions than those provided separately.

Fig. 3 shows, on the one hand, the workflow of the actions conducted between the different actors and, on the other, the main blocks that the blockchain develops according to the functionalities described above. It describes the system work and gives an understanding of each component of the proposed IoT blockchain platform. The app client provides an interface to submit transaction proposals to the blockchain network for consuming services, such as device and user registration. Before submitting a transaction, registration is required with a certificate, which contains private keys to sign the transaction. A transaction is defined as a process of reading or writing data from the blockchain network. Different devices and authorized users (farmers and technicians) can submit a transaction to register a new device or generate a new task. The IoT facility transfers the request to the blockchain network to perform operations. It can also transfer the request from a client to the device and send back collected sensing data or status changes from the device. The identity of the device owner is authenticated, and the physical device associated with the specific owner can directly submit transactions. The sensing data or status is then appended in the ledger and compared with the conditions defined by the smart contract. If the values captured reach defined levels, a notification will be generated or another task will be executed. As shown the figure, while on-premises and cloud services host client applications for data input and visualization, the blockchain network incorporates tamper-proof logic (smart contracts) to manage critical data, for example, data on environmental conditions, machine handling, timestamps of cultivation processes or access to protected facilities.

In general, a blockchain performs four actions on the transactions carried out with the client applications, the actors involved, and the IoT platform:

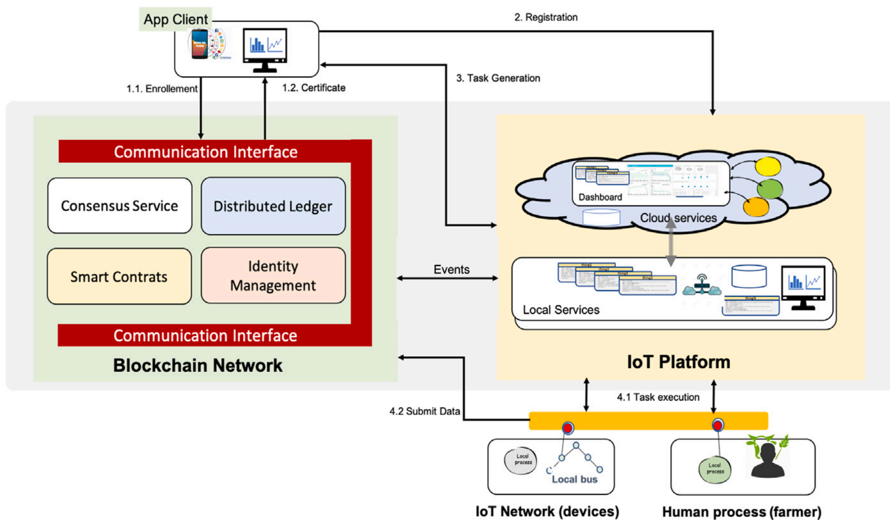

Fig. 3. Workflow between applications: blockchain and IoT platform.

1. Identity and access management, or IAM. In identity management, a blockchain enables everyone in the network to have the same source of truth about which credentials are valid and who attested to the validity of the data inside the credentials without revealing the actual data. There are three different actors in play: identity owners, identity issuers, and identity verifiers. The identity issuer, a trusted party such as the local government, can issue personal credentials for an identity owner (the user). By issuing credentials, the identity issuer attests to the validity of the personal data in those credentials. The identity owner can store those credentials in their personal identity wallet and use them later to prove statements about their identity to a third party (the verifier).
2. Consensus mechanism. This is a fault-tolerant mechanism that is used in computer and blockchain systems to achieve the necessary agreement on a single data value or single state of the network among distributed processes or multi-agent systems, such as with cryptocurrencies. It is useful in record-keeping, among other things. There are different kinds of consensus mechanism algorithm that work on different policies.
3. Distributed ledger. This is a database spread across several nodes or computing devices. Each node replicates and saves an identical copy of the ledger. Each participant node of the network updates itself independently. Blockchains are one form of distributed ledger technology.
4. Smart contracts. These are programs that run entirely on the blockchain. The properties and capabilities of the program are decided beforehand by whoever coded it. Smart contracts render transactions traceable, transparent, and irreversible. A smart contract can work on its own, but it can also be implemented along with any number of other smart contracts. Smart contracts are an extremely immature technology. Despite having significant promise, they can still be prone to problems; for instance, the code that makes up the contract must be perfect and contain no bugs.

With a blockchain suitable for integration with an IoT platform, the management properties of the identification, assurance of the consensus, and distributed network are inherently acquired. What increases the functionality is the design of the adapted smart contracts. A blockchain that integrates efficiently with the needs of the IoT is Hyperledger.

The characteristics of this blockchain, what type of smart contracts can be implemented for agricultural facilities with increased traceability, and how it is integrated with IoT services define the model. These elements are analyzed in the following subsections.

4. Hyperledger: services and network design

A blockchain is, generally, an immutable transaction ledger maintained within a distributed network of peer nodes. These nodes each maintain a copy of the ledger by applying transactions that have been validated by a consensus protocol, grouped into blocks, which each include a hash that binds it to the preceding block.

Hyperledger blockchain is a permissioned decentralized platform designed for building decentralized applications (DApps) or distributed ledger solutions on top of it. It produces efficient transactions, data transparency, and data traceability, and the process does not require third parties. From the data stored in the Hyperledger block, data traceability, control, and monitoring are tracked. In this work, blockchain services were considered as external or internal to the production process. External services are defined as those used in the supply chain, customer, or agency access. The inputs of raw materials from suppliers and outputs of the finished product are part of this type of service. The scenario that develops is diverse, with different types of actors who have different data needs. Finally, a very important type of external traceability is that offered to users, state agencies, and verification companies, which validate the processes and products (Fig. 4). This functionality is important for certain types of crops. In the case considered in this work (hemp), blockchain data access is offered to a drug agency, which can consult it for the origin of the seeds and process data and the final extraction information. Internal services, such as process control and monitoring, help optimize resources and improve crop productivity.

Therefore, this paper proposes a model that allows the integration of all the external and internal data access needs with authorizations and credentials that will allow access to specific blockchain data.

Regardless of whether the services proposed (traceability, control, and monitoring) are internal or external, the objective is always the same: to have an accessible, reliable, true, and secure record of all the processes and material conditions. These records are registered in the blocks of the blockchain. A block is a record that includes data, a value with the previous block's hash and, a value that represents its own hash.

Device users (IoT, farmers, and others) can control without a priori knowledge of the physical devices using apps and communication interfaces. Smart contracts are used to provide controlled access to the data and host the ledger functions across the network (Fig. 4). In the designed platform, we also define an access control policy, which allows participants to access a certain number of contents or transactions that are authorized. For example, only the owner of the device is permitted to access and manipulate the device. Hyperledger

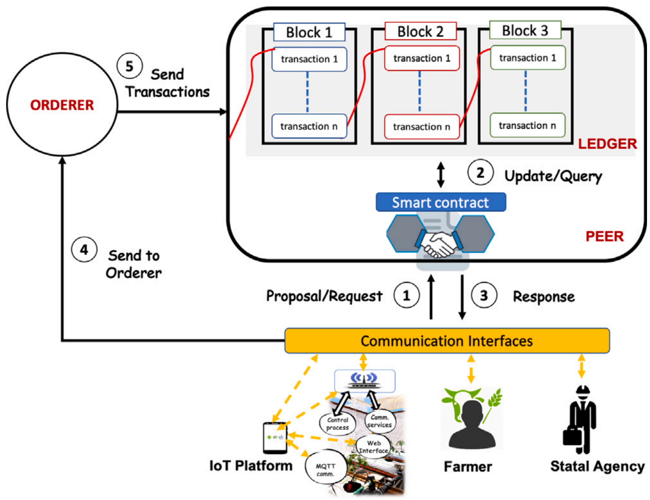

Fig. 4. Transaction process: Hyperledger blockchain and IoT integration.

is a technology not intended for large transaction data payloads, so data storage technologies are used to deal with a large amount of IoT data. In the system, a separate database (DB) is applied. This DB resides on each peer to enable large file storage and minimize duplication across the entire blockchain filesystem.

The configuration of the blockchain, necessary data transfer processes, user applications to communicate with the chain, and DBs must be designed. The configuration of the blockchain includes the design of the model and organizational policies between participants, which depend on the type of installation and established needs.

As a design model, Hyperledger offers basic patterns that can be used as a starting point. From these models, the specific needs of the installation are integrated.

Traceability, control, and monitoring services are based on access to information on products and materials throughout the processes of the value chain over time. This information is accessible, and access data are authorized by Hyperledger (blockchain) network (Fig. 5).

4.1. Hyperledger: architecture of the blockchain network

The first step in developing a Hyperledger network structure for one's application is listing the participating organizations. An organization has a security domain and a unit of identity and credentials. It governs one or more network peers and depends on a membership service provider (MSP) to issue identities and certificates for the peers as well as clients for smart contract access privileges. The ordering service, which is the cornerstone of a HF network, is typically assigned its own organization. The following diagram illustrates the designed peer network structure. Clients, MSPs, and organization groupings are proposed for traceability services. Peers are a fundamental element of the network as they host ledgers and smart contracts.

The criterion for the approval of a transaction (or invocation) is an endorsement policy. It is framed in terms of the organizations that are participating in the application network and not the peers themselves.

The sample network will consist of six organizations: suppliers (of seed and agricultural materials), producer, exporter, carrier, main ordering organization, and state agency. The suppliers and exporter organization can have different entities. Different entities are grouped into a single organization to optimize security and costs. An entity obtains the right to submit transactions or read the ledger state from its organizations in the role of a client. Therefore, the blockchain network requires different peers, each belonging to a different organization. Apart from the peers, the network consists of one MSP for each of the four organizations and an ordering service. The ordering service is implemented by a Hyperledger ordering node that accepts order transactions. Hyperledger is based on deterministic consensus algorithms; any block validated by a peer is guaranteed to be correct.

In the blockchain, six organizations come together as a consortium to form the network; their permissions are determined by a set of policies that are agreed upon by the consortium when the network is originally configured. Moreover, network policies can change over time, subject to the agreement of the organizations in the consortium. The elements that define the Hyperledger blockchain are organizations, channels, memberships, certifiers, peers, general ledger (Ledger), customer applications, and network operation policies. For the field of agricultural production, a generic organization has been designed, which can be adapted according to the specific needs of each crop or facility.

The blockchain design is illustrated in Fig. 6. Organizations O1— exploit the Hyperledger network. O4 has been assigned as the network initiator, giving it the power to set up the initial version of the network. O4 has the ordering node.

O1, O2, O3, and O6 have private communications (channel 1) within the overall network, as do O3, O4, O5, and O6 (channel 2). Each organization has a client application (A1, A2, …, A9) that can perform business transactions within the channel. Organizations O3 and O6 have client applications that can do similar work both in designed channels C1 and C2. Peer nodes P1 and P2 maintain a copy of the ledger L1 associated with C1. Peers nodes P3 and P6 maintain a copy of the ledger L1 associated with C1 and a copy of ledger L2 associated with C2. Peer nodes P4 and P5 maintain a copy of the ledger L2 associated with C2.

The network is governed according to policy rules specified in the network configuration, and the network is under the control of organization O3. Channel C1 is governed according to the policy rules specified in the channel configuration; this channel is under the control of organizations O1, O2, O3, and O6. Channel C2 is governed according to the policy rules specified in the channel configuration; this channel is under the control of organizations O3, O4, O5, and O6. There is an ordering service O that serves as a network administration point and uses the system channel. The ordering service also supports application channels C1 and C2 for the purposes of transaction ordering into blocks for distribution. Each of the six organizations has a certificate authority (CA).

The role of the IoT in the model is twofold: as a client in an organization and as a support for the development of the BCFPM model.

The agricultural installation (IoT sensors, controls, and actuators) correspond to O4 activities in the designed blockchain. Client applications that request transfers are implemented to record in L1 or L2; these transfers are automatic. They can be scheduled daily or started due to some event programmed in a smart contract. These operations are independent of manual actions and are the ones that offer communication channels to develop traceability services.

4.1.1. Creating the network

The network is formed when an order is started. In the blockchain network, the ordering service comprising a single node, O3, is configured according to a network configuration, which gives administrative rights to organization O3. At the network level, CA is used to dispense identities to the administrators and network nodes of organization O4.

The CA, which is used to issue certificates to administrators and network nodes, plays a key role in the network because it dispenses X.509 certificates that can be used to identify components as belonging to organization O3. Certificates issued by CAs can also be used to sign transactions to indicate that an organization endorses the transaction result —- a precondition of it being accepted onto the ledger.

Organization O3 updates the blockchain network to make O1, O2, and O6. After this point, a consortium formed by these organizations is stored in the network configuration. Each organization has a CA created. In the next stage of the blockchain network development, the

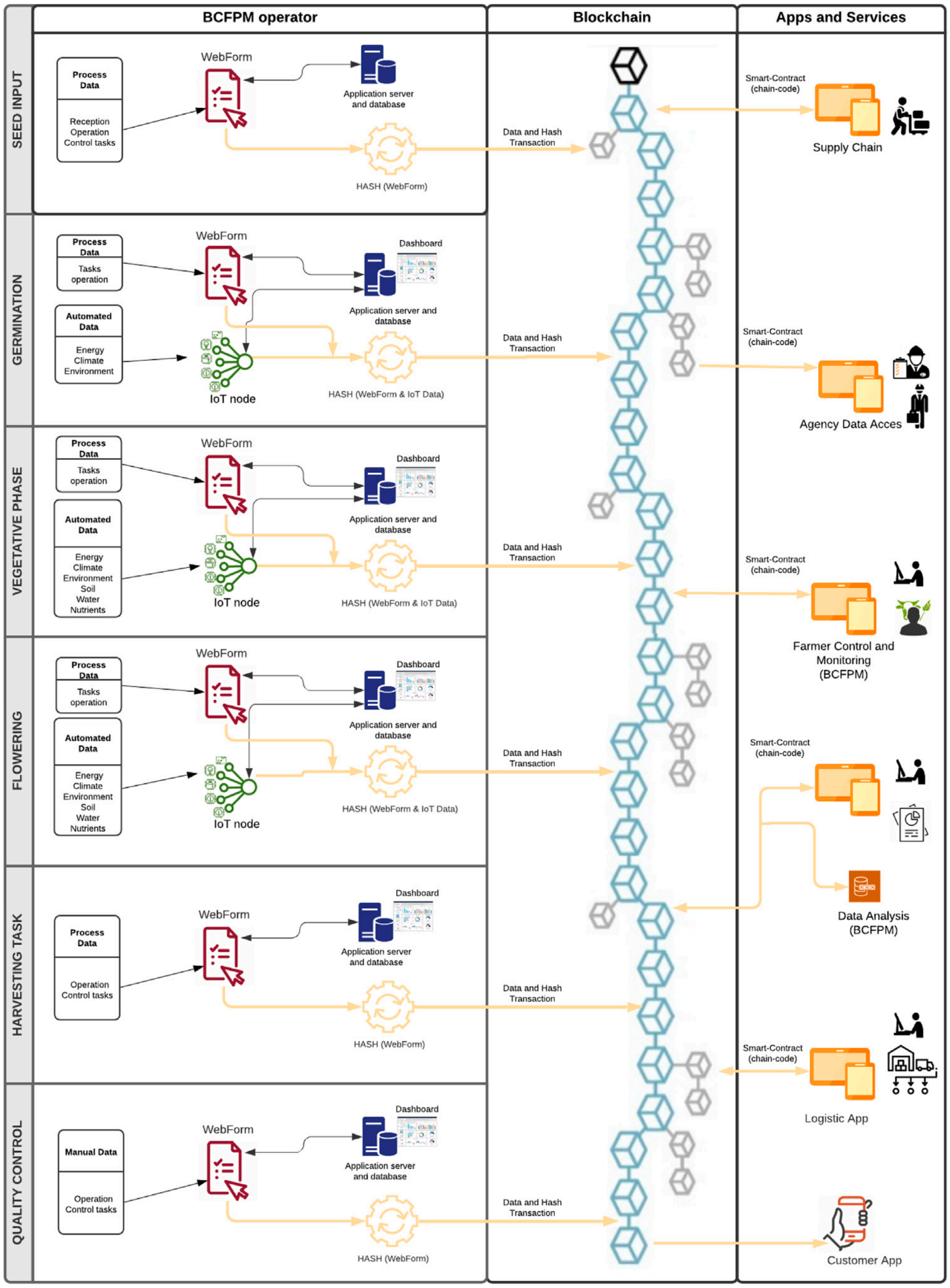

Fig. 5. Production, blockchain and services integration.

network has just acquired two new components, namely a peer node P1 and ledger instance L1.

Peer nodes are the network components where copies of the blockchain ledger are hosted. L1 is physically hosted on P1 but logically hosted on channel C1.

A key part of a P1 configuration is an X.509 identity issued by a CA, which associates P1 with organization O1. When the O1 administrator takes the action of joining peer P1 to channel C1 and the peer starts pulling blocks from the ordering O3, the orderer uses the channel configuration to determine P1 permissions on this channel. The policy channel determines whether P1 (or the organization O1) can read/write on channel C1.

Now that channel C1 has a ledger on it, client applications can be connected to consume some of the services provided by the peer.

Client application A1 can use channel C1 to connect to specific network resources; in this case, A1 can connect to both peer node P1 and ordering node O3. Channels are central to the communication between network and organization components. Just like peers and orderers, a client application will have an identity that associates it with an organization. In the blockchain network, client application A1 is associated with organization O1, and although it is outside the blockchain network, it is connected to it via channel C1. It might now appear that A1 can access the ledger L1 directly via P1, but in fact, all access is managed via a special program called a smart contract chaincode. The smart contract defines all common access patterns in the ledger. It provides a well-defined set of ways by which the ledger L1 can be queried or updated. In short, client application A1 must go through a smart contract to get to ledger L1. Smart contracts can be created by application developers in each organization to implement a business process shared by the consortium members.

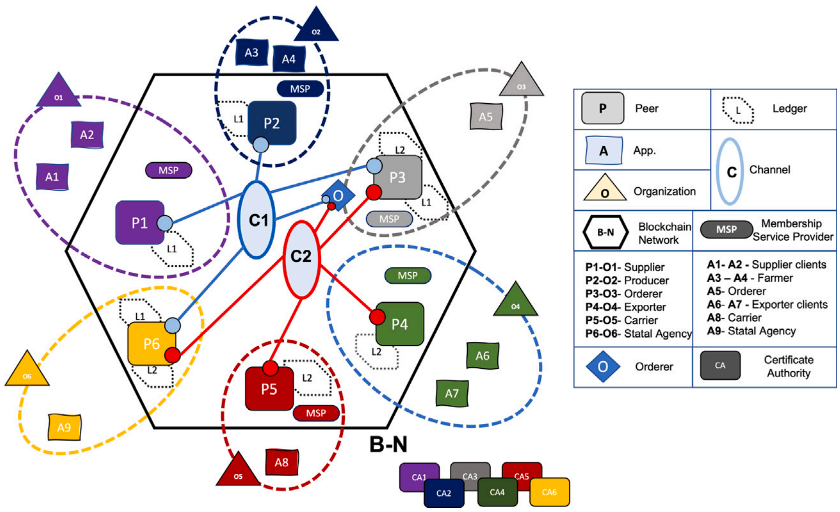

Fig. 6. Agricultural production model based on HF. Blockchain network design.

An important piece of information supplied within the chaincode definition is the endorsement policy. This describes which organizations must approve transactions before they are accepted by other organizations onto their copy of the ledger. In the blockchain network, transactions can only be accepted onto ledger L1 if O1, O2, O3, or O6 endorses them. Once a smart contract has been installed on a peer node and defined on a channel, it can be invoked by a client application. These first steps are repeated for all nodes and organizations until the operation of the network is completed.

4.1.2. Environmental impact

In recent months, the environmental impact of some blockchain networks, specifically those that support cryptocurrencies such as Bitcoin, has been called into question. This is due to the consensus mechanisms used in these networks: PoW (Proof of Work) for example, implies high computational capacity and, consequently, a growing and excessive power consumption for the mining of each new block.

In the case of a Hyperledger Fabric based network, no high computational capacity is needed, since it uses other consensus algorithms such as Kafka or Raft. Resource consumption is only due to the fact of connecting multiple computers in a network, so the power consumption and the environmental impact are substantially lower.

5. Experimental work: IoT and blockchain integration

The blockchain network design integrates different actors in the supply chain considering the productive part. To complete the supply chain, other actors not included in this work can be incorporated as new organizations with their respective applications, chaincodes, and smart contracts later. This work starts from IoT monitoring and controls a cultivation installation of industrial hemp. The type of crop and its proximity to the cannabis family means that it must be treated with a guarantee. The traceability of inputs, cultivation phases, and final processing are of interest to the organization O3 itself and to state or certification agencies (O6). The organization O3, promoting the blockchain, has an interest in developing a business model that guarantees the traceability of processes and products. A first installation is implemented and is expected to be scalable to others. Each new installation will connect to the network with its policies and processes.

Organization O2 (farmer producer) manages the applications A3 and A4. The application A3 is developed to transfer data for monitoring services and is managed by IoT control. The application A4 is used by technicians and farmers to introduce operational data processes using web interfaces.

Client applications A3 and A4 will access the records of the blockchain. The data transferred to the blockchain will be part of the traceability functionalities. A3 sends temperature, humidity, light radiation, and irrigation conditions as initially selected daily data. A4 introduces data from cultivation work (reports) and web forms completed by farmers as a daily field book.

In the IoT scenario (Fig. 7), a task computes data things (sensors and actuators) using distributed modules, taking advantage of the communication facilities. Both things and processing modules are distributed in local or global networks. The edge layer provides the reliability of response, interoperability, and time-response in control processes. Farmers and technicians in control of communication decide what the necessary applications and processes in the edge layer are. The IoT software platform is composed of data acquisition, control, communication processes, cloud services, and tools (interfaces and data storage) for users (agronomists and technicians). IoT facilities can be integrated into the blockchain network by implementing client apps. The Hyperledger framework organization requirements are treated with different communication protocols: MQTT on local control and RESTful (HTTPS) on cloud services. Computations for smaller tasks (irrigation, climate, images, crop, energy, water, and nutrients) will be implemented in a distributed control network. These smaller tasks make different interoperable data sources and control process algorithms, and all these tasks are part of the edge computing layer. In this layer, applications from machine to machine (M2M) using MQTT protocol, control, data processing, and data communication to cloud using the RESTful protocol are developed. All these protocols and resources are used to complete the integration with the blockchain and will be used to develop the blockchain network itself. MQTT is an open message protocol that enables telemetry transfer data in the form of messages from devices and sensors. Messages are a simple compact binary packet payload (compressed headers, much less verbose than HTTP) and are suited to simple push messaging scenarios, such as temperature updates or mobile notifications. They also work well connecting constrained or smaller devices and sensors to a web service, for example. The publish/subscribe model used in MQTT and many other M2M systems are mapped to resource observers.

Integrating IoT devices and data information services requires reliable (always on), responsive (fast), and massive-scale (scalable) architectures to manage high data volumes. There are different resources to implement these solutions.

The node-red framework offers a communication interface with which to integrate different APIs and platforms.

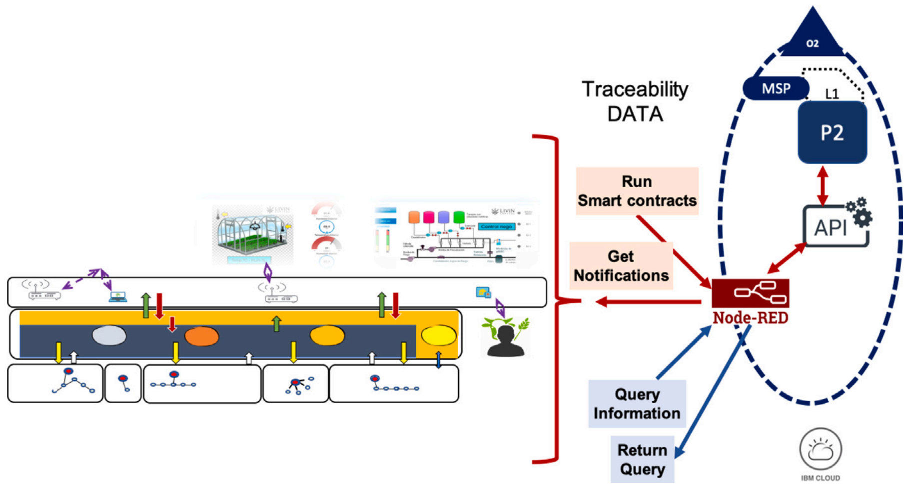

Fig. 7. IoT and blockchain integration.

Table 1
Data, services and chaincodes in the experimental Blockchain.

Phase	Data input	Blockchain chaincode
INPUT: Supplier Seed input and Storage process	Producer and Supplier data Seed type reference, license batch code Seed storage data	Authorized supply chain users and State agencies can access the data ***seedTrace chaincode***
PRODUCTION: Growing	The farmer indicates the main variables IoT data are registered	Farmer, technicians and authorized companies can access the data ***digitalBook and iotMonitoring chaincodes***
OUTPUT: Grain, Fiber or CBD extraction	Prod. and Lab report data are registered	Authorized supply chain users and State agencies can access the data *CBDextractionData chaincode*

5.1. Hemp farming

There are three products from hemp that will be of interest to the farmer: grain, fiber, and cannabidiol (CBD). For any of these end products, there will be common data for traceability and data specific to the type of product extracted.

Fig. 5 lists the data, actors, processes, and services for any type of production. Table 1 defines specific services and the first chaincodes proposed. When a chaincode is deployed, different smart contracts are available to applications. Multiple smart contracts can be defined within the same chaincode. Smart contracts are the focus of application development. Deploying a chaincode to a network makes all its smart contracts available to the organizations in that network. This means that only administrators need to worry about chaincode; everyone need only focus on smart contracts.

Fig. 8 shows information on the agricultural processes of the first plantation carried out. Crops started in the *Plant Experimentation Unit* located in the University of Alicante (Spain). Three different chaincodes are proposed to conducted data transfers and queries. In all of them, client apps are designed with node-red interfaces. This figure indicates the relationship of chaincodes in the blockchain design:

- IoT data transfers are sent automatically to control and monitor production processes. New data sent by sensors and new control services will expand the capacity of the blockchain network. Local and cloud dashboards are developed. For local access, a node-red HMI is designed for local monitoring and control. For cloud services (UBIDOTS API), different dashboards are installed with monitoring, analysis, and recording services. Transactions are made within the ***iotMonitoring*** chaincode.
- Web interfaces designed for growth control and data verification. These web forms are developed in ***seedTrace*** and ***digitalBook*** chaincodes. Using these chaincodes, smart contracts can be developed between the different actors. The data of the origin (type of seeds) of the crop and of the processes conducted in its growth are stored in the blockchain. The origin and processes can be verified according to the rules by consulting the blockchain.

Fig. 9 shows the monitoring data and control dashboard used in the IoT architecture. Local intranet and cloud services are integrated into different types of services.

5.2. Blockchain chaincodes

The first implementation is based on the resources offered in [31]. These libraries and frameworks are used to develop the integration of the IoT of the agricultural facility with the designed Hyperledger blockchain. Webform transactions, data sensors, and control and monitoring algorithms are integrated with these utilities. The goal is to decouple IoT development from blockchain implementation. In this manner, solutions can be developed independently, and any facility can be integrated with IoT devices using the enabled node-red connectors (IoT platform) and Go language chaincode (blockchain). The implemented chaincodes are ***iotMonitoring***, ***seedTrace***, and ***digitalBook***. Fig. 10 shows the chaincodes' data transfer as well as their relationships with other model components. The developed blockchain portal allows the addition of automated and manual data transactions, optimizing production and security. Queries are made from applications with interfaces designed for the different actors in the value chain (suppliers, producers, managers, consumers, certification agencies, etc.).

5.2.1. iotMonitoring chaincode

With this implementation, it is possible to automate the capturing of data that influence the crop. With the automated service, sensorization data are captured and transmitted to the B=blockchain. Agronomic experts describe the necessary variables and conditions. Sensors and data capture algorithms use MQTT, HTTP, and LoraWAN protocols and

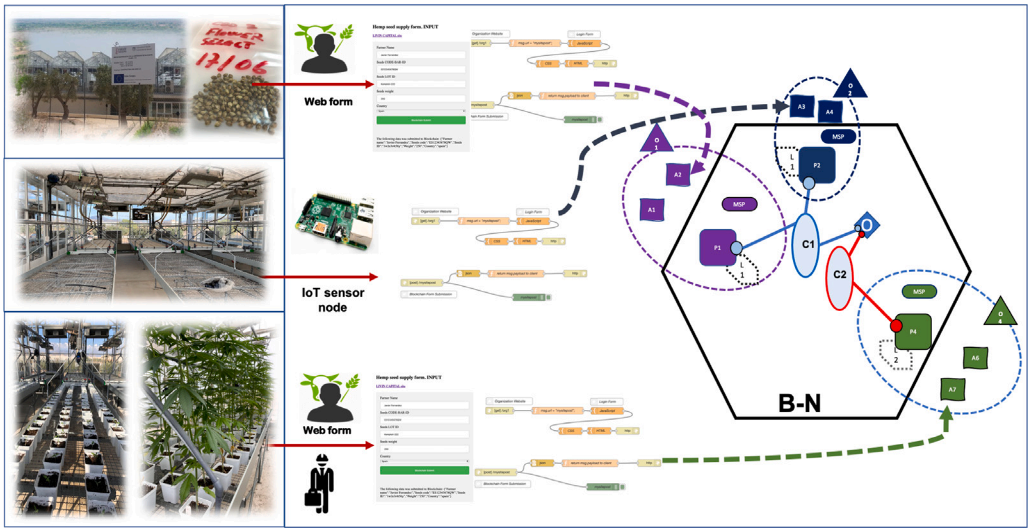

Fig. 8. First crop experimentation. Partner company: GENOMIX SL.

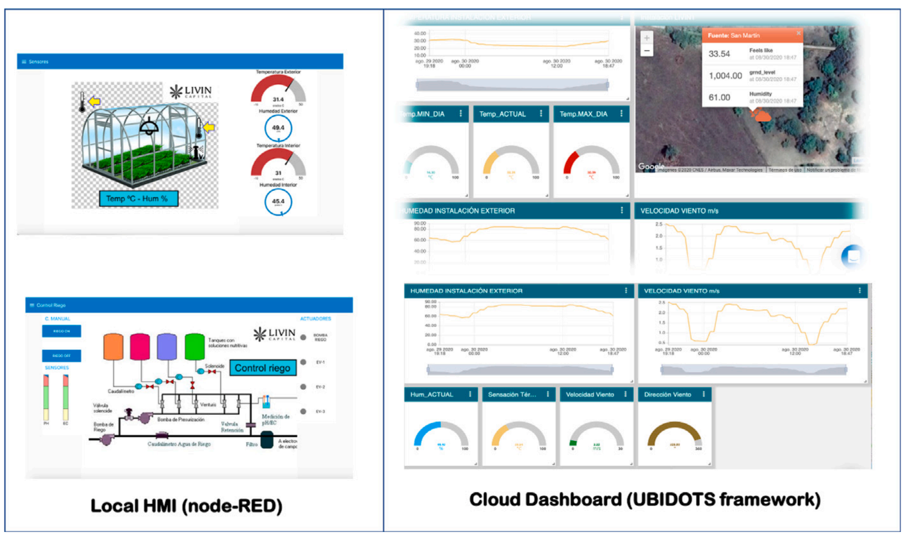

Fig. 9. Local and cloud web interfaces deployed.

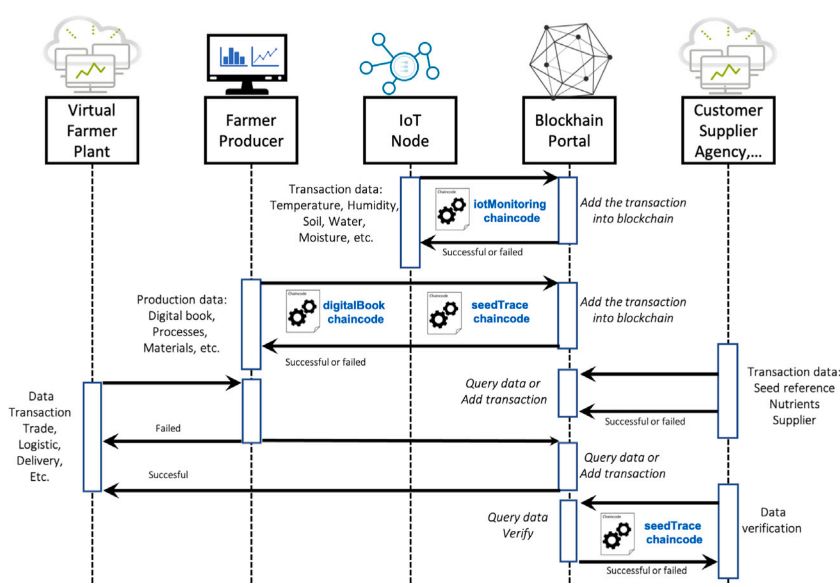

Fig. 10. Data transfer and chaincodes implemented.

node-red interfaces. Local and cloud dashboards are implemented to monitor and control the facilities. The chaincode obtains data (both local and in the cloud) to select it and store it in the blockchain. The data are filtered and processed by IoT nodes.

5.2.2. digitalBook chaincode

The objective of this chaincode is to facilitate the digitization of the different manual processes that are conducted in the growth of the crop. To obtain the necessary data, the interfaces with web forms have been implemented. The farmers and workers complete the web form for each task performed. The farmers and workers complete each workday to indicate which tasks are conducted on the crop.

5.2.3. seedTrace chaincode

Traceability is important in hemp production because it establishes safety standards for growers and producers of cannabis products. This chaincode helps to know and record the origin of the seeds. From the seed code, production is monitored; consumers and certification agencies have a secure and reliable record on the blockchain.

5.3. Blockchain portal implementation

The blockchain portal uses the Hyperledger framework, a node-red programming platform, different IoT communication protocols, and embedded electronic systems with communication interfaces. In addition, two cloud service platforms are used. With UBIDOTS, monitoring and processing dashboards of sensorization data are used. With Amazon Web Services, virtual machines that host the chaincodes and different nodes of the blockchain are used. There are two ways to request a transaction to add data: manually (through a web form) or automatically (through data capture algorithms in embedded systems). Depending on the goal, different models of web forms are designed. The web form models used in this work are integrated into the node-red platform, which acts as a gateway between the human interface and request to the API server. Node-red programming is local in scope, while the sever API can be installed locally or in the cloud. In this work, the portal was implemented in three virtual machines within the Amazon Web Services ecosystem. Sensorization data transactions are sent in time frames defined by agronomic experts. Human actions do not occur in this last type of transaction.

The experimental implementation is divided into the following phases:

- Blockchain and chaincodes.
- Local IoT, cloud platform, and web forms interfaces.
- API server development and testing.

5.3.1. Blockchain and chaincodes implementation

The consensus mechanism allows members to perform actions depending on their origin and the explicit policy criteria on the network. An example of a use case of the Hyperledger repository was used to modify it and adapt it to the model design with IoT and web form input data (***iotMonitoring***). The code below shows the chaincode structure to capture IoT data. The *asset struct* describes data used in the chaincode. The code also shows the different functions used in the creation, data transmission, and data verification in the blockchain ledger. This code has been used as a pattern of other chaicodes:***digitalBook*** and ***seedTrace***.

```
package chaincode
import (...)
        // SmartContract provides functions for managing an Asset
type SmartContract struct {
        contractapi.Contract
}
// Asset describes basic details of what makes up a simple asset
type Asset struct {
        ID              string `json:"ID"`
        Farmer          string `json:"Farmer"`
        State           string `json:"state"`
        Nday            int `json:"Nday"`
        Tmax            int `json:"Tmax"`
        Taverage        int `json:"Taverage"`
        Tmin            int `json:"Tmin"`
        Hmax            int `json:"Hmax"`
        Hmin            int `json:"Hmin"`
        Haverage        int `json:"Haverage"`
        Light           int `json:"Light"`
        Irrigation      int `json:"Irrigation"`
}

// InitLedger adds a base set of assets to the ledger
func (s *SmartContract) InitLedger(ctx contractapi.TransactionContextInterface)

// CreateAsset issues a new asset to the world state with given details.
func (s *SmartContract) CreateAsset(ctx contractapi.TransactionContextInterface,
id string, color string, size int, owner string, appraisedValue int)

// ReadAsset returns the asset stored in the world state with given id.
func (s *SmartContract) ReadAsset(ctx contractapi.TransactionContextInterface,  id string)

// UpdateAsset updates an existing asset in the world state with provided
//parameters.
func (s *SmartContract) UpdateAsset(ctx contractapi.TransactionContextInterface,
id string, color string, size int, owner string, appraisedValue int)

// DeleteAsset deletes an given asset from the world state.
func (s *SmartContract) DeleteAsset(ctx contractapi.TransactionContextInterface, id string)

// TransferAsset updates the owner field of asset with given id in world state.
func (s *SmartContract) TransferAsset(ctx contractapi.TransactionContextInterface, id string,
newOwner string)

// GetAllAssets returns all assets found in world state
func (s *SmartContract) GetAllAssets(ctx contractapi.TransactionContextInterface)
```

5.3.2. Local IoT, cloud platform and web interfaces

Local intranet is used to develop web forms and IoT data processing. The cloud platform implements blockchain services and data processing. Fig. 7 shows the architecture used in the IoT implementation. A set of sensors are selected for this first experimentation. Temperature, environmental humidity, soil humidity, pH, and electroconductivity of the irrigation water are measured by sensors installed in the greenhouse where the first hemp cultivation will be conducted. The sensor data are stored both locally (node-red) and on the cloud platform. The selected data are sent to the blockchain (Hyperledger smart contract) daily. These data are average, maximum, and minimum values calculated in the cloud IoT platform, although they could also be calculated locally. The webform is installed in a local webserver (node-red) and offers different HMIs for manual data entry. Both the web forms and IoT data capture nodes are installed on the node-red programming tool. Fig. 11 shows the steps followed by the data from when it is captured with MQTT nodes until it is sent as a transfer to the blockchain.

5.3.3. API server development and testing

A popular way of accessing an application is through the REST API implemented within some libraries. In this study, ExpressJS is used to implement one. A pattern API server is used to implement all resources. Three main utilities are implemented to interact with the blockchain: registration, transaction request, and query request. Part of this code is shown below.

```
......
app.use(bodyparser.json());
app.listen(4000,()=>{...}
// register
app.post("/register",async(req,res)=>{...}
// transaction
app.post("/tx",async(req,res)=>{..}
// query
app.post("/query",async(req,res)=>{...}
```

Once the server is installed, the Hyperledger platform has the resources to use the server through web services. Hyperledger Explorer is a tool to offer intuitive access to monitoring data transaction and blockchain status. Hyperledger Explorer is a user-friendly web application tool used to view, invoke, deploy, or query blocks, transactions, and associated data, network information (name, status, list of nodes), chaincodes, and transaction families, as well as any other relevant information stored in the ledger [32]. The Hyperledger Explorer dashboard (Fig. 12) is the home page of the HF, and it displays a set of panels that will show the latest blockchain activity. A list of the peers can be seen, followed by the latest activity and transactions by organization panels. HF is installed in the Amazon Web Services virtual machines. Access to this service is used to test the operation of transactions and inquiries. Through this intuitive access, it is possible to analyze the operation of the development platform.

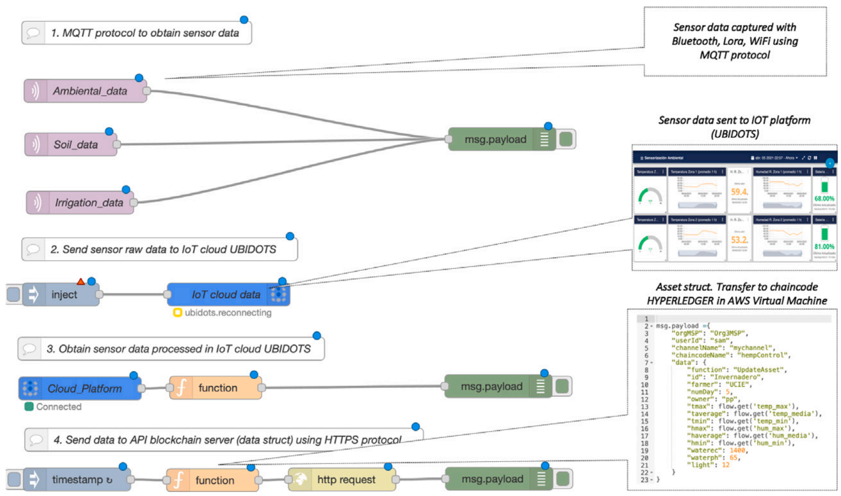

Fig. 11. IoT components in local node-red programming tool.

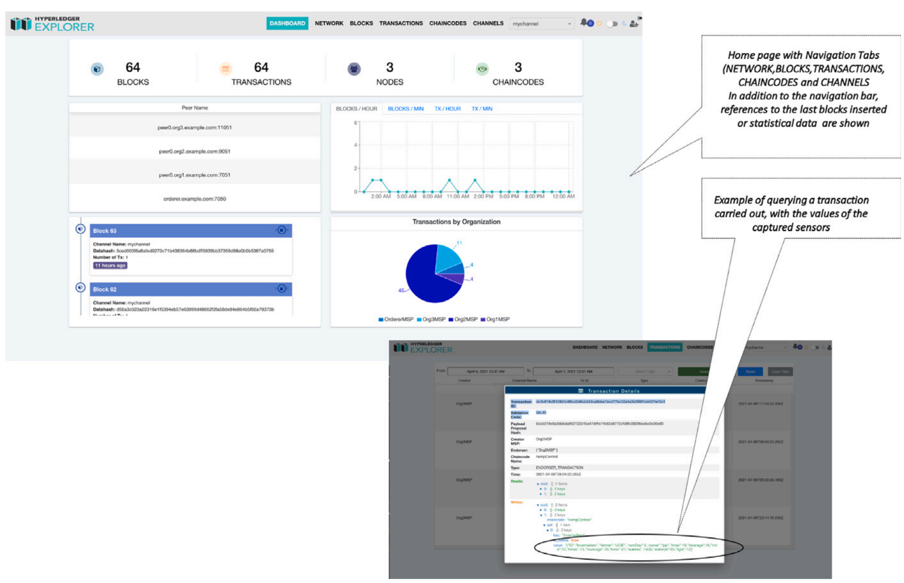

Fig. 12. Hyperledger Explorer home page for monitoring and testing. Example of query a transaction.

5.4. End-user interfaces

While the ***iotMonitoring*** chaincode can be invoked from IoT devices, the other two chaincodes developed (***seedTrace*** and ***digitalBook***) need some human interaction (farmers, intermediaries, consumers...) for data recording and querying.

To this effect, a prototype web application has been developed using HTML, PHP, and JavaScript with the Xampp development environment (Apache server). By using PHP and cURL requests we can easily invoke the blockchain network chaincodes. This prototype is intended to simulate the behavior of a future sophisticated app with the following functioning:

- On the one hand, the farmer registers in a form (Fig. 13) the different stages in the growth of the seeds, identifying them with a dynamically generated QR code. When some data are introduced by this way, a hash is applied to the data. The generated hash is stored in the blockchain ledger while the data (images, files…) are stored in a database server.
- On the other hand, the customer can use the mentioned QR code to track the seeds lifecycle. The web server loads the images correspondent to the seeds tracked, calculating their hashes, and comparing them with the ones stored in the blockchain. By this way traceability is obtained with security, checking the data integrity and reliability. This obtained data includes photographs and other information about various phases in the cultivation and transformation process (Fig. 14).

6. Results and discussion

The proposed model, as described above, has three fundamental axes: UCD, IoT technology, and the blockchain network paradigm. Therefore, it is first necessary to have an agricultural partner who supports experimentation. In the first cultivation process, the University of Alicante *Plant Experimentation Unit* and *Genomix SL* company collaborated in the process design, hardware–software implementation, and data selection for traceability, monitoring, and control services. The work aims to integrate the benefits of different technologies related to precision agriculture, IoT development, and blockchain integration. The current level of technology (sensors, actuators, embedded systems, communication protocols, and software resources) allows decisions to be made for traceability and control solutions that can be integrated

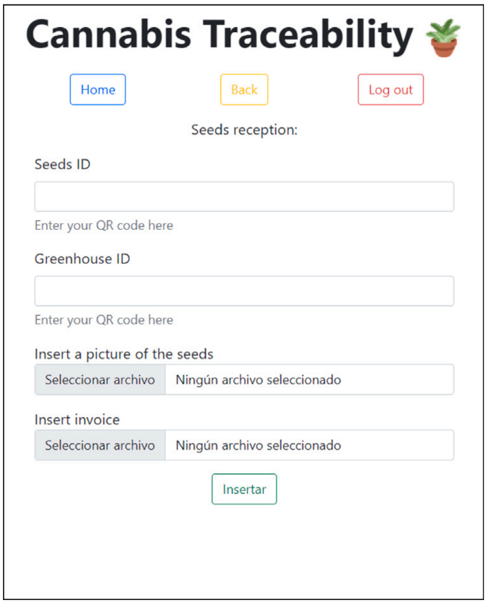

Fig. 13. End-user application from the farmer side.

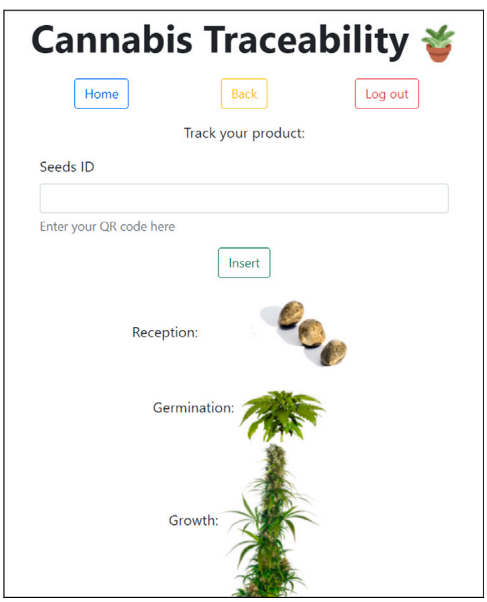

Fig. 14. End-user application from the customer side.

both in facilities already implemented and in new projects. The designed layered architecture allows each function to be integrated by levels that will make new extensions scalable. To support monitoring and control, services based on embedded systems connected with sensor/actuator networks have been designed. These networks are supported by proven technologies (Wifi, BLE, or LoRa) with mature communication protocols MQTT, HTTP, and LoRaWAN, which can operate in a local or cloud environment. Different HMI and M2M interfaces are developed depending on the farmer requirements. For such services, there are also resources to develop adapted solutions (web design, mobile apps, cross-platform, node-red language, RestAPIs, etc.). A major challenge has been the integration of blockchain with the facilities and analysis of traceability services that this technology can provide. Blockchain generally offers the ability to provide traceability solutions; however, not all blockchain technologies are suitable for integration with production facilities. In the development of this work, different alternatives were evaluated to choose the framework on which to implement the IoT integration and adapted traceability services. HF is one of those that can be applied in the model. This framework is powered by a community of companies and developers, with support that ensures its reliability. Based on the documentation in the HF development, the basic traceability services that integrate different organizations have been designed. These organizations will interact with the blockchain through client applications under a transfer and privacy policy agreed upon in the implementation of the network. The blockchain network, in turn, will connect with the facilities by automating the transfer and optimization relationship. Among the actors that are important for the type of crop are the state agencies that regulate production to ensure established quality levels. In this work, the Spanish Agency for Medicines and Health Products (AEMPS) was contacted to authorize the investigation. Once the blockchain network design has been carried out on the HF framework, the different software modules and necessary interfaces have been implemented. For this first prototype, the implementation of these basic utilities does not incur a high cost; only the necessary learning curve delays their use. In future implementations, these utilities may be designed and developed in the same way as current IoT solutions. Fig. 15 shows a summary of the results obtained in the first industrial hemp plantation, in which the knowledge of agronomic experts with advanced technologies has been successfully integrated.

7. Conclusions

With the analysis, design, and first experimental prototype work, the following conclusions were reached that reinforce the positive aspects of the applied blockchain:

- The model allows agricultural technicians and producers to participate in the design of services and business solutions.
- It provides resources and solutions to the problem of traceability.
- It can even be integrated into the business models of organizations, providing data flow security.
- It offers utilities for the optimization of internal processes.
- It allows cost saving by applying smart contracts adapted to the commercial relationships of the network participants.
- Implementation costs are not high as it allows integration with already automated installations.

This model introduces new requirements and challenges to be solved. It is software technology that must be well-designed so that it can be integrated into companies without introducing new problems. The interfaces and services must be very intuitive and suited to the way farmers and technicians work. The platform must provide for its maintenance and updating. There is also a learning curve that must be overcome. This work solves part of these requirements through the design and development of a model and experimental platform, which is demonstrated through a proof of concept. Experimentation shows the benefits of the model. The result will allow it to be used in future extensions and improvements in traceability and resource optimization services.

CRediT authorship contribution statement

Francisco-Javier Ferrández-Pastor: Conceptualization, Methodology, Software, Validation, Resources, Writing – original draft, Funding acquisition, Investigation, Supervision. **Jerónimo Mora-Pascual:** Conceptualization, Writing – original draft, Resources, Software, Investigation. **Daniel Díaz-Lajara:** Software, Writing – review & editing, Data curation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

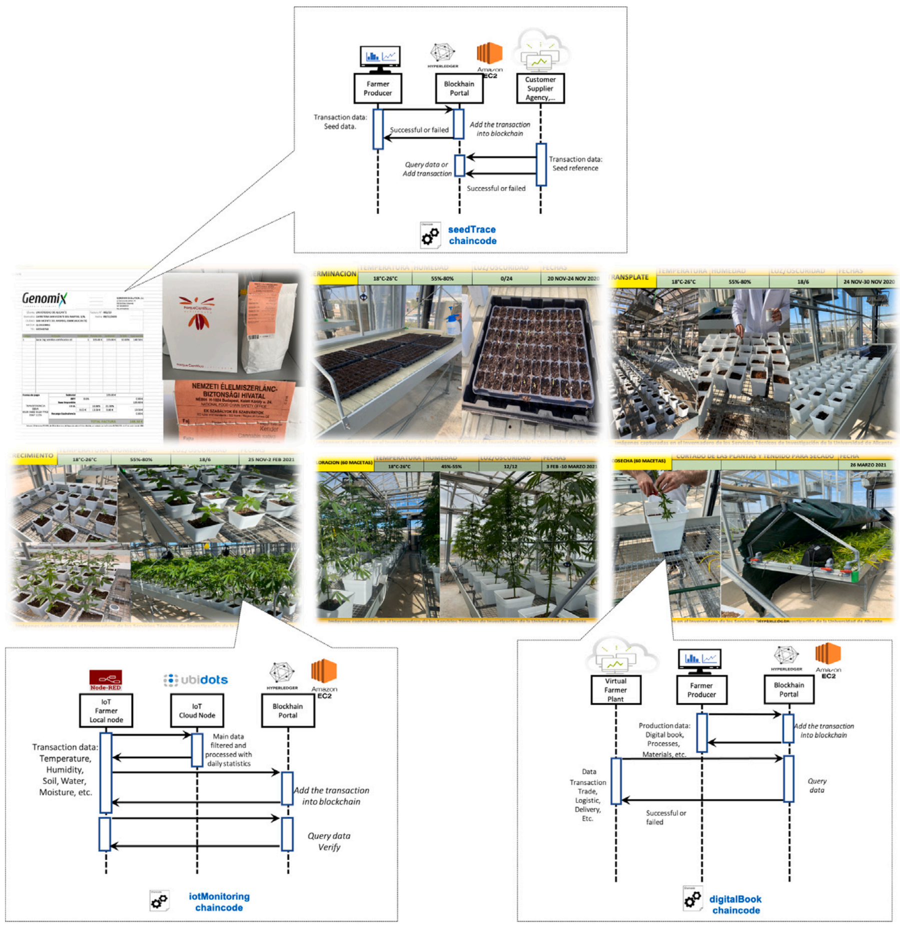

Fig. 15. First experimental hemp plantation with blockchain services integrated. Cultivation phases and their relationship with the chaincodes and data transfer.

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