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Research Article

An RFID-Based Tracing and Tracking System for the Fresh Vegetables Supply Chain

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The paper presents an innovative gapless traceability system able to improve the main business processes of the fresh vegetables supply chain. The performed analysis highlighted some critical aspects in the management of the whole supply chain, from the land to the table of the end consumer, and allowed us to reengineer the most important processes. In particular, the first steps of the supply chain, which include cultivation in greenhouses and manufacturing of packaged vegetables, were analyzed. The re-engineered model was designed by exploiting the potentialities derived from the combined use of innovative Radio Frequency technologies, such as RFID and NFC, and important international standards, such as EPCglobal. The proposed tracing and tracking system allows the end consumer to know the complete history of the purchased product. Furthermore, in order to evaluate the potential benefits of the reengineered processes in a real supply chain, a pilot project was implemented in an Italian food company, which produces ready-to-eat vegetables, known as *IV gamma* products. Finally, some important metrics have been chosen to carry out the analysis of the potential benefits derived from the use of the re-engineered model.

1. Introduction

The ability to track and trace complete information at item level in an efficient and trustworthy manner is becoming more and more important for companies, mainly due to the increased consumer concern over the safety and the quality of the purchased products. This is even more true for companies involved in the fresh vegetables supply chain, because the delicacy of fresh-cut products requires all stakeholders to organize their business processes as efficiently as possible to guarantee the end customers the highest quality products. The shift from quantity-oriented agriculture to new emphasis on products quality and people's safety has placed new demands for the development and adoption of traceable supply chains. Traceability represents the ability to capture, collect, and store information related to all processes in the supply chain in a manner that provides guarantee to the consumer and other stakeholders on the origin, location and life history of a product. In particular, the adoption of an effective gapless traceability system, in the fresh vegetables supply chain, could enable companies to (i) detect warnings associated with product contaminations quickly and accurately, and (ii) optimize their main production processes in order to reduce cultivation costs and to ensure, at the same time, production optimization. Furthermore, an efficient traceability system represents a fundamental tool for people with special needs, such as patients affected by multiple intolerances [1], who struggle every day to perform elementary actions, such as the choice of food, because of the adverse reactions that particular components could cause if taken.

The development of an efficient traceability system requires the introduction in the supply chain of the technological innovations needed for product identification, process characterization, information capture, analysis, storage, and transmission, as well as the overall systems integration. These technologies include hardware (such as identification tags and labels) and software (computer programs and information systems) solutions. In particular, two of the most important auto-identification technologies able to optimize the critical processes in a supply chain are Radio Frequency IDentification (RFID) [2] and Near Field Communication

(NFC) [3]. They promise to replace the traditional optical auto-identification solutions in near future. Among the different types (i.e., passive, semipassive, and active) of RFID transponders, often called “tags”, the passive ones are used in most tracing systems, because they are characterized by a very low cost and small dimensions, since they do not require battery to operate. Passive RFID tags can also be classified according to the frequency band used (e.g., LF, HF, UHF, etc.) and the type of coupling (i.e., magnetic or electromagnetic) between tag antenna and reader antenna. The UHF tags could occasionally encounter problems, causing performance degradation, in the presence of materials, such as liquids and metals, which absorb Radio Frequency (RF) energy. However, some recent works [4–7] have demonstrated that the design of particular UHF tags is able to resolve such issues, thus demonstrating that they represent the best solution for item-level tracing systems in the whole supply chain. NFC is a short-range wireless (HF 13.56 MHz) technology derived from the RFID family. NFC entities can share power and data over a distance of a few centimeters (less than 5 cm). They inherit the basic features of RFID technology (i.e., working in reader/writer mode with passive tags) but they are also characterized by the possibility to share data across active (powered) devices [8]. The diffusion of these RF technologies has been significantly increased by the asserting of international standards such as EPCglobal [9–12] and Global Standard 1 (GS1). In particular, the EPCglobal standard provides a promising open architecture for tracking and tracing objects over the Internet. It defines a full protocol stack able to guarantee item-level data sharing related to products that move in the whole supply chain.

The combined use of different RF technologies and standards in order to improve the supply chain management has been strongly investigated in literature [13, 14]. They were also successfully applied to the agro-food sector [15, 16]. However, the development of a complete gapless traceability system, from the land to the table of the end consumer, is still at the early stages and many issues are still open. Most works propose solutions too invasive and, therefore, not accepted by the operators. A typical example concerns the use of Wireless Sensor Networks (WSN) in greenhouses in order to achieve a precision agriculture [17–19]. Although the use of this technology promises many benefits, its adoption is very limited, since expert agronomists, that argue no sensor node can ever replace their skills, do not accept its use. Therefore, a very critical aspect in a reengineering procedure is that the proposed solution must be thoroughly understood by the operators, before to be accepted, and applied. Furthermore, costs related to the introduction of new technologies are relevant and block their wide adoption. Indeed, although most of the solutions presented in literature are exclusively based on the use of RFID tags, the cost of a tag is still too high to justify its adoption in the packaging of low cost products, such as fresh-cut products, whose price in Italy is about 1-2 euro per pack. Particular attention must be also paid to the choice of the type of tag to be used, since such tags must be used in critical conditions and, in particular, in humid environments, which absorb RF energy. Another important issue still open in the design of an effective traceability system in the fresh vegetables supply chain is related to the integration of management systems of all involved actors. Vegetables producers are generally small local farms without a proper information system, and therefore, actors interact through traditional channels (i.e., phone, fax). However, since the manufacturer can be considered the main actor of the fresh vegetables supply chain, a complete integration of the production company systems could represent an important starting point.

This work proposes an EPC-based gapless traceability system for the fresh vegetables supply chain able to exploit the combined use of different auto-identification technologies, such as RFID, NFC, and the less expensive DataMatrix. Particular attention was focused on the producer, and, therefore, on the early stages of the supply chain, which include farming in greenhouses and manufacturing of packaged vegetables. The proposed item-level tracking and tracing system is characterized by a perfect integration among the adopted hardware and software subsystems in both the greenhouses and the transformation factory, preserving the role of agronomists and reducing the costs for the adoption of new technologies. Specifically, an innovative and low-cost hybrid system, in which the gapless traceability is ensured by the combined use of EPCglobal, passive UHF RFID solution, Android NFC smartphones, NFC tags (i.e., passive HF tags), and the less expensive DataMatrix technologies, is proposed. Furthermore, an Enterprise Service Bus (ESB) [20] is adopted to deploy both traditional and innovative management services in the greenhouses. A clear separation between the logical EPC-based traceability architecture, and the physical infrastructure is a key factor in the proposed system, as it ensures a smooth, gapless, and flexible product traceability both in the greenhouse and in the transformation factory. To validate the proposed reengineered model, a pilot project was implemented in a big Italian producer company. Measurements of the main Key Performance Indicators (KPIs) [13] demonstrated the benefits derived by the use of implemented traceability system in a real scenario.

The rest of the paper is organized as follows. Section 2 introduces the reference scenario, highlighting main problems. The proposed reengineered model and its implementation in a real pilot project are reported in Section 3. Main details related to the software system architecture are summarized in Section 4. In Section 5, a description of the hardware adopted in our work is reported. A system validation is discussed in Section 6. Finally, Section 7 summarizes the conclusions and sketches future works.

2. Main Requirements and Open Issues in the Fresh Vegetables Supply Chain

The quick perishability of the *IV gamma* products, typically characterized by a shelf life of few days, makes the fresh vegetables supply chain, shown in Figure 1, a very interesting scenario.

Figure 1: The fresh food supply chain.

The three main actors involved in this supply chain are as follows.

(1) The *farm*, which produces in farmland and greenhouses the raw materials (e.g., salad, lettuce, rocket, etc.).

(2) The *transformation company*, which purchases and handles large amounts of raw materials in order to produce packaged vegetables.

(3) The *retailer*, which, in general, sells finished products to the end consumer.

In order to study the main open issues of the analyzed scenario, one of the biggest fresh vegetables producers in the South of Italy, Jentu S. Agr. r. l. [21], was investigated. It includes two production centers located in different sites but is characterized by the same product flows.

In the following, the two phases of vegetables cultivation and products transformation are separately analyzed in order to better identify the main points where the use of innovative technologies, such as RFID, NFC, and EPCglobal, could improve the production capacity of the company. Let us observe that the conducted analysis did not involve the transportation process of the harvested vegetables, from greenhouses to the transformation factory, because it is not interesting from a reengineering point of view, since it does not affect on the products quality. In the considered company, in fact, greenhouses are located very close to the transformation factory.

2.1. Vegetables Cultivation. The cultivation phase affects the whole life cycle of vegetables, and it includes the activities of seeding, growing, harvesting, and so forth. All these activities are usually coordinated by an agronomist.

In particular, the Jentu company has several greenhouses, where a portion of the raw materials used in the transformation phase is cultivated. The agronomist, during her/his usual check visit, manually performs the activities of ground sensing and vegetables evaluation. In this step, she/he stores on paper notes all qualitative information detected.

The agronomist uses the captured parameters to decide actions to apply on plants and grounds and she/he annotates all performed operations (i.e., irrigation, sowing, treatments with plant protection products) on a paper form. Periodically, these data are saved into a digital system called "Field Log". It is a management software tool that allows the farm to carefully store very important information about the operations carried out on plants, the adopted cultivation methods, and the use of approved cleaning products. Some activities, such as irrigation and temperature control, are executed in automated manner through remote terminal units and an advanced computerized control system.

Pallets, composed of bins, are used to move crops from the greenhouses to the transformation factory. The partition of a crop in different bins is needed in order to allow its partial use during the production steps, depending on retailers' orders. Before being processed, the crop is weighted, classified and made identifiable by the attached form.

Let us observe that the activities performed by the agronomists are highly exposed to human errors and imprecision, mainly due to the manual execution of the operations and the asynchronous storing of the gathered data.

2.2. Products Transformation. The products transformation phase starts when one or more pallets of raw materials, coming from the greenhouses, are moved into the transformation cycle. A first check of the incoming products is performed. In particular, the quality control manager identifies the correct greenhouse of origin, by reading manually (i.e., without the use of an electronic device) the lot number placed on each pallet, and carries out the weighing process. The obtained data are compared and checked with the information reported on the delivery note. Furthermore, before being accepted, the incoming raw materials must pass a rigorous quality control process. In this case, the operator stores all data about the received products in the company Information System (IS), and prints the "raw materials identification tag" associated with the accepted pallet. This label contains, in addition to information about the quality of the accepted materials, the incoming date and a lot number associated with the particular bin of received products. This correlation is maintained in the "goods weights registry entry" document. Moreover, the identification label includes a linear barcode encoded in Code-128 format.

The accepted pallets are temporarily stocked in a storage warehouse, where they are arranged according to the arrival order, so as to be picked up more easily. Here, the temperature is always maintained between 0°C and +4°C to avoid the deterioration of the fresh products. The pallets are moved into the transformation process according to the First In First Out (FIFO) discipline. More in detail, the operators, by reading the information written on the label associated with each pallet, choose those with the earliest incoming date. Let us observe that this process can easily lead to the selection of wrong pallets, thus increasing the amount of product to be discarded in the next steps (e.g., husking).

The transformation process is essentially composed of different activities, such as husking, cutting, sorting, washing, and drying, which transform the raw materials in finished ready-to-eat (RTE) products. It starts when the operators pick up the pallets from the storage warehouse and move them into the husking area. In this step, the operator has to fill the "line loading register", which contains important data for the product traceability, such as the lot number and the number of bins involved in the transformation process, the signature of the operator carrying out the registration, and the start and end times of the transformation process. The semifinished products are stored in a cold room where they remain waiting to be picked up for the next phase of packaging.

The finished product is packaged and labeled manually or automatically. The packaging is done in a controlled atmosphere. The label on each package reports the ingredients of the product itself, information about the producer company (name and address), the method of conservation (in the refrigerator from +2°C to +8°C), the expiration date (calculated summing 7 days to the production date), a linear bar code encoded by EAN 13, and an alphanumeric string, which identifies the lot.

Finally, the packaged products are placed in plastic boxes and arranged on pallets, according to the orders received from customers. It is important to observe that, in this step, the labels attached on some packages, chosen in a random way, are checked. If a not compliant label is identified, the product is discarded and the entire pallet is checked. The prepared pallets are then moved into the outgoing warehouse, where they remain waiting to be shipped to the point of sale.

Unfortunately, most of the activities of the transformation cycle are performed in manual mode and, therefore, they can represent critical issues of the considered supply chain, especially in terms of timeliness (time spent on the activity) and correctness.

2.3. Requirements for an Efficient Traceability System. The conducted analysis allowed us to identify the main requirements that an efficient gapless traceability system, from the land to the table of the end consumer, should satisfy as follows.

(i) Minimize the error probability in the procedure of data gathering and transcribing into the information system of the company.

(ii) Allow the company to collect automatically a high amount of data, which can be used to provide to the end consumer a complete pedigree of the purchased products, from the land to the table of the consumer.

(iii) Allow a correct and efficient flow of critical information through the whole supply chain, as the product is cultivated, transformed, transported, stored, and sold.

(iv) Allow the company to improve recall procedures, reduce contaminations, and minimize risk in the supply chain.

(v) Optimize the logistic process in terms of human resources and time.

3. Reengineered Model

The analysis of the open issues in the fresh vegetables supply chain allowed us to propose an efficient re-engineering of the main critical processes, exploiting the combined use of innovative RF technologies and the EPCglobal standard. In particular, the reengineered model was defined considering the adoption of passive RFID technologies in UHF band, such as transponders, readers, and antennas. Furthermore, a software infrastructure on top of the Fosstrak framework [22] was developed. In order to better appreciate the main benefits that the proposed model is able to provide, a pilot project was implemented and validated in the Jentu company.

3.1. Vegetables Cultivation. In the cultivation phase, the use of NFC tags is proposed to identify both the operators and the fields where vegetables are cultivated. In particular, greenhouses and fields are partitioned into small portions, where only one type of product is cultivated. Each of these plots of land is uniquely identified by a NFC tag placed on a wooden pole. In such NFC tag an EPC code, encoded with the SGLN (Global Location Number) schema, is stored. The agronomist is provided with a badge containing an NFC tag, and she/he uses an Android smartphone equipped with NFC technology to store all information about activities performed on crops into the Field Log, avoiding the use of paper notes. More in detail, at the end of a treatment on a specific plot of land, the agronomist identifies herself/himself and the treated plot of land, bringing the NFC reader integrated in her/his smartphone to the tag placed on the badge and on the pole, respectively, and automatically stores all data about the performed operations in the mobile Field Log application. These data are immediately sent to the information system of the producer company, thanks to a wireless connection (i.e., 3G). It is noteworthy that the use of small plots of land allows a considerable reduction of the amount of resources used, such as fertilizers and water (i.e., these are used only where needed), while ensuring the production optimization (i.e., it can be slowed or accelerated on the base of the requests of the company). Furthermore, during the harvesting phase, the use of bins and pallets tagged with passive UHF RFID tags is suggested. In this step, the agronomist, after identifying herself/himself as previously described, uses a portable UHF RFID reader, connected via Bluetooth with the smartphone, to scan the EPC code applied on each bin of raw materials. Finally, this association is sent to EPCglobal-based traceability system and stored in the EPC Information Service (EPCIS) repository. This solution aims at enabling a complete traceability, which started from field.

3.2. Products Transformation. As previously described, bins and pallets of raw materials, which are moved into the transformation cycle, are tagged with passive UHF RFID tags. This type of tag is considered mainly because it is able to guarantee high performance in presence of multiple readings. Furthermore, thanks to a native feature of the EPCglobal standard, a traceability system in the whole supply chain can easily trace information at different layers (i.e., pallet, bin and product). In particular, EPC Global Returnable Asset Identifier (GRAI) [23] encoding scheme is used to tag pallets; EPC Global Individual Asset Identifier (GIAI) [23] encoding scheme is used to tag bins. According to the reengineered model, the incoming warehouse of the company is equipped with a RFID gate composed of one UHF RFID reader and four Far Field antennas in UHF band. This configuration, in fact, is able to guarantee high performance in terms of successful reading rate of bins. A worker, after performing the weighing process, moves the pallets through the gate, enabling the automatic identification and validation of all incoming bins. The retrieved data are immediately compared with the information contained in an electronic version of the delivery note and saved in the information system of the producer. In such a way, the quality control manager has only to store data about the weigh and the quality control check executed on the accepted materials. All information not necessary for products traceability, but important for the company, are stored in an Enterprise Resource Planning (ERP) database. For this purpose, an ad hoc Web service has been developed. This solution aims at removing efficiency problems, due to the manual execution of control and registration operations, currently performed as described in Section 2.2.

In the reengineered model, pallets and bins of raw materials stocked in the storage warehouse are tagged with passive UHF RFID tags and, therefore, an operator, by using a portable UHF RFID reader, can easily identify the appropriate pallets or bins to move into the manufacturing process. Two snapshots of the application used by the operator in this phase are shown in Figure 2. Let us observe that, also in this case, the combined use of RFID and EPC is able to overcome the efficiency limits previously described.

An UHF RFID gate, placed at the entrance of the husking area, detects the bins of raw materials moved into the transformation process and automatically updates the information system of the producer. Let us observe that the use of RFID technology allows to substantially mitigate correctness and timeliness problems, since all the information previously recorded manually by the workers are now detected by the gate and managed by the information system. The low cost of fresh ready-to-eat products does not justify the use of RFID tags to identify each item; therefore, the adoption of the DataMatrix technology is proposed to implement an efficient item-level traceability system. Each finished RTE product is labeled using a two-dimensional barcode containing the Serialized Global Trade Number (SGTIN) EPC code in ECC 200 encoding scheme. By this way, a 2D code reader can be used to trace data on each finished product.

Finished products, before being placed in reclosable boxes equipped with UHF RFID tags, are read by a DataMatrix reader. Furthermore, the use of an UHF RFID reader enables the association between the packaged products and the boxes that contain them. By this way the system can easily trace all products included in a well-defined box. Subsequently, the boxes are arranged on pallets tagged with UHF RFID tags and moved to the outgoing warehouse, equipped with a UHF RFID gate able to automatically detect this transfer and store the associated information in the information system of the company. The combined use of RFID and EPC technologies substantially improves these activities, removing efficiency problems, due to the manual execution of the control operations described.

Finally, the use of an item-level tracing system based on the EPCglobal standard optimizes the main activities related to the return flow management process. For example, it enables the automatic identification and tracking of all products returned from a retailer. Furthermore, by using a complete traceability system, the producer company can exactly know which other products were sold to the same retailer, substantially improving the recall procedure of noncompliant products.

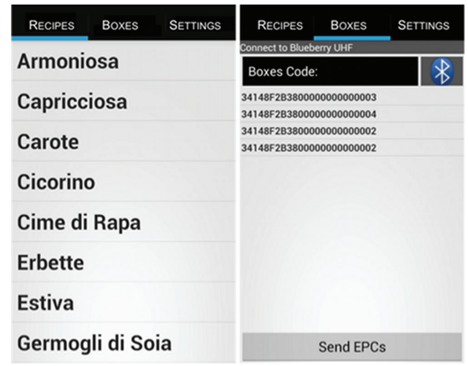

Figure 2: Snapshots of the application used by the operator in the storage warehouse.

3.3. Overview of the Pilot Project. In order to better clarify the reengineered model previously described, a graphical summary of the pilot project implemented in the Jentu company is presented in this section. In particular, Figure 3 and Table 1 summarize the main RF devices introduced in both greenhouses and transformation factory.

4. Hardware Description

In this section, the main features of the auto-identification systems selected to realize the pilot project are presented. In particular, a summary of the main devices provided by the reengineered model in each area of the considered company is reported in Table 2, while more details are described in the following.

As noted in the previous table, in the cultivation phase, the following devices are used.

(i) *NFC tags*: identification of farmers and field areas in the greenhouse is crucial in the gapless traceability system; we used two different types of NFC tags for farmers and plots of land. In particular, for the farmer identification, we used a Mifare Ultralight NFC card by NXP Semiconductors (Figure 4(a)(1)). For the plots of land we used a Mifare Classic NFC tag by NXP Semiconductors (Figure 4(a)(2)).

(ii) *Portable NFC/RFID scanner*: a smartphone Samsung i9023 Nexus S (Figure 4(b)(1)) connected to the UHF RFID reader BlueBerry of TERTIUM Technology (Figure 4(b)(2)) was used as portable scanner. In particular, the Samsung Nexus S is an Android smartphone equipped with NFC technology, while the BlueBerry reader is a small and easy-to-use device able to transmit the data to a mobile phone or a smartphone through the Bluetooth interface. All high-level operations, such as processing of the readings,

Table 1: Mapping between RF devices and working areas in the Jentu company.

	Greenhouses	Incoming warehouse	Storage warehouse	Production	Labeling area	Order composition area
NFC tags	√					
UHF RFID tags	√	√	√	√		
NFC Smartphone	√					
Portable RFID reader	√					
UHF RFID gate		√		√		
DataMatrix printer					√	√
Portable DataMatrix/RFID reader			√			

Table 2: Devices used in the pilot project.

	Vegetables cultivation	Products transformation				
	Greenhouses	Incoming warehouse	Storage warehouse	Production	Labeling area	Order composition area
NFC Tags	(i) NXP Semiconductors Mifare Ultralight NFC card (ii) NXP Semiconductors Mifare Classic NFC tag					
UHF RFID Tags	LABID INSKYL3 wet inlay	LABID INSKYL3 wet inlay	LABID INSKYL3 wet inlay	LABID INSKYL3 wet inlay		LABID INSKYL3 wet inlay
Portable DataMatrix/RFID Reader	SAMSUNG i9023 Nexus S smartphone + TERTIUM Technology BlueBerry UHF		METEOR BIP-6000 Industrial PDA			METEOR BIP-6000 Industrial PDA
RFID UHF Gate		IMPINJ Speedway Revolution R420 + 4 KATHREIN wide range antennas		IMPINJ Speedway Revolution R420 + 4 KATHREIN wide range antennas		IMPINJ Speedway Revolution R420 + 4 KATHREIN wide range antennas
DataMatrix/RFID Printer					Zebra RZ400 RFID Desktop Printer	

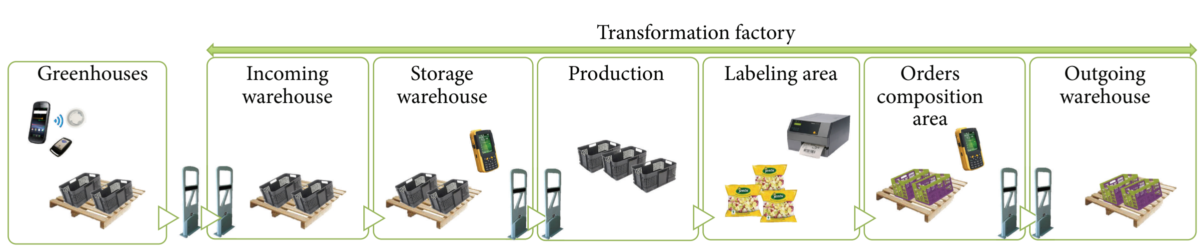

Figure 3: Main RF devices introduced by the reengineered model.

Figure 4: Main devices used in the pilot Project: (a) NFC tags: (1) Mifare Ultralight and (2) Mifare Classic; (b) portable NFC/RFID scanner composed of a (1) Samsung i9023 Nexus S and a (2) BlueBerry reader; (c) INSKYL3 passive UHF RFID tag; (d) RFID UHF gate composed of (1) Impinj Speedway Revolution R420 reader and (2) Wide Range UHF Kathrein antenna; (e) BIP-6000 of Meteor scanner; (f) Zebra RZ400 printer.

forwarding them via text message, e-mail, or GPRS, are delegated to the device the BlueBerry reader is interfaced with. Ultimately, it represents an easy way to integrate the RFID communication system to any device equipped with a Bluetooth interface (PDA, Netbook, Notebook, PC, etc.).

(iii) *Passive UHF RFID tags*: in order to choose the most suitable passive UHF tags to be used for our business scenario, a preliminary technological scouting has been performed. It is important to observe that the choice of the type of RFID tag is affected by different requirements as size of the tag itself, compatibility with EPCglobal standard, high scanning speed, high performance in presence of liquids and metals, low cost, and high stress of tag label during product life cycle. Therefore, after preliminary tests carried out in laboratory, we chose the passive UHF RFID tag wet inlay INSKYL3 of LABID (Figure 4(c)), whose size is 54 mm × 18 mm, equipped with the Impinj Monza 4 chip.

Multiple and heterogeneous devices have been chosen for the implementation of the reengineered manufacturing phase. More in detail, as shown in Table 2, the devices used in the pilot project are as follows.

(i) *RFID UHF Gate*: An RFID UHF gate, composed of a reader Impinj Speedway Revolution R420 (Figure 4(d)(1)) connected to 4 antennas Wide Range UHF Kathrein (Figure 4(d)(2)) though coaxial cables LMR-195 with weight attenuation in the range 25–35 dB per 100 m, was used in the pilot. The reader supports EPCglobal UHF Gen 2 and ISO 18000-6C protocols. It is characterized by a maximum receive sensitivity and maximum return loss equal to −82 dBm and 10 dB, respectively. The Wide Range antennas provide frequency range of 865–870 MHz and they are characterized by a circular polarization.

(ii) *Portable DataMatrix/RFID scanner*: in this case, the choice has been the handheld BIP-6000 of Meteor (Figure 4(e)). It is an industrial PDA designed to withstand the harshest working environments, certificate IP65 and equipped with 2D barcode reader and RFID reader. It also has integrated GPS, GSM, HSDPA, and WLAN, and a 3.0 megapixel camera with flash. In particular, this reader is equipped with the Android OS, which enables a simple integration with the connected system.

(iii) *DataMatrix/RFID printer*: the printer Zebra RZ400 (Figure 4(f)) was selected to print 2D code and write information in the RFID tag. It is equipped with a USB 2.0 interface and supports currently available protocols, including EPC Gen 2/ISO 18000-6C.

5. Overall System Architecture

The need to preserve and adapt the functionalities offered by the existing traceability and management systems leads us to give special attention to the technologies integration procedure in the Jentu company. The main services of the greenhouse management, such as the Field Log, must continue to be provided, beside the newer ones. Moreover, the Field Log application must become part of the new traceability system; that is, the data logged through it must be shared or reused in an EPCIS style. Furthermore, the innovative hardware and software systems, introduced in the transformation factory, must work on top of the existing architecture.

In order to satisfy the systems integration requirements, a software architecture based on the Enterprise Service Bus (ESB) [17] was defined. An ESB is an architecture model used for designing and implementing the interaction and communication among mutually interacting software applications in Service Oriented Architecture (SOA). It promotes agility and flexibility with regards to communication and interaction among applications.

In the next sections, more details about the different subsystems composing the whole architecture are given.

5.1. Greenhouse Management System. The combined use of Android smartphone, NFC, and RFID technologies is fundamental for the integration between the data producer (the agronomist working in the greenhouse) and the data consumer (the traceability system). Moreover, the use of smartphone enables an easily integration of the traceability system with any external device equipped with a Bluetooth interface (e.g., handheld UHF RFID communication system). The latter aspect is strongly important, as it allowed us to integrate the UHF RFID technology in a device that is not natively provided of it.

An agronomist Android app has been designed and prototyped; it can be seen as a write-only interface towards the traceability system. The agronomist uses the app for tracing the following main activities typical of a crop lifecycle:

(1) LAND activity: instantiate a new cultivation in a specific area of the greenhouse;

(2) FIELD_LOG activity: record a new crop observation event or intervention;

(3) HARVESTING activity: mark the cultivation as cropped when it reaches the maturation date.

Each activity involves the recording of the gathered information both in the EPCIS and in the Field Log system, so that the new and the legacy systems are bridged.

The UML sequence diagram, shown in Figure 5, is used to model the full interaction between the agronomist and the traceability system architecture for the FIELD_LOG activity.

The agronomist identifies herself/himself and the plot of land in the greenhouse; after filling the requested fields, she/he clicks the "Save" button and a request is built and forwarded to the ESB. Notice that a single click is needed to register the event both in the Field Log application and in the EPCIS, exploiting the high configurability of the ESB. The event is stored in the EPCIS as an ObjectEvent with the EPCIS property "ACTION" set to "OBSERVE".

In Figure 6, a screenshot of the agronomist mobile application for the FIELD_LOG activity is shown.

The agronomist fills the following fields.

(i) *Agronomist*. It is the full name of farmer that is encoded by the unique 7 hex digits ID stored in the farmer's Mifare NFC badge. Every NFC tag contains a read-only factory-assigned worldwide-unique serial number that can be used as a key into a database. The agronomist is needed because every detection is mapped with the responsible farmer in the EPCIS; the farmer app automatically fills this field when a farmer NFC card is in range.

(ii) *Greenhouse*. When the farmer wants to operate on a portion of land, she/he identifies it through the assigned NFC tag; so the field in the application is auto-filled.

(iii) *Date and Start/End Time*. The farmer stores the treatment duration by filling the fields representing the beginning and the end of the treatment.

(iv) *Agricultural Phase*. Each agricultural phase identifies one of the possible statuses of the considered portion of land. The farmer selects from a list the current status of the land (i.e., sowing, growing, etc.).

(v) *Treatment*. It represents the particular operation performed by the farmer on the considered portion of land. This value is selected from a preloaded list.

(vi) *Commercial Product*. In this field the farmer inserts the commercial product that she/he uses to facilitate and improve the achievement of specific effects on the ground and/or the plants.

(vii) *Machine*. The farmer selects from a list the equipment she/he uses during the treatment.

Let us observe that, in order to ensure a gapless traceability, only information about the date and the time related to the execution of a treatment must be stored. It is automatically saved in the EPCIS repository when the ObjectEvent is generated. However, the Field Log system requires also the storage of the duration of each performed treatment. To meet this requirement, in an efficient but simple way, the "Date and Start/End Time" fields have been introduced in the mobile application.

5.2. Hybrid Tracing System. The proposed tracing system is an innovative and low-cost hybrid system, in which the gapless traceability is ensured by using an EPC-style tracing and tracking system in the greenhouses, performed by the agronomist using Android NFC smartphones and NFC tags,

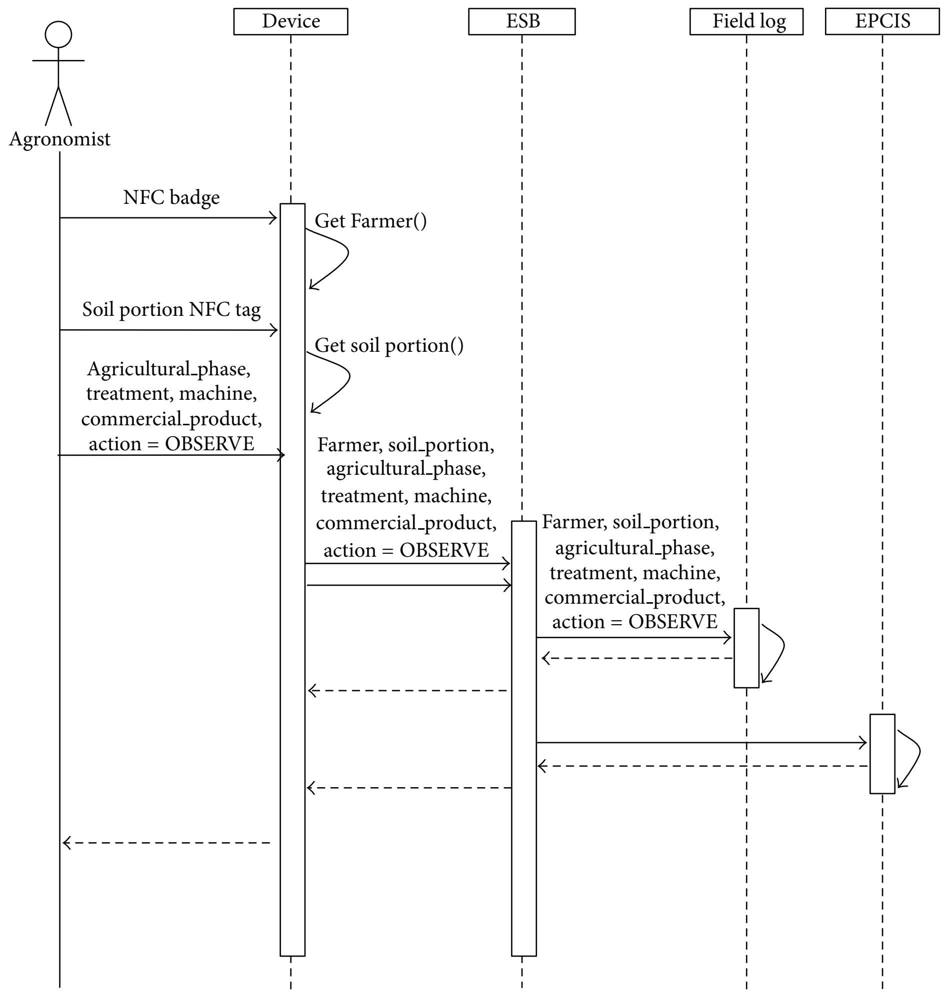

Figure 5: Sequence of interactions between the agronomist and the traceability system when a new observation or treatment is performed in the greenhouse.

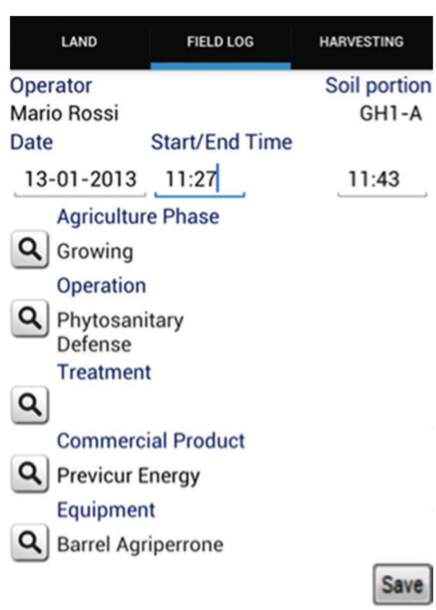

Figure 6: The agronomist's Android app interface.

and a classic EPCglobal architecture in the transformation factory, implemented using both UHF RFID and the less expensive DataMatrix technologies.

A clear separation between the logical EPC-based traceability architecture, and the physical infrastructure, based on UHF RFID, NFC, and DataMatrix technologies, is a key factor in the proposed system, as it ensures a smooth, gapless and flexible product traceability both in the greenhouse and in the transformation factory.

We used the Fosstrak platform [22] as open-source EPCglobal implementation. It is Java-based and provides supporting components for the development and integration of tracking and tracing applications. The Fosstrak EPCIS component runs on Apache Tomcat servlet container and exposes two SOAP services: the Capture interface, for storing EPC events into the EPCIS repository, and Query interface, for extracting EPC event data.

The Fosstrak ALE Middleware implements EPCglobal's ALE 1.1 specification [24]. To communicate with readers, the Fosstrak ALE Middleware uses the Low Level Reader Protocol (LLRP). For readers that do not support LLRP, the ALE Middleware uses the Fosstrak Hardware Abstraction Layer (HAL). The HAL Adaptor is a Java class interface, which we implemented in three classes:

(i) the LLRPAdaptor class, already implemented in the Fosstrak framework, in order to get readings from the EPC UHF RFID readers;

(ii) the NFCAdaptor class, which is synchronously called by a Java servlet listening on a specific URL for POST requests incoming from NFC smartphones;

(iii) the DataMatrixAdaptor class, implementing the communication with a DataMatrix IP Camera connected to the company's network.

In Figure 7, a high level UML class diagram showing how the different technologies are cabled inside the Fosstrak ALE Middleware is reported.

The LogicalReader class is a logical representation of different physical sensors, for each of these an Adaptor was implemented. Being the NFC reading performed manually (volunteered) by the agronomist, the only way to model the interaction with the LogicalReader class is to expose a Java Servlet running in Fosstrak. When the servlet is called, the EPCBuffer is filled with EPCs; so the NFCHTTPController can asynchronously get the EPC list from the buffer.

In the next section, a deep look on how to publish the servlet URL onto the Enterprise Service Bus will be given.

5.3. Information Systems Integration. Many ESB vendors, also open source, exist. In this work, the WSO2 (Oxygenating the Web Service platform) [25] vendor was used, since it was identified as one of the most robust solution by Gartner and Forrester [26]. The WSO2 ESB engine is Apache Synapse [27], which plays a role of broker in the software architecture and supports many open standards (e.g., XML, XSLT, XPath, SOAP, JMS, WS-Security, WS-ReliableMessaging, WS-Addressing, SMTP).

In Figure 8, the overall system architecture is shown.

The architecture is split into four macro-areas.

(i) *Delivery Channel Architecture*. It includes all the services' interfaces, both legacy and innovative. The information generated and requested by the clients flow within a unique logical link toward the information system and it is conveyed by using a mapping configured in the WSO2 ESB.

(ii) *Shared Service Infrastructure*. It is the core WSO2 ESB implementation, as it allows delivering the services requested by the applications by totally hiding the service implementation details. The different subsystems comprised in this layer was properly configured to map the requests incoming from the delivery channel architecture layer; we configured different protocols at different ISO/OSI levels, for example, REST for mobile application, SOAP for the traceability interfaces, TCP/IP sockets for UHF RFID readers, and connections with the DBMS instantiated by legacy applications.

(iii) *Service Enabled Applications*. This layer includes the SOA-ready services. Communication flow is depicted as bidirectional also for delivering service composition and for talking with nonservice-enabled assets. The EPCIS resides here. A Field Log adaptor has been introduced, in order to let the agronomist mobile app also save data into the field log as well as into the EPCIS (service composition).

(iv) *Nonservice-Enabled Assets*. Non-SOA-ready services such as legacy systems and ISO/OSI transport layer services (e.g., socket based) find place in this layer. Existing bundled systems (i.e., Irrigation Control System, Enterprise Resource Planning, Outsourcing Inventory Management) fall into the Packaged software category. Fosstrak's Application Level Event (ALE) middleware is deployed on an Apache Tomcat servlet container. It establishes LLRP protocol links with the UHF RFID reader placed in the Delivery Channel Architecture, and a classical TCP/IP socket with the Capturing Application, which push event to the Fosstrak EPCIS subsystem. Database Management Systems are also included in this layer.

In the WSO2 proxy configuration file, Fosstrak's EPCIS repository query endpoint and the web services needed by the agronomist Android app are mapped by specific proxy services. A proxy services define virtual services hosted on the ESB that can accept requests, mediate them, and deliver them to an actual service. Proxy services could perform transport or interface switching and expose different semantics than the actual service, that is, WSDL, policies, and QoS aspects like WS-RM, WS-Security, and so forth. Through the use of endpoints, it is possible to define a specific destination for a message. Once the endpoints are defined, it is possible to call the configured Web services by invoking a URL following this schema: http://<esb_ip>:<esb_port>/services/<proxy_name>/<service> where:

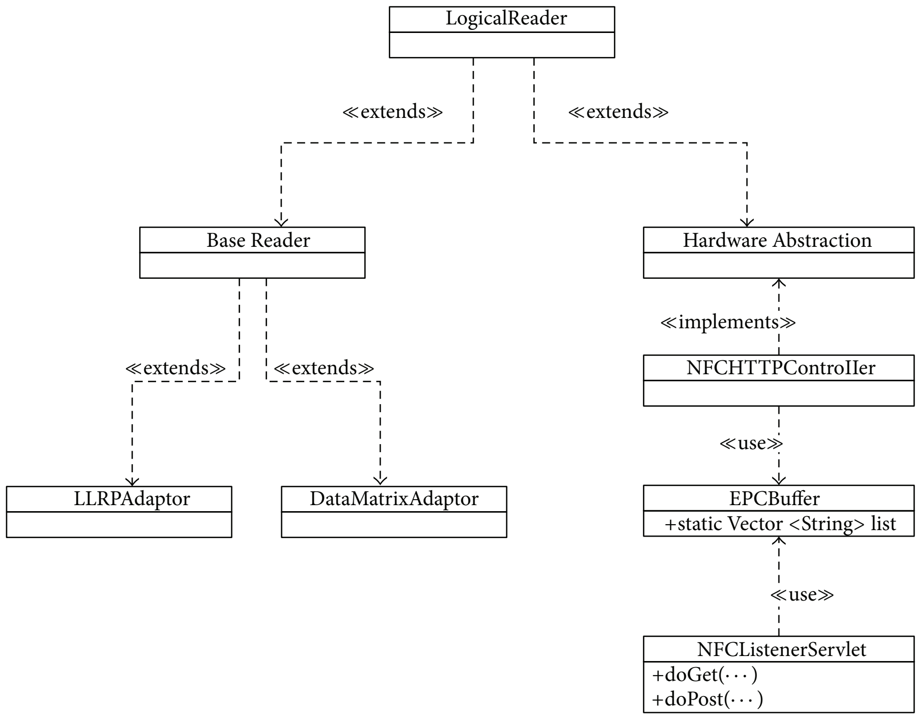

Figure 7: The integration of different physical sensing technologies in Fosstrak.

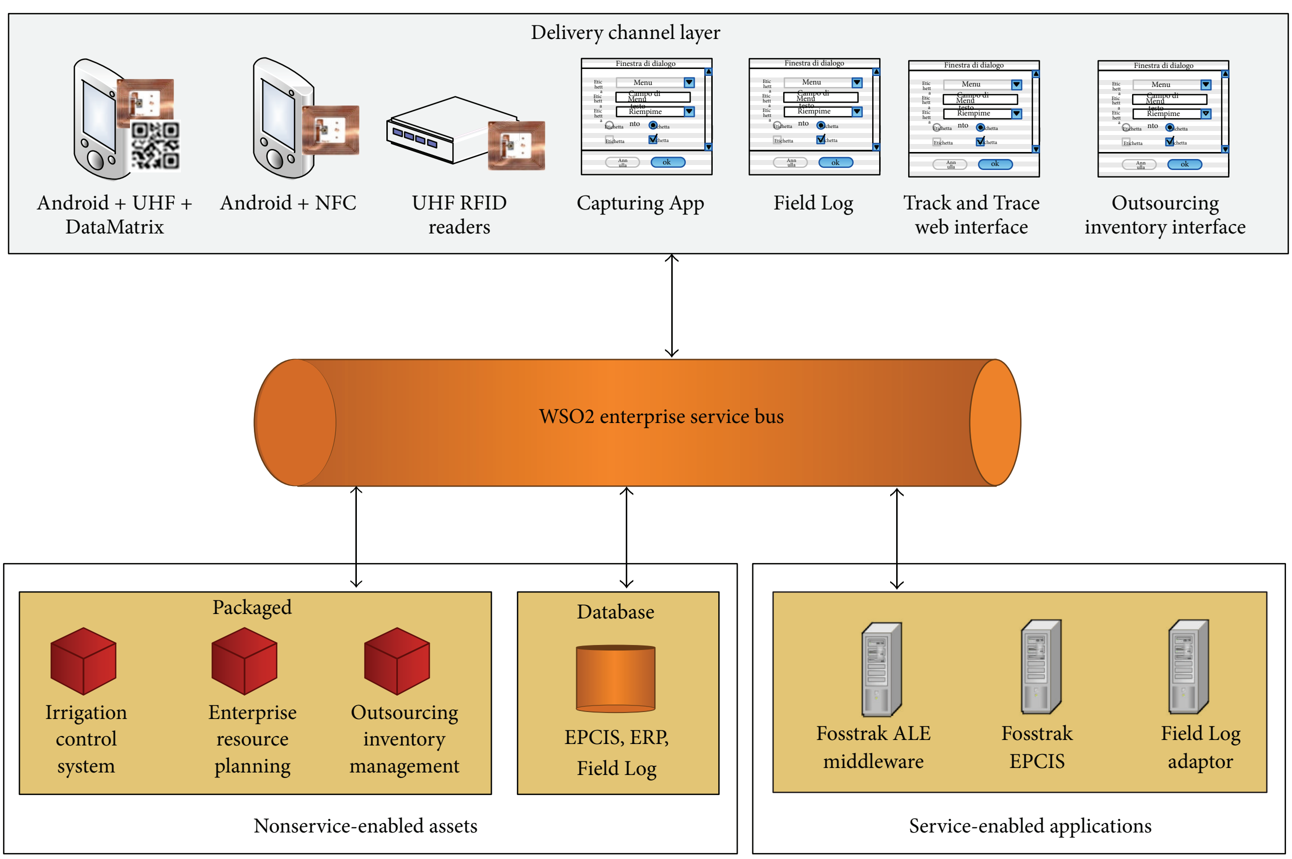

Figure 8: The overall system architecture.

(i) the <esb_ip> is the IP address of the server on which WSO2 runs; notice that this IP address is unique for each service;

(ii) the <esb_port> is the TCP port on which WSO2 is listening;

(iii) the <proxy_name> is the name of the proxy service configure into the ESB configuration file;

(iv) the <service> identifies a precise service retrievable from the specified proxy.

Using proxy services, the implementation of existing and innovative Web services onto the company architecture is almost immediate and requires few lines of codes. We deployed both SOAP and REST Web services. In particular, we deployed some REST Web services involved in the communication between the Android app of the agronomist and the tracing system. For instance, two Web services CultivationPhases and Formulation are used by the Android app to populate the static field views in the app interface by retrieving these from a well-defined vocabulary of terms. A FieldLog service is used to save the gathered information to the legacy Field Log application.

6. System Validation

The system validation phase was carried out by using both a Living Laboratory approach and a pilot project. In particular, the first method allowed us to obtain initial experimental results, in a controlled test environment, demonstrating that an accurate choice of passive UHF RFID solutions is fundamental to guarantee high performance of the proposed tracing system in each step of the supply chain. On the other hand, the development of the pilot project enabled us to validate the complete traceability system (i.e., hardware and software), and to appreciate the potential benefits derived by the use of RF technologies and EPCglobal standard in a real scenario. In particular, measurements of the main Key Performance Indicators (KPIs) demonstrated how the proposed reengineered process is able to mitigate the timeliness and correctness problems previously described.

Therefore, different preliminary tests, carried out in our laboratory environment, allowed us to identify the most suitable RFID tag to be used in the considered scenario. The experimental campaigns were designed to measure the successful reading rate of different tags during two of the most critical steps of the supply chain: (i) the movement of a pallet composed of tagged bins of raw materials, and (ii) the identification of tagged bins during the harvesting procedure, through the use of a portable RFID reader connected, via Bluetooth, to an Android smartphone.

Seven different types of commercial passive UHF RFID tags, equipped with an Impinj chip, were used.

(i) DOGBONE, whose size is 86 mm × 24 mm, equipped with the Impinj Monza 4 chip;

(ii) WEB, whose size is 30 mm × 49 mm, equipped with the Impinj Monza 4 chip;

(iii) UH423, whose size is 30 mm × 50 mm, equipped with the Impinj Monza 5 chip;

(iv) UH3D40, whose size is 40 mm × 40 mm, equipped with the Impinj Monza 4 chip;

(v) INSKYL3, whose size is 54 mm × 18 mm, equipped with the Impinj Monza 4 chip;

(vi) SKL4020, whose size is 40 mm × 20 mm, equipped with the Impinj Monza 5 chip;

(vii) XC-TF8024-C06, whose size is 50 mm × 30 mm, equipped with the Impinj MonzaTM 4 QT chip.

More in detail, in the first experimental campaign (Figure 9), a pallet with 28 plastic boxes containing finished products, organized on seven layers and tagged on their short side, able to cross the UHF RFID gate, was used. In order to simulate realistic conditions, several pallet compositions were analyzed.

(i) *Configuration I*: the pallet was prepared placing the boxes with their tag antenna oriented toward the outside and avoiding the overlapping of tag antennas.

(ii) *Configuration II*: the pallet was prepared placing the boxes with their tag antenna oriented toward the center of pallet itself and trying to obtain the overlapping of tag antennas.

(iii) *Configuration III*: the pallet was prepared placing the 50% of the boxes with their tag antenna oriented toward the outside and the remaining boxes oriented toward the center of pallet.

Each of the previous configurations were evaluated according to two different movement modes of the pallet as follows.

(i) *Translation*: it simulates the crossing of the pallet through the gate in direct direction; in such a case the tags on the boxes are parallel to the antennas of the gate during the movement.

(ii) *Rotation*: it simulates a rotation of the pallet when it crosses the gate; in such a case the tags on the boxes are perpendicular to the antennas of the gate for much of the time.

With regard to the first experimental campaign, 100% of successful reading rate has been measured in all tests confirming that the physical, chemical, and biological properties of the vegetable products do not affect the performance of the RFID tags.

The second test campaign aims to evaluate the tags performance when the portable RFID reader is used considering different reading distances (e.g., 5, 10, 15, 20, 25, up to 90 cm) and different reading angles (e.g., −30°, 0°, +30°) between reader and tag antenna. In this test, a single box was used, and, for each tag, from 20 to 60 reading attempts were performed. This test demonstrated that all preselected UHF tags show optimal (i.e., 100% of successful reading) performance for distances in the range from 5 cm to 25 cm. Furthermore, the INSKYL3 tag obtained the 100% of reading rate also for

Figure 9: Pallet configuration during the first experimental campaign.

longer reading distances, up to 80 cm. The performed tests demonstrated that tags performances are not substantially affected by the reading angles (angles in the range from +30° to −30° did not show substantial changes).

This preliminary analysis led us to identify the INSKYL3 RFID tag as the tag to be used in the pilot test.

As previously declared, the pilot project allowed us to validate the proposed reengineered model. To demonstrate the proper operation of the proposed system, a screenshot of the traceability interface, evidencing the history (ePedigree) of the product from the sowing up its entry in the plant as raw material, is shown in Figure 10. In the "GRAI general information" table, all read events related to pallet used to carry the raw materials from greenhouse to company are reported. The box "EPCs children list" shows the aggregation among pallet and raw material bins. The supplier information is shown in the box called "Detailed information". Finally, in the "Field log" table, all treatments performed on the soil portion by operators are listed.

Furthermore, a KPI comparison between the current model and the reengineered model was performed considering the two main analyzed phases separately: (i) vegetables cultivation and (ii) products transformation. This analysis is summarized in Table 3.

Considering the first phase, the reengineered model substantially reduces the timeliness metric of "average time to write a report", which passes from a value of 90 seconds, in the current model, to a value of 25 seconds, thus ensuring a reduction of about 70 percent. Similar results can be appreciated for metrics related to the correctness, such as "percentage of reports with errors," "percentage of lost reports," and "percentage of error in the data entry activity," whose values, which are equal to 17, 10, and 15 in the current model, are reduced to zero in the reengineered model.

The combined use of RF technologies has highlighted similar benefits also in the transformation phase. As example, the timeliness KPIs regarding the processes of incoming and storage of raw materials are substantially improved. In particular, the "average time to receive a pallet" is reduced from a value of 195 seconds, in the current model, to a value of 55 seconds, in the reengineered model; the "average time to store information about raw materials and print the identification tag" is reduced from a value of 90 seconds to a value of 0 second; the "average time to identify an accepted pallet" passes from 120 seconds to 15 seconds. Similarly, the "percentage of error in the data entry procedure" and the "percentage of wrong pallets moved into the transformation process," which are equal to 15 and 30 in the current model, are reduced to zero in the reengineered model.

7. Discussion and Conclusions

In this paper, a gapless traceability system, based on the use of innovative RF technologies and EPCglobal standard both in the company's greenhouses and in the transformation factory, was proposed. According to the reengineered model, the agronomist uses an NFC Android smartphone to map the performed interventions and the sensed variables to a specific plot of land. This technique leads to overcome the paper-based classification of crops in the greenhouses, and to improve the efficiency of the subsequent phases of the transformation process. In such a way, each phase of the cultivation and transformation processes is traced and it becomes available for the traceability service. The use of DataMatrix instead of RFID tags to tag the final products ensures low costs and easy access to the traceability service for the end consumer. Furthermore, an ESB-based architecture has been introduced in order to integrate the company's legacy systems with the innovative technologies. It guarantees low impact in relation with the processes currently held both in the cultivation and transformation processes, and, at the same time, great flexibility and scalability towards future extensions.

In order to evaluate the benefits of the proposed reengineered model, a pilot project was implemented in an important company of the South of Italy. The conducted analysis allowed us to demonstrate the potential benefits introduced by the combined use of the innovative RF technologies in the fresh vegetables supply chain.

Nevertheless, business benefits are not the only ones obtainable by using the innovative traceability system presented in this work. It enables also important advantages for the consumers, as it copes with the consumers' concerns over the safety and the quality of the purchased food. This is an important aspect for (at least) two reasons: (i) the spread of a "public consciousness" among people about the need for a more valuable diet is leading the consumers to prefer products whose origins can be clearly stated and certified; (ii) people suffering of food intolerances need to avoid adverse reactions derived by the assumption of some kinds of food [1]. Such people must fight every day also in performing regular human activities, as having meals; in this case, the drastic solution of removing a particular food (e.g., tomatoes) from a patient's diet is not the right choice, as the same product would not lead to any adverse reactions if cropped in different soils (e.g., far from industrial plants) or with different treatments (e.g., excluding chemical products). Also the opposite is true: a product definitely stated as safe for the patient's health status may not be secure if the same vegetable is produced by a different company with different treatments in a different geographical area.

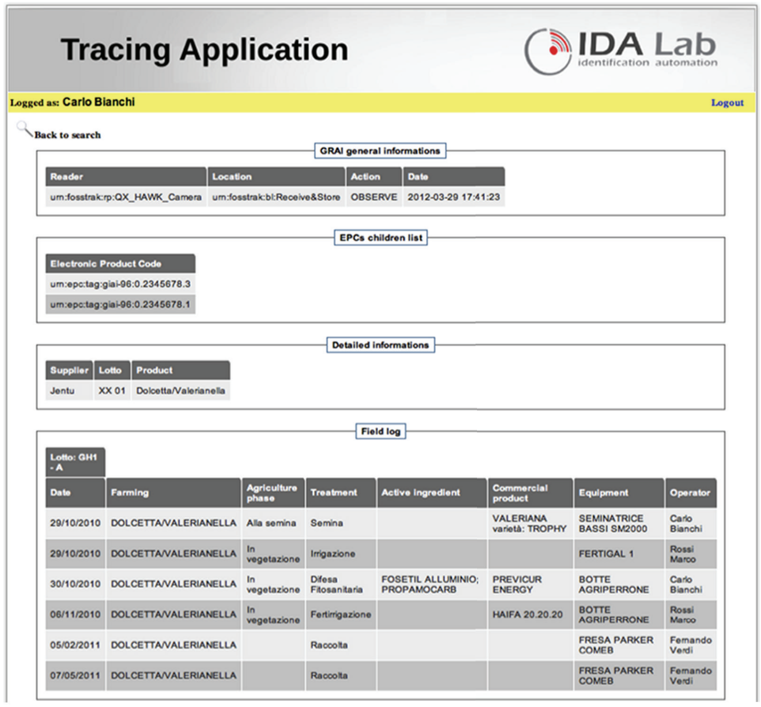

Figure 10: The ePedigree for a specific product.

Table 3: Main KPI used to compare current and re-engineered models.

Phase	KPI	Current model	Reengineered model
(i) Cultivation	Average time to write a report	90 sec per report	25 sec
	Percentage of reports with errors	17%	0%
	Percentage of lost reports	10%	0%
	Percentage of error in the data entry activity	15%	0%
(ii) Transformation	Average time to receive a pallet	195 sec	55 sec
	Average time to store information about raw materials and print the identification tag	90 sec	0 sec
	Percentage of error in the data entry procedure	15%	0%
	Average time to identify an accepted pallet	120 sec	15 sec
	Percentage of wrong pallets moved into the transformation process	30%	0%

However, several problems have been encountered during the design and development of the presented traceability solution. First of all, the implementation of the ESB has highlighted some difficulties mainly related with the integration of packaged legacy systems like the Field Log. The application in use in Jentu did not provide any sort of software interfaces like Web services; that is, it was not SOA-ready. Anyway the ESB engine WSO2 was flexible enough to forward and inward data directly dealing with the application's database. Obviously this led us to carefully check the integrity of the information in the Field Log application. Secondly, the need of making the Android app suitable for agronomists contrasted with the high complexity of the EPCglobal industrial standard. For example, RFID readers usually transmit strict event data like the EPC code and few other technical parameters. Business data like the information on the crops and the performed operations shall be added later in the capturing application, running on a separate PC. We eased this step by leveraging the concept of the EPC ECreport custom fields, by which the Android app can generate rich events including custom business information as well as the EPC IDs, sending them to the traceability server in a single tap onto the smartphone screen.

Finally, let us observe that the improvement of the proposed traceability system, considering, as an example, the tagging of machines and boxes of products used during the treatments in the greenhouses to further automate the introduction of their associated data in the system, will characterize future works.

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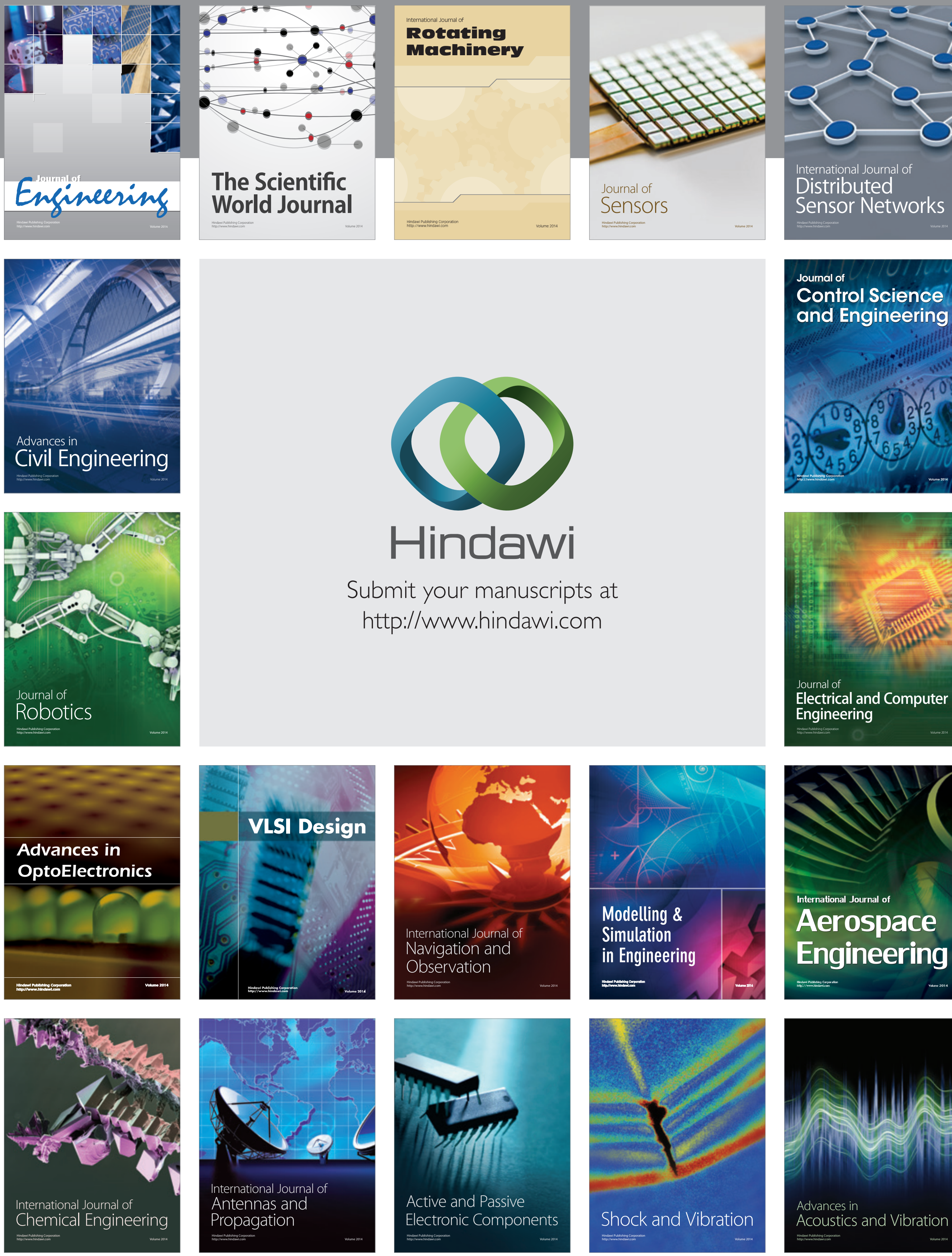
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