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On Improving Automation by Integrating RFID in the Traceability Management of the Agri-Food Sector

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***Abstract*—Traceability is a key factor for the agri-food sector. RFID technology, widely adopted for supply chain management, can be used effectively for the traceability management. In this paper, a framework for the evaluation of a traceability system for the agri-food industry is presented and the automation level in an RFID-based traceability system is analyzed and compared with respect to traditional ones.**

Internal and external traceability are both considered and formalized, in order to classify different environments, according to their automation level. Traceability systems used in a sample sector are experimentally analyzed, showing that by using RFID technology, agri-food enterprises increase their automation level and also their efficiency, in a sustainable way.

***Index Terms*—RFID, Traceability Management, Agri-food Sector.**

IN many countries traceability is a mandatory requirement for the agri-food sector. An effective traceability system brings many benefits, such as increasing the security and confidence of customers, and limiting withdrawal of commodities.

The characteristics of a traceability system, and mainly its automation level, strongly affect the traceability cost and accuracy. Automation is defined as the execution by a machine agent of a function that was previously carried out by a human being; the provided economic benefits are known in many domains, from aviation to medicine [1].

Although food sector is characterized by technologically advanced innovations, e.g. new sterilization methods [2] and food evaluation [3], its companies typically have not an advanced level of automation, because of lack of assets of small enterprises, the extensive condition of agricultural fields, and the historic distance between rural life style and technology. However, in large enterprises, there are examples of high automation. In the most technologically advanced countries, there is an advanced agriculture that uses standardized technology and that is subject to rapid changes [4][5].

The most advanced agricultural enterprises are characterized by a tightly aligned food supply chain and by the important role of information and communication technology (ICT) [4]. Usually, these enterprises use spontaneously a traceability system, which typically is very efficient and fully automated. Instead, small enterprises that have an efficient traceability system often add the traceability management to their normal operations, decreasing the efficiency and increasing the costs. The lack of assets and the difficulties to see the benefits due to the use of an effective traceability system, bring them to implement the traceability management in the most simple way, often manual or semiautomatic. Presently one considerable challenge in the agri-food business is the developing of appropriate traceability technology for small-scale farmers [6].

One of the most important novelties in supply chain management technologies is the availability of the Radio Frequency Identification (RFID) technology. An RFID system [7] typically includes a reader and some tags. The reader is able to access tag memories by means of a wireless communication. The memory, which plays an important role in the tag architecture, contains the unique identification number (ID) and may have up to several kilobits of storage capacity. Normally RFID tags have not cryptographic capabilities, however solutions to avoid security and privacy threats are under study [8][9]. It is important to note that, for the adoption of an RFID system by a company, the acceptance problem should be considered [10]. RFID is a mature technology, and in the last decade its applications increased in number and diffusion, due to the high reduction of its costs. As for supply chain management [11], RFID could be properly used for traceability management.

According to the technological novelties and opportunities introduced by the application of ICT in the agri-food sector, the main contributions presented in this paper are the analysis of the automation characteristics of traceability systems used in the agri-food sector and the evaluation of the automation improvement achievable by RFID technology.

In order to test RFID-based traceability systems, we selected the fruit sector, since it presents interesting characteristics, such as the high numbers of direct relations among companies in the chain, of total companies in the same chain, of different products and of product characteristics. Different RFID traceability systems were examined, then a system based on RFID was put on trial in a fruit company, in order to compare its characteristics with respect to the ones of traditional systems.

The experimental results show that the adoption of an RFID system increases the efficiency of traceability management and

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reduces the labor costs.

The remaining of the paper is organized as follows: in Section I the traceability management systems are presented and their automation characteristics are detailed. In Section II, a case study that involves the tests on a traceability RFID system is described and the results are evaluated. Finally, in Section III some conclusions are drawn.

I. Framework for Traceability Analysis

In this section the characteristics of traceability systems are presented and the established internal traceability systems are described.

A. Traceability Management

ISO 9001:2000 defines traceability as the "ability to trace the history, application or location of that which is under consideration" [12].

In EU, Regulation (EC) No 178/2002 of The European Parliament And of The Council [13] establishes that the operators shall be able to identify, for the competent authorities, any business which supplied them with alimentary commodities, and any business which takes food from them; they shall, also, label adequately food, in order to facilitate the traceability.

The traceability management requires many operations that can be divided in two macro activities:

- *external traceability*, which is the ability to follow the path of a specific unit along the production chain, forward and backward; this macro ability can be divided in micro activities:
  - *business-to-business traceability*, i.e., information exchange in the production chain from a business to the next one;
  - *business-to-customer traceability*, i.e., the management of the information transfer from the retailer to the final customer;
  - *whole chain traceability*, i.e., the management of the information about the whole path of a commodity, from the producer to the final customer;
- *internal traceability*, which is the ability to correctly follow the whole path of a specific unit within the company.

For external traceability management there are two main approaches. The first is based on the recording of all the data in a unique distributed database, often by using XML [14]. This approach entails high efforts, mainly for standardization, since all the enterprises have to use the same recording method. This approach allows to manage all the micro activities that compose the external traceability in an integrated way. In the second approach, each enterprise stores in its database the information about any enterprise that supplied it, and about any enterprise that takes food from it. According to this approach the whole chain traceability is managed by checking each database of the enterprises in the chain; the business-to-business traceability is managed by single transfer of information. The first approach allows more efficient traceability management, but it requires that all the businesses in the supply chain adopt it.

Considering a single enterprise, the operations required for the external traceability are limited to a transaction into a database. Although this operation may get many resources, the critical activity for agri-food businesses is the internal traceability, since it requires continuous operations and, if it is inefficiently managed, may impair the work rate.

B. Internal Traceability System Features

The main operation executed by an internal traceability system is the identification/registration, which is repeated every time that a product is subjected to an action.

In this paragraph the main features of internal traceability systems are illustrated.

- **Data storage**. Data must be stored during the permanence of the commodity in the enterprise and after its exit. When the commodity exits, data must be maintained, in order to manage the external traceability. The elements that characterize the data storage are:
  - <u>data location</u>
    - *totally distributed*, data are stored on commodities by using labels;
    - *compressed and distributed*, data are stored on commodity labels in a compressed form -e.g. short codes-, and it is possible to read the information from the object by using reference tables;
    - *centralized*, commodities are matched with an ID that is stored on commodity label; the ID is used as a link to a record in a central database;
  - <u>the type of database</u>
    - *paper database*, requires a manual transcription and a large amount of work;
    - *computer database*, can be updated by a manual transcription or by an automatic transcription.
- **Tagged objects**. Labels are used in order to identify and store data. There are two alternative methods of tagging, which is the activity of labeling objects:
  - *commodity tagging method*, the tagged objects are the commodities themselves; the tag is uniquely matched to the commodity and it is not reusable.
  - *container tagging method*, the tagged objects are the containers of commodities; in this way each tag is matched to one container, and the tag could be potentially used for the whole life of the container.
- **Kind of data**. Kind and number of data can differ according to precision and effectiveness aims; the quantity of data affects the size and the time used to manage them. The stored data are divided in three groups:
  - *identification code*, this code identifies the object;
  - *commodity characteristics*, these data are used to identify the commodities and to save additional information that can be useful for activities such as value adding, supply chain management or quality certification;
  - *operation data*, they describe the history of the object, the operations executed on it, its movements, and its timetable.

TABLE I
LIST OF SYMBOLS

Symbol	Description
TIR	Total time requested by IR operations
IR_i	average time requested by the ith IR operation
IT	number of ITems
$ITCN$	Number of ITems in a Container
CN	Number of Containers
n	Number of the kinds of IR operations
AR	Average time for a Reading
AW	Average time for a Writing
AT	Average time for a Tagging
DBC	average time for a Database Connection
DBQ	average time for a Database Query
C_i	average time for Computation in the ith IR op.
CC_i	av. time for Computer Comput. in the ith IR op.
HC_i	av. time for Human Computation in the ith IR op.
MV_i	average time for MoVement in the ith IR op.
o_i	Occurrences of the ith IR operation
e_i	Error occurrence probability
r_i	number of Readings in the ith IR operation
IDr_i	number of tag ID Readings in the ith IR operation
Mr_i	number of tag Memory Readings in the ith IR op.
w_i	number of Writings in the ith IR operation
t_i	number of Taggings in the ith IR operation
d_i	number of Database queries in the ith IR operation
TT	Total time for Tagging
$RFID_ARID$	Average time for an RFID Reading of a tag ID
$RFID_ARM$	Average time for a Memory RFID Reading
$RFID$	prefix for systems with RFID
$Traditional$	prefix for systems without RFID
i	subscript for the ith IR operation

- **Data format**. Data can be represented in different formats, which differ for technological levels; more than one format can be used simultaneously. There is a tight coupling between the adopted format and the automation of the operation that manages the data, so the choice of the data format depends on the required automation. The main choices are:
  - *written words*, data are written directly by human operators;
  - *alphanumerical code*, data are contracted and conveyed by an alphanumerical written code;
  - *barcode*, data are contracted and conveyed by a barcode that needs to be read by an appropriate device;
  - *electronic code*, normally through RFID tags; the number of recordable data is limited by the size of the tag memory, but it is the largest among the analyzed formats.

C. Writing/Reading and Tagging Automation

The *identification/registration* (IR) activity (see Table I for the list of symbols), which is composed by the reading and, if needed, by the writing and the tagging, is the core of the internal traceability system. Since these actions are iterated continuously, they get large resources, so enterprises have to execute them in an optimized way.

The traceability system of each company requires a set of specific IR operations, each of them is composed by a specific number of reading, writing and tagging operations.

In a system that employs the commodity tagging method normally the same IR operations are performed on each product, and so the total time requested for IR, TIR, is a function of IT, which is the number of single items: $TIR = f(IT)$. An execution of the ith type of IR operation, among the n IR operations applied, requires an average time IR_i, and it is executed o_i times on each commodity. TIR is also affected by the error management; according to the kind of errors, the execution of corrective operations (e.g., the repetition of the faulty operations) is required, so

$$TIR = IT \sum_{i=0}^{n} (o_i \cdot (1 + e_i) \cdot IR_i).$$

where, e_i is the error occurrence probability. In a system adopting the container tagging method, a set of IR operations are performed on each container. IT must be divided by the number of items per container ($ITCN$), and

$$TIR = \frac{IT}{ITCN} \sum_{i=0}^{n} (o_i \cdot (1 + e_i) \cdot IR_i)$$

In each traceability system IR_i is dependent on the type of employed technology. The time requested by one single operation is mainly dependent on the automation of the employed technology. IR_i corresponds to the sum of the time required by each operation that composes the ith IR operation; these operations are:

- the *reading* that requires an average time AR and that is executed r_i times,
- the *writing* that requires an average time AW and it is executed w_i times,
- the *tagging* that requires an average time AT and that is executed t_i times,
- the *access to a database* that requires an average time DBC and that is executed one or zero times,
- the *elaboration in the database* that requires an average time DBQ and that is executed d_i times,
- the *elaboration* of the ith operation that requires the average time C_i, and
- the *movement* of the entity that executes the ith operation that requires the average time MV_i.

Therefore, the formula for calculating IR_i is:

$$IR_i = r_i \cdot AR + w_i \cdot AW + t_i \cdot AT +$$

$$+ \min(d_i,1) \cdot DBC + d_i \cdot DBQ + C_i + MV_i.$$

Each operation involved in an internal traceability system is executed with different automation levels. The automation levels, according to the classification used by [15], are:

- **manual**, the activities are executed directly by a human operator; the C_i and the MV_i are respectively used by the human operator to analyze the operation, and to move in the right position for the execution of an action;
- **semi-automatic**, an operator uses a hand-device to improve the efficiency of the work; the time MV_i is used by the human operator to bring the device in the correct position; the time C_i is composed by the time used by

the tool to elaborate the data (CC_i), and the time needed by the human operator to analyze the operation (HC_i):

$$C_i = CC_i + HC_i;$$

- **automatic**, human operators only control the activities, which are done by a mechatronic device; C_i corresponds to the time needed by the device to elaborate data; normally in an automatic system MV_i is null.

The automation level is closely tied to the adopted data format; in the following the different operations are detailed.

- **Reading**. The reading of the labels has the purpose to identify commodities and to get the commodity data, which can be used for other operations. The reading is the core part of IR activity, since each IR operation requires at least one reading: $r_i > 1; \forall i$. The average time of a reading (AR) is dependent on the automation of the action.
  - The *manual* reading is performed directly by human operators and it is characterized by a low value of r_i and a high value of AR.
  - The *semi-automatic* reading is performed by human operators that use hand device and it is characterized by a high value of r_i, and a low value of AR.
  - Usually, the *automatic* reading is performed by fixed readers, or by mobile readers. Like the semi-automatic one, it is characterized by a high value of r_i, and a low value of AR.
- **Writing**. The writing operation changes the data on the labels, so this operation is required only by some IR operations. In order to write data on the labels, the data must be in a suitable form for the used method of writing. The average time of a writing (AW) is dependent on the automation of the action (manual, semi-automatic, or automatic).
- **Tagging**. These operations can take a long time; the total time requested by the tagging actions (TT) mainly depends on the employed tagging method. In a system that employs the commodity tagging method every item must normally be tagged at every writing, so TT is a function of the number of items: $TT = f(IT)$.
  In a system that employs the container tagging method, if the labels are not rewritable, every container must be tagged every time that a writing is required, and IT must be divided by $ITCN$. If the labels are rewritable and the containers are reusable, each container can be tagged only once, since all the writing operations can be executed on the same label. Furthermore, the tagging operation can be performed off-line. The TT is a function of CN, which is the number of containers: $TT = f(CN)$. The average time required for each tagging action (AT) is mainly dependent on the automation level.

D. Established Internal Traceability Systems

The list that follows contains a representative sample of traceability systems adopted by agri-food enterprises.

- **Fully manual tag system**. In this system there is no automation. The commodities are not identified singly, but they are organized in groups with common characteristics.
- **Stamp system**. The automation is almost absent. The commodities are identified only as part of a group with the same characteristics. This system uses labels with an alphanumeric code. The labels are tagged and written in a semi-automatic way by human operators that use hand labelers and stamps. Operators manually read the labels.
- **Printed tag system**. Only some traceability operations are executed in an automatic way. This system uses labels with written words. The labels are tagged, in a semi-automatic way, by human operators that use hand labelers; human operators read the labels. The data about the set of commodities and about the operations are stored in the central database.
- **Fully automatic barcode system**. All the traceability operations are executed in a fully automatic way. The recorded data are the ID of the single commodity, a set of characteristics, and the time of the operations. The ID and the commodity characteristics are located both on the commodity and in the central database, while the time of the operation is recorded only in the database.

II. Case Study

In order to evaluate the automation improvement achievable by RFID technology, a fruit warehouse was selected as a case study. In this section the selection of the fruit warehouse is motivated and the case of study is analyzed.

A. Fruit warehouse

The typical fruit chain is represented by at least four elements: the producer; the fruit warehouse, where the fruit is treated; the distributor and finally the retailer. The fruit warehouse is a proper case study since it possesses the main characteristics that affect the traceability management of companies in the agri-food sector. A fruit warehouse buys fruit from many producers and sells it to different distributors; in a warehouse the fruit is treated and products from different groups are merged, so the internal traceability is not a trivial operation.

In order to detect the characteristics of fruit warehouses and in particular of their traceability systems, 10 small/medium fruit warehouses companies and one big fruit warehouse company were analyzed, then the collected data were evaluated in collaboration with 2 companies that supply consulting to agri-food companies. In the following fruit warehouse characteristics, achieved by our survey, are described.

Fruit warehouses are mainly differentiated by production size and destination market. In the warehouse the fruit is held in containers called bins, which can usually hold 250-300 kilograms of fruit, and which are moved by fork lifts. The dimension of a fruit warehouse usually is measured in bins: a medium warehouse disposes of a number of bins between 1000 and 100000; each calibration line can treat 50 bins/hour.

A warehouse uses treatments and its own image presentation methods according to its destination market. A fruit warehouse

needs a premium brand and high quality treatments in order to access to markets with high quality standards.

Regardless of differences among different warehouses, the main operations that they have to exploit are the same:

- *storing in refrigerating room*; its aim is preserving fruit; this can be executed more than once, or not executed at all; in the refrigerating room the fruit is held in bins;
- *calibration*; its aim is to separate fruit according to its caliber; fruit bins are loaded in the calibrator machine, a queue of other empty bins is filled by one of the output lines of the calibrator, one for each caliber;
- *fruit packing*; this operation is often required before fruit departure; the filled bins are emptied into the packer.

The operations can be executed in any order, and some of them could be not executed, according to characteristics of the fruit. In addition, other operations, such as quality selection, fruit cleaning and color selection, are often matched to calibration or packing.

In Italy the majority of fruit warehouses are small and medium companies. This kind of companies is often characterized by a low automation. The calibration and the packing are usually executed by automatic machines. The management of refrigerating rooms is performed by an automatic system. Inside the warehouse, the movement of bins is performed by using a fork lift; in big companies some highly utilized paths can be constituted by conveyor belt. The quality selection in small and medium companies is executed manually by workers that visually examine the fruits in a production line. In some big companies there are video cameras that detect some characteristics of the fruits.

These traceability management systems are composed by two macro-activities: the identification of the fruit in the bins and the recording of the information about the fruit in a central database. The identification, which aims at matching bins with the data that identify the contained fruit, involves tagging, reading and writing tags. Instead, the automation of the data recording in the central database usually depends on the kind of the identification activities: if the identification is highly automatic, hardly the company employs a paper database, because it would nullify the benefits of automatic identification; only if the identification system manages digital data, these can be automatically recorded in the database, otherwise a manual transcription is needed.

Table II shows the analyzed traceability systems, which can be classified according to the general models shown in Section I-D. Additionally, the printed/manual tag system column represents an hybrid case, where the print of labels is joined or alternated to manual writing.

The majority of the analyzed warehouses employ a “Printed Tag” traceability system. Two warehouses utilize printed tags, but they utilize also written labels when it is more useful, e.g., when the number of labels is small. Only one warehouse employs the “Stamp system”. The “Fully automatic barcode system” is employed only by the large company.

TABLE II
ANALYZED TRACEABILITY SYSTEMS

Enterprise dimension	Fully manual tag system	Stamp system	Printed tag system	Printed/ Manual tag system	Fully automatic barcode system
Large	0	0	0	0	1
Small/Medium	0	1	7	2	0

B. RFID for Fruit Warehouses

The RFID technology can be used for many activities in the agri-food traceability. Using RFIDs for internal traceability, reading and writing operations are managed by RFID tags and readers. All the data are digital, so they can be used for an easy automatic update of the central database.

The memory of every RFID tag holds an ID that can uniquely identify the tagged object, furthermore some tags have a rewritable memory that can contain data about the object. The data in the memory can directly describe the object, alternatively they can hold short codes that are used like links to reference tables, which are stored in a central database, or located on distributed devices. Therefore, an RFID-based internal traceability system can employ any data location described in Section I-B. An RFID-based traceability system normally uses a computer database, in order to get advantage from the digital form of information.

RFID can be used both for commodity tagging method and for container tagging method. The systems based on written labels or barcodes, by using the container method, have to tag containers every time the contained products change. So for those systems tagging the containers in comparison to tag commodities does not bring real benefits, except the labels saving and the tagging time saving. Barcode-based system could match one ID to a container for its whole life, and they could use it like a link to a database, but normally fruit warehouse operators prefer to use codes that describe the commodity, where each part of the code has its own meaning, and the use of this kind of code requires the change of the barcode every time the commodities in the container are changed. Instead RFID-based systems allow to rewrite data on tags every time the commodities in the container are changed, so they can reach the full saving due to container tagging method.

The high number of produced fruits makes the commodity tagging method unfeasible; in fact, also traditional methods employ the container tagging method. For an RFID-based system the inadequacy of the direct tagging method is increased by the higher cost of RFID tags, so it must employ the container tagging method. In a warehouse the fruits with different characteristics are often merged, and the data system must manage this situation. The container tagging method, applied in a fruit warehouse, can be used with all the described identification methods:

- *Totally distributed*. The information about the fruit is directly written in the tag memory, and the ID identifies the fruit bin. The information must be updated, according to the changes of the fruit in the bin.
- *Compressed and distributed*. Short codes that describe the fruit are stored in the tag memory, and also in this case the ID identifies the fruit bin, since the tag and the bin are

uniquely matched. The codes must be updated, according to the changes of the fruit in the bin. The system needs to manage the reference tables to get the codes.

- *Centralized*. The ID of the tag identifies a fruit bin. The ID is used to access to the information about the fruit in the bin, which are stored in the central database. The information has to change according to the changes of the fruit in the bin.

An RFID system can manage many data, both when the ID of the tag is used like a link to the database and when the tag memory holds some codes that describe the commodity. If the information is stored in the database, the size could be considered as unlimited; if the information is described by codes or it is directly written in the tag memory, the memory size represents a strict limit.

Another critical point is the required time. The identification of a commodity requires an RFID transmission and optionally a query to the central database. These communications require some time, but they are often faster than traditional identification system. Furthermore the management of detailed information can increase the frequency of identifications and so the employed time, for example the additional registration of an operation could require an additional brief stop, according to the modalities of the identification. The managed information must be carefully chosen, according to the time saving and the accuracy targets of the system.

In a fruit warehouse, the typically treated data are the producer, the caliber, the variety, the culture of the fruit, and the operations executed on fruit. Manual systems try to treat the minimum possible number of information, but producer, caliber, variety and culture are required for identification.

The most important characteristic for a company that is evaluating the adoption of an RFID based internal traceability system is the *automation* of the system. In a fruit warehouse, which adopts an RFID based traceability system and the container tagging method with centralized data or rewritable tags with any kind of data location, every bin has to be tagged only once, since bins and tags are both reusable; this activity is not embedded in the production flow, and it can be performed off line. So the TT required by RFID based systems ($RFID_TT$), differently from TT required by traditional systems ($Traditional_TT$), is not function of the quantity of treated fruit, but it is a function of the number of bins owned by the warehouse. Furthermore, according to the formulas described in Section I-C, the number of tagging actions $RFID_t_i$ that contribute to the average time required by each ith IR operation in an RFID-based system ($RFID_IR_i$) is $RFID_t_i = 0$, so

$$RFID_t_i \leq Traditional_t_i.$$

The *tagging* can be manually, semi-automatically or automatically executed, as described in Section I-C. The implementation of this activity, can be chosen without considering the production flow, but only evaluating the number of bins, the required work hours and the device cost.

Reading and *writing* operations can be semi-automatic or automatic. The RFID technology allows executing both these operations by a digital communication. The IR activity, that is composed by the reading and if needed by the writing, is the core of the internal traceability system. The TIR required by RFID based system ($RFID_TIR$) is a function of the number of treated fruits IT. Therefore, to optimize the internal traceability system firstly the IR activity must be optimized. According to Section I-C, the complete formulas to calculate $RFID_TIR$ are:

$$RFID_TIR = \frac{IT}{ITCN}\sum_{i=0}^{n}(o_i \cdot (1+e_i) \cdot RFID_IR_i);$$

$$RFID_IR_i = r_i \cdot RFID_AR + w_i \cdot RFID_AW +$$

$$+ \min(d_i,1) \cdot DBC + d_i \cdot DBQ + CC_i + HC_i + MV_i.$$

However, normally it is not possible to use a single $RFID_AR$, since the average time that is required by a reading of the tag ID ($RFID_ARID$), which is performed IDr_i times, is usually several times larger than the time for a reading of a normal area of the tag memory ($RFID_ARM$), which is performed Mr_i times. Therefore,

$$\begin{aligned} RFID_IR_i &= IDr_i \cdot RFID_ARID + \\ &+ Mr_i \cdot RFID_ARM + w_i \cdot RFID_AW + MV_i \\ &+ \min(d_i,1) \cdot DBC + d_i \cdot DBQ + CC_i + HC_i \end{aligned} \quad (1)$$

The IR operations that can be executed in a fruit warehouse are shown in Table III. The underlined words represent the data that every traceability system must record. Each operation involves also the error checking, i.e., coherence comparison with previous operations. Furthermore, there is also an additional error management operation ($i = 7$). The characteristics of this operation are strictly related to the employed traceability system. o_7 represents the average number of wrong data insertions performed for each filled bin.

Fig. 1 shows the interaction diagrams of automatic and semi-automatic IR implementations with centralized (a) and distributed (b) data location

In a *semi-automatic* system the reading and writing actions are executed by using mobile devices, like a Personal Digital Assistant (PDA). Human operators, for every described operation that is supported by the implementation, have to move the mobile reader next to the tag and to type the information needed by the operation. When an error affects a writing or a reading (e_i), the whole operation is repeated. This kind of error is mainly due to the incorrect use of the devices. Furthermore, when the system detects the introduction of possible wrong data (o_7), it requires that a human operator confirms the operation.

In an *automatic* system based on RFID portal gates the reading and writing actions are automatically executed by the portals. Human operators normally do not need special devices, but for some operations, like the entrance of the fruit in the warehouse, they have to type the data about the fruit. However, this kind of system must allow RFID reading by using manual devices, in order to allow operators to supervise the system. Differently from a semi-automatic system, an automatic system can interact with tags for a strictly limited time, and the use of multiple RFID reading and writing operations can be a problem. In an automatic system the

TABLE III
IR OPERATIONS AND THEIR PARAMETERS FOR CENTRALIZED (CEN) AND DISTRIBUTED (DIS) IMPLEMENTATIONS. THE UNDERLINED WORDS REPRESENT THE DATA THAT EVERY TRACEABILITY SYSTEM MUST RECORD.

i	Operation	Characteristics of the fruit	Data on the operation	o_i	r_i		w_i		t_i	
				All	Cen	Dis	Cen	Dis	Cen	Dis
0	Entrance into the warehouse	Culture, variety, producer, weight	Date and time	1	1	1..14	0	8..12	2..7	off line
1	Entrance into the refrigerating room	None	Date and time, room number	0..3	1	2..8	0	5..7	1	off line
2	Exit from the refrigerating room	None	Date and time	0..3	1	2..8	0	5..7	1	off line
3	Calibrator emptying	None	Date and time	0..1	1	1..11	0	5..7	2	off line
4	Calibrator filling	Caliber	Date and time	0..1	1	4..11	0	9..13	1..2	off line
5	Packing	Pack ID	Date and time	1	1	1..11	0	5..7	2	off line
6	Exit from the warehouse	None	Date and time	1	1	1..11	0	0	2	off line

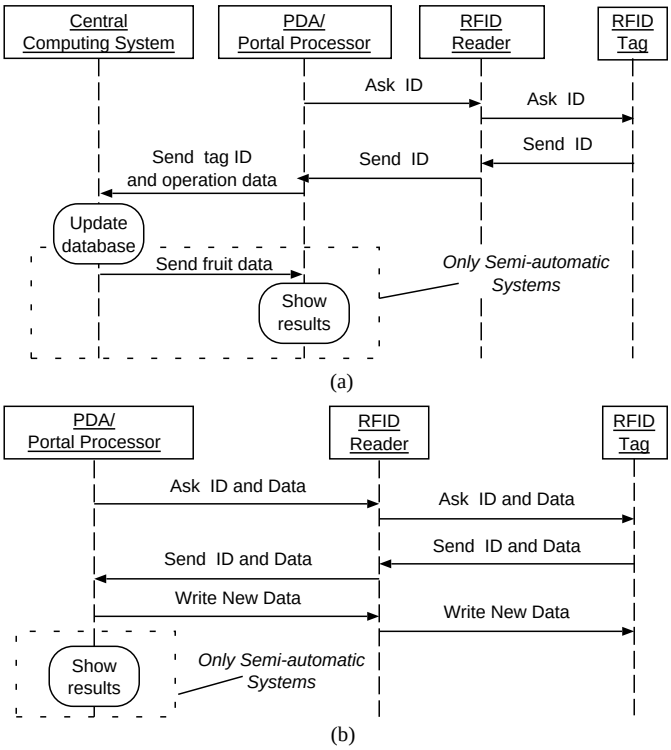

Fig. 1. Automatic and semi-automatic IR interactions with centralized (a) and distributed (b) data location

highest threat is the missed detection of a tag. The system may use devices like infrared sensors in order to detect the correct number of bins, and so to alert human operators of the missed detection of a bin.

By analyzing the practical implementations of the described RFID based traceability systems, we identified the ranges of possible values of constants in (1) that are shown in Table III.

C. RFID-Based Traceability System Performance

A semiautomatic RFID-based traceability system was tested in a working fruit warehouse in order to evaluate the automation improvements. The description of a preliminary implementation of the tested tool was presented in [16]. The testing was conducted in a single calibration line warehouse in Italy; sets of bins were tagged and tracked along the normal production flow.

TABLE IV
OPERATION OCCURRENCES OF THE TESTED RFID SYSTEM (RF) AND TRADITIONAL SYSTEM (T)

Parameter	RF	T	RF	T	RF	T	RF	T	RF	T	RF	T
	$i=0$		$i=1$		$i=2$		$i=3$		$i=4$		$i=5/6$	
o_i	1	1	2	2	2	2	1	1	1	1	1	1
IDr_i	2	0	1	0	1	0	2	0	2	0	2	0
Mr_i	12	1	7	0	7	0	9	0	9	1	9	0
w_i	9	1	4	0	4	0	1	0	8	1	1	0
t_i	0	1	0	0	0	0	0	0	0	1	0	0

The used hardware included RFID passive tags SRIX4K from STMicroelectronics, compliant with ISO14443, with an EEPROM of 4 kbits; and an RFID reader ACG Dual ISO CF Card Reader Module, compliant with ISO14443, at frequency 13.56 Mhz. The test tool was programmed in C# language by using Microsoft Visual Studio 2005, and it requires just 70 Kbytes on PDAs and 200 Kbytes on a central PC. The operators can interact with the tool by using a graphical interface on the PDA. The tool on the PDA manages the communications between the PDA reader and the tags, and it sends the resulting information to the central PC. The tool on the PC receives the information and it interacts with a Microsoft SQL Server 2005 database in order to record them.

The employed readers cost about 260€, the PDAs cost 180€each; one RFID tag unit costs up to 0.7€. Therefore, the hardware for a system that involves 10 readers and 10000 tags costs less than 11000. The software development has required about 20 developer-months. The estimated cost of the software, including customization, for a small-medium company is lower than 5000€.

The characteristics of the RFID system are:

- Data storage: compressed and distributed, computer database.
- Tagged object: container tagging method.
- Kind of data: ID, commodity characteristics, operation data.
- Data format: electronic code.
- Writing/reading automation: semiautomatic.
- Tagging: off line.

According to the specific production flow of the warehouse used for the testing, the packing ($i = 5$) and the exit ($i = 6$) are managed as a unique activity. The average occurrences of the

operations are shown in Table IV. The tagging is performed off line, so ti is always null. The number of readings and writings is high, since it represents the call to a reading method of the RFID reader. In a manual system, as shown in Table IV, the number of reading is lower, but the time required by each reading operation is quite longer. The average time required by the system to execute the operations is:

$RFID_ARID = 205ms$; $RFID_ARM = 21ms$;
$RFID_AW = 37ms$;
$CC_i = \{30ms; 25ms; 25ms; 94ms; 85ms; 94ms\}$.
For $i = 0...5$.

e_i is inversely proportional to the experience of the operators with the tool. Considering a pessimistic case, let assume that e_i is under 0.01 for each type of operation. o_7 is partially due to the low experience with the tool, and to normal errors, so its value in a semi-automatic system approaches the same value of a traditional system. However, for a traditional system the effects of wrong data insertion is negligible on TIR, so o_7 is close to 0. The time MV_i depends on how the production flow is organized. However the MV_i of a semiautomatic system is similar to the manual one. When the traceability IR activity is performed by a suitable operator the MV_i will be quite low, approximately 2 s; however, when this activity is performed by the operator that drives the forklift, the MV_i is larger, approximately 10 s. Let assume that an efficient organization requires that an operator is in charge of the execution of traceability operations. At the entrance of a bin the operator sets its characteristics, so HC_0 is similar to the C_0 of a manual system. For all the other activities HC_i is very low, approximately 200 ms, since the evaluated semi-automatic tool manages all the data, and the operator does not need to know and to analyze them. The resulting $RFID_IR_i$ and $RFID_TIR$ are:

$RFID_IR_0 = 3025ms + HC_0, RFID_IR_1 = 2725ms$,
$RFID_IR_2 = 2725ms, RFID_IR_3 = 2930ms$,
$RFID_IR_4 = 3170ms, RFID_IR_5 = 2930ms$;

$$RFID_TIR = \frac{IT}{ITCN}\sum_{i=0}^{n}(o_i \cdot 1.01 \cdot RFID_IR_i) =$$
$$= (IT/ITCN) \cdot (23185ms + 1.01 \cdot HC_0).$$

The characteristics of the traditional traceability system employed by the warehouse are:

- Data storage: distributed, computer database.
- Tagged object: container tagging method.
- Kind of data: ID, commodity characteristics.
- Data format: written words.
- Reading automation: manual.
- Writing automation: automatic.
- Tagging automation: manual.

The second and third steps ($i = 1$ and 2) are not supported. The data about the treatments are not recorded for any bin, so only the exit from the calibrator and the entrance in the warehouse require writing operations, but each writing involves also a tagging operation. The reading is used for the traceability management only before calibration and packing. The approximate average time required to execute the operations is:

$Traditional_AR = 2s; Traditional_AW = 2s$;
$Traditional_AT = 5s$.

$e_i = 0$, since it is negligible for manual systems. $C_i = HC_i$, so C_i is steady for all the steps, and it is similar to the HC_0 of the RFID tool. MV_i is longer for the steps that involve a tagging operation, where it requires about 5 s, since this operation requires that the operator gets the labels; for the other operations MV_i is similar to the MV_i of the RFID system. The resulting traditional IR_i are:

$IR_0 = 12s + C_i, IR_1 = 0, IR_2 = 0, IR_3 = 4s + C_i$,
$IR_4 = 12s + C_i, IR_5 = 4s + C_i$;
$Traditional_TIR = (IT/ITCN) \cdot (32s + 4C_i)$.

In order to evaluate the feasibility of the RFID traceability system we need to compare it to the printed tag system. According to the previously specified characteristics we can state that:

$$\frac{IT}{ITCN}(23.18s + 1.01HC_0) < \frac{IT}{ITCN}(32s + 4C_i);$$

by simplifying ($IT/ITCN$), and since HC_0 is almost equal to C_i, we have:

$$RFID_TIR < traditional_TIR.$$

Therefore, with an efficient organization of the work we can state that the RFID system manages more detailed data, in a shorter time than the printed tag system. The time saving allows increasing the production flow of the company. The RFID semi-automatic systems require a larger starting cost than traditional systems, but the maintenance of both the systems is mainly due to labor cost. According to the time analysis and to the described costs, for small/medium companies that spend the equivalent of 1 full time employer for traceability management, the estimated payback period is about 2 years. This result is also compatible with a previous analysis on an RFID trial [17].

III. Conclusion

The traceability in agri-food sector is a key factor, and its management has a great impact on the production flow of a company. For this reason an effective traceability system is fundamental for avoiding large waste of resources. Automation is regarded as the key factor to realize an effective internal traceability system, since manual activities require more time. Furthermore, a high automation brings warranties of accuracy, completeness, and reliability. Therefore, to implement traceability without carefully considering all the automation options could entail the wastage of human and economic resources.

In this paper a full framework for the evaluation of traceability systems is presented. According to this framework an RFID-based traceability system was evaluated and compared to the established ones. The case study analysis has shown that the application of RFID technology to traceability management can provide to agri-food sector efficiency improvements, since an RFID-based system can manage more data in less time.

In order to analyze the traceability management, a precise definition of traceability, and a classification of the automation

levels of the agri-food company have been presented and described. The proposed framework may allow both researchers and practitioners to perform deterministic analysis on the performance of traceability systems.

An RFID-based traceability system can treat several data in short time. The analyzed system, which is based on a semiautomatic implementation, can reach good benefits: it is inexpensive, it requires a larger starting cost than traditional systems, but its maintenance is smaller; it manages detailed information about products and treatments, and it requires lower execution time than traditional systems. The analysis has shown that the majority of the reached time saving is due first to the tagging operation, which in RFID system can be performed off line, and second to the differences between the time required by semiautomatic reading/writing operations, and manual reading/writing operations. Furthermore, the analysis has shown that manual systems require more time in order to allow employers to analyze the operations and to make decisions.

References

[1] R. Parasuraman and V. Riley, "Humans and automation: Use, misuse, disuse, abuse," *Human Factors*, vol. 39, no. 2, pp. 230–253, June 1997.

[2] S.-Y. Tseng, T.-F. Wu, and Y.-M. Chen, "Wide pulse combined with narrow-pulse generator for food sterilization," *Industrial Electronics, IEEE Transactions on*, vol. 55, no. 2, pp. 741–748, Feb. 2008.

[3] W. Xu, J. Torrance, B. Chen, J. Potgieter, J. Bronlund, and J.-S. Pap, "Kinematics and experiments of a life-sized masticatory robot for characterizing food texture," *Industrial Electronics, IEEE Transactions on*, vol. 55, no. 5, pp. 2121–2132, May 2008.

[4] M. Boehlje and O. Doering, "Farm policy in an industrialized agriculture," *Journal of Agribusiness*, vol. 18, no. 1, pp. 53–60, March 2000.

[5] J. F. Reid, Q. Zhang, N. Noguchi, and M. Dickson, "Agricultural automatic guidance research in north america," *Computers and Electronics in Agriculture*, vol. 25, no. 1-2, pp. 155 – 167, 2000.

[6] L. U. Opara, "Traceability in agriculture and food supply chain: a review of basic concepts, technological implications, and future prospects," *Journal of Food, Agriculture and Environment*, vol. 1, no. 1, pp. 101–106, 2003.

[7] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*. New York, NY, USA: John Wiley & Sons, Inc., 2003.

[8] E. Sanchez, F. Gandino, B. Montrucchio, and M. Rebaudengo, "Public-key in RFIDs: Appeal for asymmetry," in *Security in RFID and Sensor Networks*, Y. Zhang and P. Kitsos, Eds. Auerbach Publications, TaylorFrancis Group, in print.

[9] A. Juels, "Rfid security and privacy: a research survey," *Selected Areas in Communications, IEEE Journal on*, vol. 24, no. 2, pp. 381–394, Feb. 2006.

[10] M. Hossain and V. Prybutok, "Consumer acceptance of RFID technology: An exploratory study," *Engineering Management, IEEE Transactions on*, vol. 55, no. 2, pp. 316–328, May 2008.

[11] S. Chalasani and R. Boppana, "Data architectures for RFID transactions," *Industrial Informatics, IEEE Transactions on*, vol. 3, no. 3, pp. 246–257, Aug. 2007.

[12] ISO Std. 9001-2000.

[13] "laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety," REGULATION (EC) No 178/2002 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 28 January 2002.

[14] M. Cimino, B. Lazzerini, R. Marcelloni, and A. Tomasi, "Cerere: an information system supporting traceability in the food supply chain," in *E-Commerce Technology Workshops, 2005. Seventh IEEE International Conference on*, July 2005, pp. 90–98.

[15] E. Sahin, Y. Dallery, and S. Gershwin, "Performance evaluation of a traceability system. an application to the radio frequency identification technology," in *Systems, Man and Cybernetics, 2002 IEEE International Conference on*, vol. 3, Oct. 2002, pp. 6 pp. vol.3–.

[16] F. Gandino, B. Montrucchio, M. Rebaudengo, and E. Sanchez, "Analysis of an RFID-based information system for tracking and tracing in an agri-food chain," in *RFID Eurasia, 2007 1st Annual*, Sept. 2007, pp. 1–6.

[17] M. Krkkinen, "Increasing efficiency in the supply chain for short shelf life goods using RFID tagging," *International Journal of Retail & Distribution Management*, vol. 31, no. 10, pp. 529–536, 2003.

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