Traceability issues in food supply chain management: A review

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Abstract

In recent years, traceability aspects have become recognised as an essential tool for guaranteeing food safety and food quality. On the other hand, the design of a traceability system requires a thorough rethinking and reorganising of the whole food supply chain. This paper presents a comprehensive literature review on the aspects of supply chain management that are influenced by traceability, which is herein considered fully integrated in the chain management and not kept separately.

The objective of the paper is twofold: the first goal is to analyse how traceability concepts, requirements and technologies influence modern supply chain management and are handled by the ensuing optimisation principles. This analysis is based on an in-depth scrutiny of the state of the art, and it is supported by precise pointers to the literature on the subject. The second goal is to highlight what could be, in the authors' opinion, the future trends and perspectives in this field of research.

Keywords: traceability, traceability system, food supply-chain management, optimisation.

Nomenclature

α	Coefficient accounting for notification, logistics etc.
ARC	Average recall cost
BDC	Batch dispersion cost
BSE	Bovine spongiform encephalopathy
$C(e)$	Cost induced by the possible reduction in efficiency
$C(overall)$	Overall cost of traceability system
$C(q)$	Cost induced by the possible reduction in quality
$C(tt)$	Cost of the system
CTP	Critical traceability point
D_b	Chain dispersion measure
FSC	Food supply chain
GA	Genetic algorithms
GM	Genetically modified
HACCP	Hazard analysis and critical control point
IP	Identity preservation
IU	Identifiable unit
IUU	Illegal, unreported and unregulated
MILP	Mixed integer linear programming
n	Number of the retailers by a lot
NL	Non-linear
NN	Neural networks
P_r	Retail value
Q_R	Product quantity
RC	Recall cost
RE	Risk exposure
RFID	Radio frequency identification
TRU	Traceable resource unit
TS	Traceability system
$WCRC$	Worst-case recall cost

1. Introduction

The definitions of *traceability* and of *traceability system* (TS) that can be found in the literature can be very broad or strict, see for instance Karlsen et al. (2013), Bosona & Gebresenbet (2013), and Olsen & Borit (2013), but in all cases they refer to the ability to guarantee that products "moving" along the food supply chain (FSC) are both tracked and traced. Tracking is the ability to follow the downstream path of a product along the supply chain, while tracing refers to the ability to determine the origin and characteristics of a particular product, obtained by referring to records held upstream in the supply chain (Bechini, 2008). The ability to trace the history of a food product, collecting in a rigorously formalised way all the information related to its displacement along the supply chain, is essential for modern companies. This is motivated by many different reasons, among which are compliance with mandatory regulations, international standards and certifications requirements, the implementation of marketing strategies and programmes, the attestation of product origin, identity and quality, and, most importantly, the necessity of effective methods to react against the spreading of sanitary outbreaks (in the EU the main steps were determined by the main food safety crisis – BSE etc.). This last aspect is becoming crucial due to the constant increase in the frequency of food-crises due to safety issues. This demands increasingly efficient traceability systems, which in turn require a thorough rethinking of the tasks and objectives of the whole food supply chain management. To explicitly quantify the effectiveness of FSC management policies dealing with traceability, recent research has been devoted to the definition of precise criteria for measuring the performance of TSs. Even if these criteria are nowadays closely related to the ability of the FSC management to limit the quantity of recalled product in the case of a crisis, they could also take into account other aspects quantifying how traceability contributes to product valorisation, guarantees identity preservation, prevents counterfeiting, etc. The introduction of such criteria is crucial for improving the performance of the whole FSC management and, from a technical point of view, for developing efficient techniques for TS performance optimisation.

Tracking and tracing involve managerial decisions on the value chain in order to reach efficiency improvements in processing organisation and risk management, and a good level of buyer-supplier coordination (Rabade and Alfaro, 2006). Nevertheless, FSC stakeholders typically attribute different values to traceability: for the consumer it represents an added value related mainly to safety and quality information, while for food producers it is a tool to avoid market breakdowns which might strongly affect the brand, as well as to guarantee policy requirements. This discrepancy leads to different possible ways of evaluating costs-benefit ratios and of adopting ex-post or ex-ante traceability systems (Hobbs, 2004).

The level of detail in traceability is not dependent on a single company, but the efficiency of the tracking and tracing method relies on the agreements among the group of companies: lack of transparency in one node affects the whole chain (see, for instance, explanatory applications for vegetable and poultry supply chains in Hu et al., 2013 and Lavelli, 2013, respectively). The increasing share of the food market that requires short preparation before consumption leads to new multi-ingredient products that are often produced by different stakeholders. In this case, cross-contamination could be more frequent if the companies inside the supply chain lack proper coordination (Souza-Monteiro and Caswell, 2010).

Automation in data collection enhances the precision and the reliability of identification of the traced unit. Technologies and devices are continuously improved. Among these, optical systems (bar code, data matrix, QR code) as well as radio frequency identification devices (RFID) have been successfully deployed and their applications to different food products (Costa et al., 2013), living beings (Barge et al., 2013) and even flows of bulk products (e.g. Kvarnstrŏm et al., 2011 and Liang et al. 2013) are constantly increasing. From a technological viewpoint, it can be stated that the devices for identifying and tracing the products have nowadays reached a good level of industrialisation, providing new and efficient opportunities for FSC management. Even if their description goes beyond the scope of this paper, the interested reader is referred for instance to Ruitz-Garcia and Lunadei (2011) and Sarac et al. (2010), and references therein, for a survey on the technological solutions to traceability.

The objectives of this paper are: i) to carry out a comprehensive literature review of the aspects of supply chain management that are influenced by (and that influence) traceability, and that are fully integrated and inseparable in FSC management, ii) to provide ideas on possible future research directions related to the management of traceability systems. The paper is structured in two main parts: in the first one, consisting of Sections 2 and 3, the mainstream aspects and solutions currently available are streamlined and discussed based on the literature, keeping the authors' opinion out of the picture as much as possible. In particular, in Section 2 the different aspects of European and US legislation, together with ISO and private standards that are related to food traceability issues are outlined and discussed. Section 3 discusses in detail the aspects of traceability in FSC management and optimisation: the problem of food crisis management and consequent product recall, the problem of tracing bulk products, the issues related to quality and identity preservation, and the problem of fraud prevention and anti-counterfeiting. The second part of the paper, Section 4, reports the authors' viewpoint on the possible trends and perspectives in traceability-oriented food supply chain management. Finally, concluding remarks are reported in Section 5.

2. **Traceability related legislations and standards**

As a consequence of recent sanitary outbreaks, (Spongiform Encephalopathy or BSE, *Escherichia Coli* strain O157:H7, *Salmonella, Listeria monocytogenes*, dioxin, etc.), different countries have developed and implemented legal requirements on traceability, and defined methods and control authorities to monitor unsafe food products which have to be quickly removed from the market by recall actions.

In parallel, due to increasing concerns for consumers on food safety, certified voluntary traceability has been introduced by different private companies to make the public aware of the safety and the quality of food products or brands, including also further information on for instance ethical issues (Coff et al., 2008), religious requirements, organic production methods (Maryuama, 2010), genetically modified organisms (GMO) absence, sustainability and environmental information (Bremmers et al., 2011; Manzini and Accorsi, 2013).

International importing of food due to the global market has increased efforts to apply traceability strategies at the international level, and this issue was debated within the UN's joint Food and Agriculture Organization (FAO) and World Health Organization (WHO), leading to the Codex Alimentarius, where traceability in the food sector is primarily defined as *“the ability to follow the movement of a food through specified stage(s) of production, processing and distribution”* (Codex Alimentarius Commission, 2006). Here it was recognised that, at the international level, methods are not harmonised and are often complicated, thus also leading to barriers to trade (Codex Alimentarius Commission, 2007).

The traceability concept was further defined with some modifications in laws and standards adopted by different countries, as can be found in Ringsberg and Jönson (2011) and Mewissen Velthuis, Hogeveen and Huirne (2003).

2.1. European and US legislations

In Europe, EC General Food Law Regulation 178/2002 (European Commission, 2002), applied since 2005 and followed by further modifications concerning specific matters as for instance GMO (European Commission, 2003ab), allergens (European Commission, 2003c), food hygiene (European Commission, 2004abc), requires the establishment of a traceability system for all food products. The General Law clearly states that the detail of traceability is to be extended also to each ingredient of the food, defining traceability as *“the ability to trace and follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing and distribution.”* However, the General Food Law does not state any specific method or technique that food operators have to follow (Folinas et al., 2006; Asioli et al., 2011). Therefore, in the absence of other more restrictive laws related to a specific food product or national laws of the member states, some details such as, for instance, the lot size are not defined, since the requirement for traceability is limited to ensuring that businesses are at least able to identify the immediate supplier of the considered product and the immediate subsequent recipient, with the exemption of retailers to final consumers (one-step-back one-step-forward). The General Law, at art. 33, established the *European Food Safety Authority* (EFSA) and the *Rapid Alert System for Food and Feed* (RASFF) for food alert notifications from member states (on the basis of art. 50, 51 and 52).

The European traceability framework is regulated at three levels (Souza Monteiro and Caswell, 2010; Meuwissen et al., 2003): European Commission policies, country level policies and standards and private voluntary certification. Voluntary traceability methods in the food sector are certified by private companies that normally have to comply with specific legal rules. In the case of meat, which was traced early at individual level (European Commission, 1997), specific mandatory as well as voluntary traceability data allowed for labelling are defined (European Commission, 2000).

In the US, compulsory traceability was only recently introduced for the food sector (Donnelly and Thakur, 2010; Smith et al., 2005), and food safety was previously assured mainly by private companies in order to guarantee a good quality to the consumer (Kramer et al., 2005). Traceability first became mandatory only to react against bioterrorism (United States, 2002). The Food Safety Modernization Act (United States, 2011), signed on January 2011 by the US President, introduces a system of preventive controls, inspections and compliance authorities, as a response to violations (recalls) on domestic as well as on foreign US food.

2.2. International standards

Prior to the introduction of different country regulations, in some cases the food industry had already developed efficient traceability methods for the management of logistics and warehouses, based on the balance of costs and benefits of the traceability system level. For instance, the TraceFood Framework, discussed by Storøy et al. (2013), represents a valuable example. Especially in the US, traceability was implemented early, before legal requirements, mainly motivated by the increase in revenue due to lower-cost distribution systems, reduced recall expenses and expanded sales of high safety and quality products (Golan et al., 2004).

Several International Standards and European norms that are related to traceability in the food chain have been published (exhaustive discussions can be found in McEntire et al., 2010 and Schulze et al., 2008). These standards are in the following areas: quality management systems, food safety management systems, traceability of fish products, data capture techniques and electronic interchange of data elements and documents in commerce, industry and administration. While standards in *internal traceability*, which refers to records kept inside the business unit, are not specifically requested, in *external traceability,* defined as the sharing of information among the different stakeholders of the supply chain (Moe, 1998), standards and methods for data interchange are crucial.

The International Organization for Standardization (ISO) has delivered, in the context of the ISO 9000 series for Quality Management Systems, a number of standards concerning traceability. ISO 22000:2005 specifies the requirements for food safety management systems. In particular, it addresses the establishment and application of TS *"that enables the identification of product lots and their relation to batches of raw materials, processing and delivering records"* (Int. Organization of Standardization, 2005). ISO 22005:2007 introduces principles and basic requirements for the design and the implementation of a food (and feed) TS. Even if it does not specify how this should be achieved, it introduces the requirement that organisations involved in a FSC have to define information that should be, at each stage, obtained and collected from the supplier and then provided to customers, in addition to product and processing history data (Int. Organization of Standardization, 2007). In ISO 9001:2008 the concept of product identification is introduced, requiring that *"where appropriate, the organization shall identify the product by suitable means throughout product realization and where traceability is the requirement, the organization shall control the unique identification of the product and maintain records"* and that *"preservation shall also apply to the constituent parts of a product"* (Int. Organization of Standardization, 2009). To this extent, a number of ISO Standards (e.g. ISO/IEC 15961, 15962, 24791, 15459,15418, and 15434) have been delivered to regulate data encoding on radio frequency identification devices and their interoperability with barcode-based systems (see Chartier & Van Den Akker, 2008 for a complete report delivered by the Global RFID Interoperability Forum for Standards).

Parallel to these, commercial standards have been delivered by organisations and associations to set traceability requirements, facilitate traceability data sharing and adopt product identification standards for commercial purposes. This is the case, for instance, for GS1 standards (GS1 US, 2010), GlobalGAP (GlobalGAP, 2013) and British Retail Consortium (BRC) Best Practice Guidelines for Traceability (British Retail Consortium, 2013), where requirements for traceability, principles of effective TS design and guidelines to undertake traceability tests are addressed. Satisfaction of these commercial standards, which usually corresponds to obtaining a specific certification, represents a necessary condition for a company to access a given market.

3. **Traceability in food supply chain management**

The ability of a traceability system to monitor the composition and the position of each lot in the production and supply chains represents a very powerful tool that can be used to define new management objectives and to improve the overall performance of the FSC. In this section, we introduce the main concepts and definitions present in the literature, and then discuss in detail the different objectives driving a traceability system and the relative actions to be undertaken for their fulfilment.

3.1. Definitions

According to McEntire et al. (2010), see also Golan et al. (2004), the level of traceability can be described by four quantities: *breadth* (amount of attributes connected to each traceable unit), *depth* (how far upstream or downstream in the FSC the TS traces the lot/unit correctly), *precision* (the degree of assurance with which the system can pinpoint a particular product's movement or characteristics), and *access* (the speed with which tracking and tracing information can be communicated to supply chain members and the speed with which the requested information can be disseminated to public health officials during food-related emergencies).

Breadth is based on the quantity of information related to the traced food unit. Together with the size of the unit, traceability depth level has been deeply discussed by economic as well as safety points of view. Depth varies with the type of attribute and the interest in the different stages of production and marketing agreements. Information flow can be coupled to physical flow also in aggregated form or can be physically distributed and accessed remotely at different levels of detail (Bechini et al., 2008; Triekenens and Beulens, 2001) and even contracted independently.

In the case of quality management through the supply chain, some attributes can even change dynamically (e.g. temperature data). As the benefits of traceability could be different for each supply chain actor, a cost-benefit analysis and the establishment, for instance, of premiums to enhance the willingness of collecting and transferring information, especially in the first production phases (e.g. farmers), followed by a network coordination in sharing the information along the supply chain, will lead to an enhancement of precision and a reduction of costs of traceability of the whole chain all the way to the consumer.

The definition and the evaluation of the performance of a traceability system is the first step in developing traceability-oriented management policies. Different criteria have been proposed based on the elaboration of the recall costs.

To formalise this problem, some nomenclature has to be introduced. Moe (1998), on the basis of the terminology first introduced by Kim et al. (1995), proposed the concept of *traceable resource unit* (TRU) for batch processes as a *"unique unit, meaning that no other unit can have exactly the same, or comparable, characteristics from the point of view of traceability."* This concept has been formalised in the ISO Standard 22005/2007 (International Organization for Standardization, 2007), where the notion of lot is defined as a "*set of units of a product which have been produced and/or processed or packaged under similar circumstances.*"

Bollen et al. (2007) further elaborated on this concept by introducing the notion of *identifiable unit* (IU), which represents the unit of product that must be uniquely identifiable within each system in which it is used. The size of the IUs is responsible for the *granularity* of the traceability system. Many definitions of granularity have been proposed in literature. Karlsen et al. (2012) defined granularity as a quantity *"determined by the size of a traceable unit and the number of the smallest traceable units necessary to make up the traceable unit at a specific granularity level."* Granularity level is determined by the size and number of batches, and a finer granularity allows for adding even more detailed information about the product, and for acting at a more detailed and range-limited level in the case of a possible recall. The optimal granularity level is very difficult to determine, since it depends on product type and customer. Unfortunately, in most parts of current supply chains, the granularity at which the products involved are traced does not come from the results of a formal analysis and optimisation study, but it is principally the consequence of a combination of tradition, short-term convenience and use of available facilities.

The notion of IU allows for a formal definition of the precision of a traceability system, which can be evaluated, as discussed in Bollen et al. (2007), as the ratio between IUs at two points in the supply chain. It is the consequence of the number and the nature of the transformations that IUs incur, and of the extent, nature and accuracy of the recorded data. If an IU is split up, the separated parts keep the identification of the parent IU, while if some IUs are joined, the identification of the IU is different from the identification of the parent IUs. Hence, precision reflects the degree of assurance with which TS can pinpoint a particular food product movement or characteristic (Golan et al., 2004). *Purity* is defined as the percentage (in terms of composition) of an output lot sourced from a single raw material input lot (Riden and Bollen, 2007). In other words, for a given lot, purity expresses the percentage of the input lot making the largest contribution to its composition.

Degradation in the performance of a TS occurs whenever systematic information loss takes place, as for instance when information about the composition or process conditions is not properly linked to the product and systematically recorded. The point where this loss occurs has been defined by Karlsen et al. (2010) as *critical traceability point* (CTP). The identification and mapping of CTPs is performed by qualitative methods (direct observation, structured interviews and document analysis), and leads to the definition of a *critical traceability point analysis* plan (Karlsen and Olsen, 2011). Some application of CTP mapping and validation can be found in Donnelly et al. (2009); see also Karlsen et al. (2011) and references therein.

Finally, an important aspect of the TS is the definition of monitoring schemes to evaluate the effectiveness of the system. Whenever possible TS response should be validated by other methods (typically physicochemical, genetic, or microbiological) able to identify and discriminate products (see Peres et al., 2007 and the very recent papers by Galimberti et al., 2013 and Aceto et al., 2013). The correct functioning of ICT procedures should be periodically checked, as discussed by Randrup et al. (2008) in a Nordic fish supply chain case study, simulating a food safety hazard, and by Mgonja et al. (2013). The importance of validation methods is also reported as a main requisite in ISO 22005:2007 (Section 5.1 General design considerations) where it is stated that "*the traceability system should be verifiable*".

3.2. Traceability-driven issues in food supply chain management

This section lists and discusses in detail the different aspects of FSC management that are directly connected to traceability issues, or can be dealt with by means of proper TS design. These features go beyond the normal ability of the TS to track and trace food products, which is here taken for granted, involving additional aspects or specific ways of organising the FSC that may significantly impact on the TS and, in turn, on the FSC performance.

3.2.1 Food crisis management

A traceability system has to provide strategic information in the unfortunate case when a food crisis forces the recall of a batch of product. Product recalls are an increasing concern for food companies and government agencies (e.g. FDA for US and RASFF for EU) and can be voluntary, when issued by the food manufacturer itself, or forced (Kramer et al., 2005).

The main causes of recalls are failures in good manufacturing practice, incorrect labelling and packaging and, of course, the identification of conditions that can compromise the safety of the food and consumer's health (microbial agents, chemical contamination, foreign material, undercooking of product etc.). Another frequent cause is the (undeclared) contamination of raw and semi-processed materials with allergens (especially eggs, peanuts, dairy and wheat). The occurrence of food and feed recalls is increasing (Potter et al., 2012) and in the EU, in 2011, exceeded 3,700 notification cases (RASFF, 2011). This fact can also be imputed to new government regulations and food safety standards, to the development of new detection technologies, and to increasing imports from less developed countries, where food safety standards are usually less severe.

The management of a recall procedure has to be performed by the top management of the company, and involves many activities, ranging from risk assessment and the identification of the interested products to the notification of the measure to the actors of the supply chain (suppliers, distributors, buyers etc.) and, finally, the recall action. In this context, Wynn et al. (2011) identified common data requirements for traceability and data exchange, and analysed opportunities for the automation of the notification process in case of a recall.

The first consequence of a recall is the potential drop in consumer confidence (Kumar and Budin, 2006; Skees et al., 2001). A negative brand image can remain in the subconscious of potential consumers for many years. Additionally, the company has to incur costs related to the logistics of the recall and the destruction of all the products that are, in some way, connected with the incriminated batch (Jacobs, 1996).

Since this could be absolutely critical for a company, some studies for modelling and forecasting the effects of recall actions have been carried out (e.g. see Kumar and Budin, 2006, Randrup et al., 2008 and Fritz and Schiefer, 2009). Most companies do not have reliable methods to manage a recall strategy, nor to estimate the real amount of product that has to be discarded in case of a recall.

The recall of a product typically follows two steps that need to be performed in a very short time: the backward identification of potentially deficient lots and then the forward identification of potentially affected products that have to be withdrawn (Fritz and Schiefer, 2009). The performance of a traceability system can therefore be directly associated with its ability to hold down the amount and cost of the product to be recalled. Hence, a *recall cost* (*RC*) can be directly associated with the material that has to be recalled, which depends on different factors such as i) the size of the batches that have been individually tracked and managed by the traceability system, ii) the way the batches of the different materials have been processed and mixed to obtain the final product, and iii) the level of segregation adopted by the company to manage and maintain different batches of product separate. Direct costs associated with a recall action include the costs for the notification of the recall, the logistics to retrieve the product and lost sales. Resende-Filho and Buhr (2010) consider all these cost components as directly proportional to the amount of product to be recalled, that is

$$RC = \alpha P_r Q_R$$

where P_r denotes the retail value of the product, Q_R the quantity of product to be recalled and $\alpha > 1$ is a coefficient accounting for notification, logistics etc. Similarly, Fritz and Schiefer (2009) express the overall cost of a traceability system as the sum

$$C(overall) = RC + C(tt) + C(e) + C(q)$$

where $C(tt)$, $C(e)$ and $C(q)$ represent, respectively, the cost of the system, and the costs induced by the possible reductions in efficiency and in quality caused by the adoption of the tracking and tracing system.

An estimate measure of *RC* was proposed in Dupuy et al. (2005), with the introduction of the *downward* and *upward dispersion indices* and, more generally, of the *batch dispersion cost* (*BDC*) of a TS. The downward dispersion of a lot represents the number of batches of finished product that contain part of the lot, while the upward dispersion of a finished lot of product is constituted by the number of raw material lots used to produce that lot. The measure of the total batch dispersion of a system is then given by the sum of downward and upward dispersion indices of all raw materials. It follows that when the performance of a traceability system is associated with batch dispersion, it is measured by the number of active paths (links) between raw materials and finished products. Concerning the distribution phase, Rong and Grunow (2010) introduced the *chain dispersion measure* defined as

$$D_b = \frac{n(n-1)}{2}$$

where n is the number of retailers served by the lot b. As for *BDC*, D_b depends on the number of links, but it increases quadratically for $n > 1$.

However, it should be remarked that the typical interest of a company is to know the largest possible amount of product that it could be necessary to recall. For this reason, Dabbene and Gay (2011) introduced the *worst-case recall cost* (*WCRC*) index, defined as the largest amount of product that has to be recalled when a batch of raw material is found unsafe. Analogously, they defined the *average recall cost* (*ARC*) index, which represents the average mass of product to be recalled when one of the entering material is found inappropriate. The formalism introduced by Dupuy et al. (2005) and also adopted in Dabbene and Gay (2011) stems from the consideration that, from a traceability viewpoint, the production process can be modelled as an interconnected graph, where the different lots of raw materials are represented as nodes, and the arrows represent the mixing operations that lead to the final products. A very simple example of this model is reported in Figures 1a and 1b, which depict two similar situations in which three different raw materials A, B, and C enter into a mixing/splitting process obtaining two intermediates (D and E) and three final products F, G, and H. The numbers on the arrows represent the quantity (mass) of material involved in the mixing. This example illustrates the meaning of the *BDC, WCRC* and *ARC* indices. Notice that, in two cases that differ only in the position of one link, the three costs can significantly differ. In particular, while the batch dispersion (which corresponds to the total number of links from raw materials and final product) does not vary in the two cases, the *worst-case recall cost* is rather different.

The importance of determining, for each step in the production and supply chains, appropriate batch sizes and mixing rules in order to enhance the performance of the traceability system is clear. This problem was first introduced by Dupuy et al. (2005), who designed mixing rules aimed at minimising the batch dispersion measure. As previously discussed, this measure is indeed related to the final quantity to be recalled, since it aims at reducing the mixing of different batches, and was proven effective in the above-mentioned works. However, as already remarked, the minimisation of this index does not necessarily result in the minimisation of the quantity of products to be recalled in a worst-case (or in an average) situation, and the direct minimisation of *WCRC* or *ARC* indices is to be preferred. Since the number of variables and constraints in the optimisation problem can be high, Tamayo et al. (2009) proposed the adoption of genetic algorithms (GA) to solve the same problem. Unfortunately, even for medium-size problems, GA can lead to suboptimal solutions, as numerically shown by Dabbene and Gay (2011) for the sausages case of Dupuy et al. (2005). Donnelly et al. (2009) applied batch dispersion concepts to the case of the lamb meat industry, specifying resources joining and splitting points via detailed material and information flow diagrams. The identification of traceability critical points showed once more the role of mixing operations in the performances of traceability systems.

Different approaches were developed starting from the introduction by Dupuy et al. (2005) of the concept of *batch dispersion*. In particular, Rong and Grunow (2010) proposed a joint production and distribution model that also takes into account simplified product degradation dynamics. The optimisation of the lot sizing and routing is then performed by means of a MILP solver and a specifically-designed heuristic. Wang et al. (2009) proposed an optimisation procedure that integrates operational and traceability objectives, incorporating both risk and cost factors. In particular, they introduced a risk rating parameter, influenced by various factors causing quality and safety problems, which is associated with the probability of product recall. Saltini and Akkerman (2012) studied and quantified the potential impact of the improvements of a chocolate TS on production efficiency and on product recall. They consider two different scenarios, the first one adopting the maximum processing batch size and the second focused on reducing batch dispersion, to simulate three traceability systems which differ in the number of the actors involved in the traceability process of the supply chain (i.e. the depth of the TS). The engagement of all nodes of the supply chain (cocoa farmer, local buying station, the exporter and the chocolate manufacturer) would reduce the recall size by up to 96%.

From the discussion so far, it follows that an efficient way to improve the performance of the TS is to reduce mixing. However, there are cases in which mixing operations concerning different lots of the same type of raw material are necessary to obtain delivered products which meet buyer requested specifications. This is the case, for example, with grains (Thakur and Donnelly, 2010; Thakur et al., 2010) and coffee, where blending of different batches allows the achievement of the desired parameters, such as sensory properties, moisture content and test weight. To this extent Thakur et al. (2010) present a multi-objective optimisation model aimed at minimising the number of storage bins (that represents a measure of lot aggregation) and the total cost of blending and shipping the grains. The optimisation is constrained by, besides product availability, the contract specification expressed in terms of moisture content, test weight, presence of damaged and foreign material.

More generally, the literature on modelling and optimisation approaches to traceability systems design is very wide. For the sake of completeness, Table 1 presents a summarising view of the different approaches and solutions to TS design. The table concentrates on the works where the managing and optimisation aspects, which represent the main focus of our review, are central.

3.2.2 Traceability of bulk products

Many industries use ingredients that are liquids (milk, vegetable oils, etc.), powders (cocoa, powdered milk, flour etc.), crystals (e.g. salt, sugar) or grains that are stored, in many cases, in huge silos which are very rarely completely emptied, so that many lots are contemporaneously kept in the same container. In the case of liquid food, Cocucci et al. (2002) stressed that cleaning between two product batches is *"of primary importance*" to allow distinct separated batch identities. In particular, *cleaning-in-place* procedures involve pumping water and detergent through the production equipment and, besides guaranteeing high hygienic standards and cleaning, are foreseen as the only way of strictly guaranteeing that the different batches cannot contaminate each other. However, these cleaning procedures usually represent a high cost for the firm, and become particularly undesirable for *continuous production systems* (such as, for instance, milk production in a dairy). In these processes, in which products are refined gradually and with minimal interruptions through a series of operations (Dennis and Meredith, 2000), a continuous flow of liquid/granular raw material is necessary to maintain the production and, as pointed out by Skoglund and Dejmek (2007), any interruption for cleaning would require stopping the production so that *"there is an incentive to clean as seldom as possible."*

Moreover, for these kinds of bulk products, it is very difficult to associate any label, marker or identifier that could directly identify the lot. Indeed, some specific technology based on RFID markers has been developed in the case of continuous granular flows (specifically, iron pellets) by Kvarnström et al. (2011). These allow *on-line* traceability of continuous flows, thus improving upon previous *off-line* solutions based on the introduction of specific tracers into the grains, such as chemical compounds or radioactive tracers (see Kvarnström and Oghazi, 2008, for detailed a discussion and references on these techniques). However, in the case of food products, the situation is complicated by the obvious requirement that the markers should not compromise in any way the integrity and quality of the food. Thus, any

RFID-based traceability system would require the development of a technology for safely removing the tracing devices from the final product (e.g. before grain grinding). Recently, some solutions have been proposed by Liang et al. (2009), Lee et al. (2010), and Liang et al. (2013) for the specific case of grains, which involve inserting particular pill-sized food-grade tracer particles into the grains during harvest. These tracers carry identity information related to product origins, and are composed of materials that can be safely eaten such as sugar or cellulose. In particular, specialised ink-jet printers have been devised to print bar codes or data matrix (DM) code symbols on the particles with food-grade ink. Anyway, these solutions remain principally an off-line approach suitable for modelling and validation purposes, since collecting and identifying the tracers would usually still require interrupting production.

The problem of fluid product traceability has been seemingly first addressed, for the case of continuous processing, by Skoglund and Dejmek (2007), where dynamic simulation was used to model the changeover of lots of a liquid product in a pipe. The presence of portions of product deriving from the partial mixing of two subsequent lots led to the introduction of the concept of *fuzzy traceability*. By introducing a threshold, new *virtual batches* are then generated. These ideas have been further developed in Comba et al. (2013), where the definition of lot given in the ISO Standard 22005/2007 is rigorously formalised. In particular, the authors define a criterion, named *composition-distance*, to formally establish the homogeneity of a lot from the point of view of its composition in terms of raw materials that need to be tracked. The composition distance measures the difference of two products in terms of percentage content of *supply-lots* (raw materials), thus leading to a formal definition of homogeneity: two portions of product can be considered as homogenous (and hence part of a single lot) if their composition-distance is less than a given quantisation level. This approach is in accordance with the current regulation for the management and traceability of genetically modified (GM) products (European Commission 2003a, b), which states that a product can be labelled as GM-free if its percentage of GM content is less than 0.9%. The management of homogenous lots of products (referred to as *cohorts*) and of their flow inside the production line is then governed by means of compartmental models. This methodology allows tracking of the composition, in terms of lots of raw material, of any portion of product processed in the plant, and has been previously successfully used (Comba et al.,

2011) to determine precise thermal conditions of fluid products processed in mixed continuous-discontinuous flow conditions.

An interesting approach has also been proposed by Bollen et al. (2007) and by Riden and Bollen (2007), who considered the case of apples processed in a packhouse. Apples, supplied to the packhouse in bulk bins, are moved in a bulk flow (water dump) up to the grader that handles individual fruits and directs them into packaging lines. At the end of these lines the fruits are placed into homogeneous (in terms of colour or size) packs. During their flow in the water dump and then in the packaging lines, a level of mixing among lots of apples occurs. Note that, even if apples are discrete items, their fluidised flow can be considered as a flow of small particles. In their first paper, Bollen et al. (2007) developed and validated a set of statistical models using the measured arrival sequence of 100 blue marker balls. The proposed models are able to assign a probability of bin origin to any individual fruit in the final packs.

3.2.3. Quality and identity-preservation concerns

The recent development of active RFID tags provides interesting new opportunities to the FSC manager. These tags embed specific sensors (e.g. temperature, humidity etc.), and are able to transmit the measured data, together with the item identification code. In this way, the traceability system can automatically capture joint information concerning product identity, properties and related data (e.g. temperature history), thus providing the managing system with a complete description of the current state of the FSC. This opens the way to new dynamic optimal planning methodologies that can overcome the hypothesis of fixed life of a perishable product by utilising real-time information. In this context, lot sizing and routing of fresh food supplies can also be steered by estimating the remaining shelf-life from data obtained by the traceability system. An example can be found in Li et al. (2006), where a dynamic planning method, which uses a linear-in-temperature approximation of the deterioration of food supplies, is proposed for the minimisation of the loss value of the product. Temperatures are captured by the RFID, allowing the TS to identify the product and to upload its time-history at the same time. Similarly, Abad et al. (2009) demonstrated and validated an automated TS that integrates online traceability data and chill-chain conditions monitoring, applied to an intercontinental fresh fish logistics chain.

Traceability by itself cannot enhance quality but, especially if paired to quality systems, it could be used to associate to each lot of product information concerning sensory, health, nutrition, composition or process attributes that allow a specific and individual economic value to be assigned. Quality systems include testing, verification and chemical, physical, microbiological, biomolecular, as well as organoleptic analysis. Hence, lot assigning, definition and management should be driven also by quality attributes, thus allowing differentiation of price based on quality standards (Jang and Olson, 2010).

An important aspect that should be taken into consideration is the specific nature of the product that is being considered in the supply chain. Indeed, in the case of fresh-food products, for instance fresh and fresh-cut produce, fruit, or meat, the design of the supply chain cannot be implemented without considering the perishable nature and the variability of the products travelling the chain, as noted by Dabbene et al. (2008a, 2008b). It follows that lot sizing policies and lot creation should take into account both the residual shelf life of the products and their quality, which is continuously varying. To this end, it would be necessary for the optimisation scenarios to take into explicit account the dynamic transformations which the product (and hence its quality) incurs, in line with the ideas proposed by Dabbene et al. (2008a), where continuous-time dynamics accounting for product quality evolution were directly embedded in a logistics optimisation framework, and by Rong et al. (2011). The interested reader can refer to the complete review paper by Akkerman et al. (2010). Some initial steps in this direction have been taken in the work of Wang et al. (2009), where some elements of shelf life management were integrated in the proposed traceability-oriented operation planning, while Piramuthu et al. (2013) introduced a time-exponential quality degradation function in the optimisation. Accurate and updated knowledge of the composition and state (in terms of quality and shelf life) of the lots also opens the road to optimal pricing policy design (see, e.g., Wang and Li, 2012 and Shah et al., 2005).
Moreover, due to an increasing need for product differentiation, *identity preservation* (IP) is becoming a very important aspect that adds economic value to the product. The concept of identity preservation refers to the ability to maintain particular traits and/or attributes

(Bennet, 2009). In particular, credence attributes or process attributes are those which are difficult to perceive or are not detectable at all by the consumer, but add value for the buyer. Among these, one can list food safety, country of origin, GMO, organic, kosher, halal, "free-range" livestock, contamination by allergens or microorganisms, animal welfare, dolphin free, fair wage and trade, low carbon footprint, etc.

These attributes are not necessarily dependent on quality characteristics, but they increase the value of the product as perceived by the consumer (Niederhauser, 2008). As in many cases the consumer cannot directly verify the preserved attributes, these need to be guaranteed by certification along the whole supply chain. There are also cases, such as pharmaceutical-grade products, where a very high degree of purity is crucial (Elbeheri, 2007).

The evaluation of IP costs and benefits at supply chain level has been specifically addressed by constructing models that explicitly consider contracted premiums (Desquilibet and Bullock, 2009; Hueth and Melkonyan, 2004).

Once the attributes of interest have been properly selected, according to the specific situations and needs, IP can be assured by designing proper structures, plants and facilities and by implementing traceability and certification systems. Traceability systems, besides keeping trace of any operation, play a fundamental role in the management of lot assignment and routing. In particular, IP objectives add new constraints to the optimisation problems discussed in Section 3.

Especially in the US, identity preservation is widely applied to distinguish varieties of GM corn and soybeans (BT maize or Roundup-ready soybean) from non-genetically modified ones (Sobolevski et al., 2005). The coexistence in a grain elevator or in a plant of GM and non-GM requires specific attention to avoid undesired or accidental mixing above the legal level. The main technological solutions to deal with the IP problem are spatial and temporal separation strategies, where the first is based on segregation in different driers and silos, and the latter on an accurate scheduling of the times of grain collection and of the use of the facilities (Coléno, 2008). Examples of different strategies and related costs have been discussed in several works regarding engineering and logistics of harvest planning and delivery (see e.g. Maier, 2006).

IP is also adopted to separate lots of products with particular traits or with particular known compositions that have to be used to mix with others to enhance the properties of the resulting mixed blend. This is the case, for instance, for balancing protein content in flour or acidity and ethanol content in wine. In some particular cases, for diet food, baby food or industrial needs, some components must be higher or lower than in the traditional product. In the case of corn, high contents of lysine, oil, amylose, and extractable starch are sometimes desired, while for soybeans, high (sucrose or isoflavone) and low (low saturate, low-linolenic) varieties have a different economic value (Elbeheri, 2007; Wilson and Dahl, 2008).

3.2.4. Fraud prevention and anti-counterfeit concerns

In the food sector, frauds and fakes are increasing and, especially for high-end products (e.g. wine, cheese, caviar, extra-virgin oil, ham), they result in reputation and economic losses in unfair competition. Traceability tools can be exploited by the FSC manager to prevent, deter, and eliminate illegal, unreported and unregulated (IUU) productions. The capability of a TS to prevent frauds in a FSC derives from its main features: i) ability to trace the history, process and location of an entity by means of recorded identification, ii) unique identification of TRU. It is the duty of the FSC manager to guarantee that these issues are respected without infiltrations, mixing or exchanges of unauthorised products and to ensure that the adopted coding is indeed unique and inviolable.

More specifically, fraud prevention and anti-counterfeiting can be performed by overt (visible) and covert (difficult or impossible to see with naked eyes) technologies for product authentication, which, in any case, are paired to methods for tracking and tracing movements through the supply chain (Li, 2012; Wang & Alocilja, 2012; Tin and Tsang, 2012; Sun et al., 2013). Machine-readable devices (barcodes, QR codes, data matrix) allow the number of checks to be enhanced and electronic data that can be shared on secured networks to be captured. RFID systems seem to be the most promising because of their unique features for automatic, non-line-of-sight identification and tracking of objects. RFID authentication can be performed by “centralised database checking”, by “offline object authentication” or, more recently by “track and trace” methods. Centralised database checking relies on online product authentication in real-time by a plausibility check of the unique code performed over Internet. These systems are very efficient, but the cost of maintaining a back-end database is very high, and it is also difficult to establish appropriate privacy levels.

Offline systems include encrypted tags where authentication is performed, for instance, by cryptographic algorithms embedded in handheld devices. In some cases, besides authentication, information about the product is stored in high capacity memory tags (e.g. a card) that can be physically shipped with the goods and immediately accessed on-site; these systems are currently applied to meat by certified quality supply chains of associations of producers who perform weight-by-mass-balance control through “intelligent” selling scales, which release sales receipts with voluntary traceability information only until the carcass weight is reached.

TSs could be used to implement data in a “product pedigree” which could be completed only by maintaining the supply chain integrity of genuine products (Cheung and Choi, 2011). Anti-counterfeiting systems based on traceability could be shared among different partners by increasing and broadening the monitoring activities of suspicious transactions. If the consumer is involved and can connect to the authentication server by means of handheld devices such as mobile phones, the level of trust of the company should be enhanced. Chinese authorities, after having applied a prototype of these systems for high-end wines in Futian Bonded Zone (Shenzhen), have recommended the extension to other food products (Yin et al., 2012). A very recent case study of IUU fishing prevention based on a TS in a Nordic fish supply chain is proposed in Borit & Olsen (2012).

In any case, most of the anti-counterfeit systems are based on information collected along the FSC. As the cost for traceability is already included for other purposes, the track and trace anti-counterfeit systems can lower the price of methods for protecting from fakes without losing competitiveness.

4. Trends and perspectives

Regarding the aspects related to supply chain optimisation techniques oriented at improving traceability and at minimising product recall costs, the theory is already rather well developed. However, in the authors' opinion, there are still some important unexplored aspects that should be taken into consideration in future developments.

So far, these considerations highlight the need for developing models that allow evaluation and comparison of methodologies in a unified framework, both from an operational as well as from an economic point of view, considering the costs and benefits arising from the introduction of an optimised TS. Indeed, as evidenced also by Wang et al. (2009), the economic trade-off existing between the investment necessary for TS implementation and use, and the savings in the case of product recall should be directly considered in the optimisation when designing a strategic operational plan. Hence, optimisation models should explicitly take into account these different cost components to obtain a solution that is optimal in a global sense.

Moreover, to be really effective, a TS should be conceived and implemented at the entire supply chain level, going beyond the basic principle of "*one step back-one step forward* traceability" adopted to comply the EC Regulation 178/2002 (European Commission, 2002), where every actor in the chain handles only the data coming from his supplier and those sent to his client. One of the problems encountered by many companies in sharing information at supply chain level is the lack of widely accepted standards. Improving traceability in the whole supply chain and engaging all the stakeholders involved would allow the greatest benefit to be realised. Besides the opportunity to increase the depth of the TS (see, for instance, the cocoa case study in Saltini and Akkerman, 2012), the implementation of an inter-organisational communication and sharing information system between all organisations across the food supply chain can lead to fast and efficient data exchange (Anica-Popa, 2012). This allows for i) the reduction of the necessary time to identify, for a foodstuff, all the movements and the food processors involved along the chain, ii) the detection and elimination of possible traceability critical points (Karlsen and Olsen, 2011), iii) the adoption of more sophisticated management rules that take into account the whole history of a product. These benefits can be achieved by extending optimal lot sizing and mixing policies from production to distribution, reducing the overall lot dispersion. To this end, the adoption, as proposed by Rong and Grunow (2010), of chain dispersion to optimise both the production, in terms of batch sizing, and distribution (i.e. batch sharing among retailers) strategies is envisaged, as the reduction of the overall dispersion limits the complexity in case of a possible recall.

Notice that integrated production and distribution planning is a very recent and promising approach which characterises not only traceability but, more generally, modern management policies (see e.g. Amorim et al., 2012 or, in the setting of lean production, Kaynuma and Tawara, 2006 and Zarei et al., 2011).

There are many practical situations where the company manager can perform a risk analysis and estimate a corresponding *risk exposure* (RE). Risk can originate from raw material supplies or from processing phases. In the first case, RE can be estimated by evaluating the trustworthiness of the supplier and/or the potential level of criticality of the material and of the upstream supply chain. Whenever the manager has access to reliable statistics, RE can be expressed in terms of probability that a specific risk event will take place. An example is given by the *process risk model* developed by Cassin et al. (1998) for the quantitative risk assessment for *Escherichia coli* O175:H7 in beef hamburgers.

The knowledge of RE could be explicitly taken into account in the formulation of the ensuing optimisation problem. In particular, by associating with each lot of raw material entering the system a specific probability of being subject to a failure and subsequent withdrawal (and/or to each unit processing operation a specific risk of failure), one would be in the position of being able to introduce significant probabilistic measures for the recall costs. For instance, besides the measure of the worst-case recall costs, the concept of *expected* recall costs could be considered.

This aspect has been partially considered in some recent works. For example Wang *et al.* (2009) proposed a *risk rating* parameter accounting for the possibility of a recall, which is estimated on HACCP-inspired criteria, but does not tackle the problem from a probabilistic viewpoint. Analogously, Tamayo et al. (2009) proposed the measurement of the criticality of production as an estimate of its state of current risk. This index is computed by means of a neural network, on the basis of three parameters: i) the dispersion rate (the ratio between real dispersion and optimal dispersion of the lot), ii) some measure of the quality and reliability of the supplier, and iii) the remaining shelf life. Resende-Filho and Buhr (2010) used the probabilistic model proposed by Cassin et al. (1998) for *E. coli* O157:H7 contamination of ground meat to estimate the probability of recall in a hamburger supply chain, and finally to evaluate the effect of the TS and possible intervention on the quality control system to reduce the costs of a contingent recall.

Another important aspect worth investigating relates to the expected nature of the information provided by the TS. Indeed, as discussed by Riden and Bollen (2007), information from TS has always been expected to be exact, but the reality is that most processes are driven/affected by underlying stochastic phenomena (as, for instance, the apple lot mixing in the water dump considered by Bollen et al., 2007). In many industrial cases, the achievement of this absolute certainty is obtained by over-bounding the size of the lots, with the consequence of obtaining conservative TSs with ensuing poor performance in terms of *WCRC*. The achievement of better performance (via increased precision or finer-graded traceability) can only be attained by relaxing the absolute certainty constraint, thus admitting tolerances, possibly also very low, typically expressed in probabilistic terms. In this way, the composition of an output lot will be described very finely, up to a small tolerance. This goes in the same direction as the already mentioned EC Regulation 1829/2003 (European Community, 2003), which provides a tolerance-based definition of GM and non-GM products.

We should also point out that the methods presented in the literature to date mostly consider traceability optimisation in a static framework: the network is optimised by considering a "snapshot" of the supply chain, without taking into consideration the fact that the production line is indeed a dynamic system continuously evolving in time. In the approaches presented in Dupuy et al. (2005) and successive works, it is implicitly assumed that the processing and mixing of the material is done in a time-frozen environment, where all the processing operations are completely known *a priori*.

Usually, production is considered during a given fixed window of time (for instance, a day or a week), and product routing is decided by means of a “batch” analysis. This could indeed be the case (at least approximately) for some specific productions, as for instance the situation considered in Dupuy et al. (2005), where the authors consider the mixing and processing of batches of meat for the production of sausages with different compositions or the case of cheese production (Barge et al., 2013). In this case, the manager has a clear vision of the daily planned production, and he can decide *a priori* (say, at the beginning of the day) the routing of the various products in the chain.

On the contrary, in the general case in which the production line is continuously evolving, with new raw material entering the systems at specific times, thus creating the necessity of distinguishing the batches containing this new material from those produced until that moment. More generally, the number of traceable products in the supply chain at any point, at any time, depends on the rate of production, the shelf life and the rate of consumption. This consideration motivates the necessity of developing an optimisation and planning framework able to explicitly take into account the "time" variable. The goal is to closely track the evolution and changes into the production line, dynamically updating and adapting the planning strategies to the changes.

Solutions that can be envisaged should, for instance, involve moving-window strategies, where the routing optimisation is performed only over those quantities of product that the manager can plan on a daily or weekly basis.

Moreover, the fact that the supply chain is indeed a dynamic system impacts on other aspects of traceability management. For instance, even if modern industries comply with art.18 in EU Regulation N.178/2002, in many cases they are not fully prepared to quickly start the recall after the primary signals of potential injuries and then trace back their product along the supply chain. To this extent, Mgonja *et al.* (2013) introduced the concept of *rapidity* to evaluate the speed of TS in responding to information requests regarding the traded items. Note that the reduction of recall time is essential for several reasons: a delay in the recall can be perceived by the consumer as negligence on the part of the company and, what is worst, it can increase the number of possible injuries and even deaths (Magno, 2012). Anyway, the recall process requires some time to effectively take place, and this introduces delays into the planning strategy, thus generating an implicit relationship between the rapidity in removing the products involved and the measure of their dispersion, now considered as a function of time also. Clearly, the earlier the contaminated product is removed from the production line, the smaller its dispersion will be. This intrinsic time-dependency cannot be captured by a static framework.

5. Concluding remarks

Increasingly stringent requirements for food safety, as well as a growing demand for food characterised by a certain identity (GM, non-GM, ethical, organic, low carbon footprint, subject to religious constraints etc.), call for the development of increasingly large and efficient traceability systems. The efficiency and the performance of TS can be improved by orienting management policies to account also for these needs. If on the one hand, traceability by itself cannot change the quality and safety of the food products, on the other hand it can be an important element in the more general control scheme of production and distribution. A traceability system, coupled with other tools (HACCP, production planning, logistics), may indeed lead to significant improvements on the performance of the whole supply chain. In addition to the interesting results already obtained so far, the immediate future in research and industrial applications is very promising. The growing diffusion of new technologies for automatic identification & sensing (e.g. active and passive RFID embedding sensors and localisation devices), together with the availability of new computational and simulation models and of new mechanical systems for the segregation of lots, pave the way for new solutions able to guarantee a higher level of control of the supply chain.

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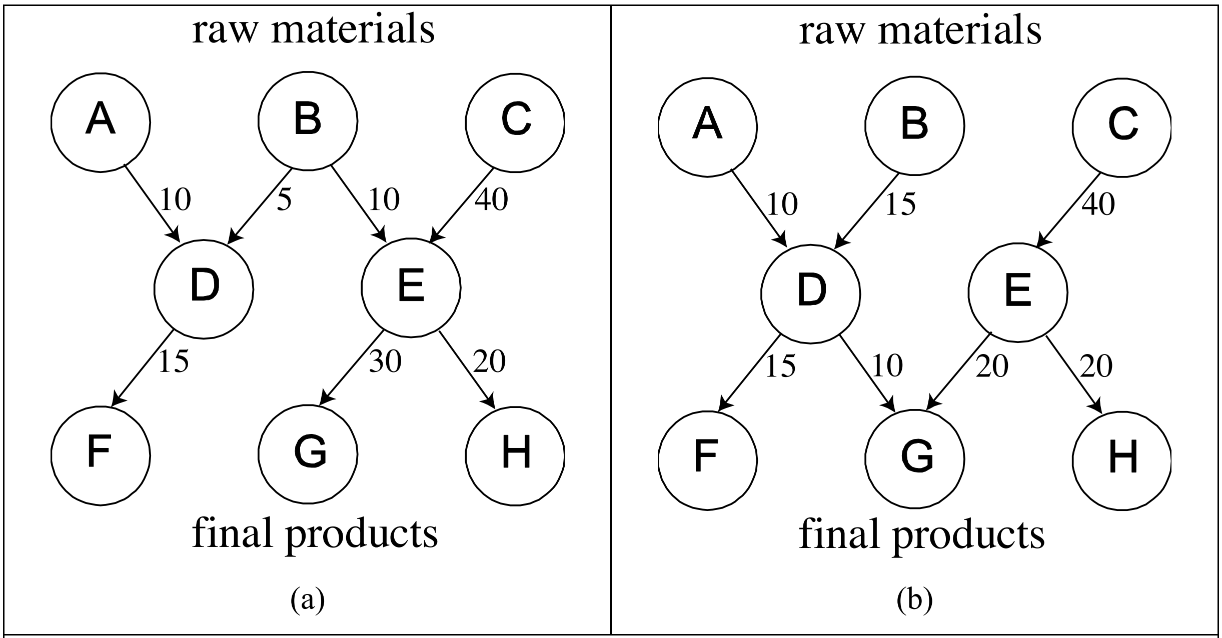
Figure 1



(a) (b)

Figure 1: example of computation of different traceability performance indices. In both cases, the batch dispersion cost *BDC* is equal to six. The worst-case recall cost *WCRC* of (a) is 65, and it is relative to raw material B (if B is found defective, all the final products have to be recalled). The *WCRC* of (b) is 50, and is relative to raw material C (if C is found defective, only final products in batches G and H have to be recalled). The average recall cost *ARC* is 43.3 for (a) and 46.6 for (b), respectively.

Table 1 – Overview of modelling and optimisation approaches to traceability systems design. Method: (A) analysis; (M) modelling; (O) optimisation; (S) simulation; (V) validation of a TS; (MILP) Mixed Integer Linear Programming; (NL) Non-linear

	Method		**Product**	**Characteristic**
Bollen et al. (2007a)	MV	Probabilistic model	Fruit (apples)	Develops statistical models to describe fruit mixing through an apple packhouse; uses marker balls to quantify the level of mixing; proposes interventions to improve the performance of the TS, reducing the level of mixing
Bollen et al. (2007b)	S	Probabilistic model	Fruit (apples)	Studies, via simulation, the effect of input and output lot sizes on dispersion-like measures, precision and purity of the TS. Introduces the concept of different precision and tolerance (non-absolute traceability) for TS.
Dabbene & Gay (2011)	MO	MILP	General method, example on meat (sausages, the same case study proposed by Dupuy et al. 2005)	Defines the measure of the performance of a TS as the *worst-case* (or average) *quantity of product to be recalled* in the case of crisis; optimises the design of the TS on the base of this cost function
Donnelly et al. (2009)	M	Graphs	Meat (lamb)	Models materials and information flows in a lamb meat industry with particular attention to traceability critical points (loss of product and

Dupuy et al. (2005)	MO	MILP	General method, example on meat (sausage)	Introduces the measures of *batch dispersion, downward dispersion, upward dispersion*. Optimises mixing policies to minimise batch dispersion
Karlsen et al. (2011)	A	-	Fish (salmon)	Identifies critical traceability points in fish feed and farmed salmon supply chain; discusses the effect of different granularity levels on the performances of the TS
Karlsen & Olsen (2011) **Karlsen et al. (2012)**	A	Qualitative methods	Fish (salmon and seafood)	Discusses the validity of qualitative methods for the determination of critical traceability points; introduces the *critical traceability point analysis*; evaluates the effect of different granularity levels on the TS
Li et al. (2006)	MO	NL, spreadsheet solver	Perishable food	Proposes a supply chain dynamic planning method which uses a RFID-based TS able to provide real-time product quality information
Mngonja et al. (2013)	V	Qualitative methods	Fish	Diagnostic tool to validate performance of the TS
Piramuthu et al. (2013)	MO	MILP	Perishable food	Minimises a joint liability cost, introducing a time-exponential quality degradation function in the optimisation
Randrup et al. (2008)	V	-	Fish	Validation and performance evaluation of TS via simulated product recall in Nordic countries

Resende-Filho & Buhr (2010)	MS	Spreadsheet solver	Meat (ground meat and hamburgers)	Proposes conceptual models for assessing the probability of recall and the dissemination of product in the supply chain (size of recall) to individuate break-even expected investment in traceability
Rong & Grunow (2010)	O	MILP + heuristics	General method (for food)	Joint optimisation of lot sizing and distribution routing; introduces a measure for the chain dispersion in the distribution phases; accounts for product degradation; adopts specific heuristics to solve the problem
Saltini & Akkerman (2012)	S	Basic, spreadsheet solver	Chocolate	Different scenarios are simulated to evaluate the impact of the depth and the strategy of a TS on production efficiency and product recall
Tamayo et al. (2009)	O	Genetic algorithms (GA) and Neural Networks (NN)	Meat (sausages, the same case study proposed by Dupuy et al. 2005)	Proposes GA methods for *batch dispersion*-type problems (Dupuy et al. 2005); uses NN to estimate a *criticality index* of the production
Thakur & Hurburgh, (2009)	AM	DBMS	Bulk grain	Model the information exchange between actors in grain supply chain using relational databases formalism
Thakur et al. (2010)	MO	MILP	Bulk grain	Multi-objective optimisation taking into account blending rules. The cost considers logistics aspects (number of storage bins) and total cost of blending grain

Thakur & Donnelly (2010)	AM	-	Soybean	Identifies a standardised list of information to be recorded for the traceability of a soybean value chain
Wang et al. (2009)	OS	MILP	Perishable food (UK cooked meat)	Integrated operation-traceability planning model for perishable food management; uses a risk rating factor to take into account the different levels of recall possibility