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# 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.

28 **Nomenclature**

29

$\alpha$	Coefficient accounting for notification, logistics etc.
<i>ARC</i>	Average recall cost
<i>BDC</i>	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
<i>WCRC</i>	Worst-case recall cost

30

31 **1. Introduction**

32

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

60

61 Tracking and tracing involve managerial decisions on the value chain in order to reach  
62 efficiency improvements in processing organisation and risk management, and a good level  
63 of buyer-supplier coordination (Rabade and Alfaro, 2006). Nevertheless, FSC stakeholders

64 typically attribute different values to traceability: for the consumer it represents an added  
65 value related mainly to safety and quality information, while for food producers it is a tool to  
66 avoid market breakdowns which might strongly affect the brand, as well as to guarantee  
67 policy requirements. This discrepancy leads to different possible ways of evaluating costs-  
68 benefit ratios and of adopting ex-post or ex-ante traceability systems (Hobbs, 2004).

69

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

78

79 Automation in data collection enhances the precision and the reliability of identification of  
80 the traced unit. Technologies and devices are continuously improved. Among these, optical  
81 systems (bar code, data matrix, QR code) as well as radio frequency identification devices  
82 (RFID) have been successfully deployed and their applications to different food products  
83 (Costa et al., 2013), living beings (Barge et al., 2013) and even flows of bulk products (e.g.  
84 Kvarnström et al., 2011 and Liang et al. 2013) are constantly increasing. From a  
85 technological viewpoint, it can be stated that the devices for identifying and tracing the  
86 products have nowadays reached a good level of industrialisation, providing new and  
87 efficient opportunities for FSC management. Even if their description goes beyond the scope  
88 of this paper, the interested reader is referred for instance to Ruitz-Garcia and Lunadei  
89 (2011) and Sarac et al. (2010), and references therein, for a survey on the technological  
90 solutions to traceability.

91

92 The objectives of this paper are: i) to carry out a comprehensive literature review of the  
93 aspects of supply chain management that are influenced by (and that influence) traceability,  
94 and that are fully integrated and inseparable in FSC management, ii) to provide ideas on  
95 possible future research directions related to the management of traceability systems. The

96 paper is structured in two main parts: in the first one, consisting of Sections 2 and 3, the  
97 mainstream aspects and solutions currently available are streamlined and discussed based on  
98 the literature, keeping the authors' opinion out of the picture as much as possible. In  
99 particular, in Section 2 the different aspects of European and US legislation, together with  
100 ISO and private standards that are related to food traceability issues are outlined and  
101 discussed. Section 3 discusses in detail the aspects of traceability in FSC management and  
102 optimisation: the problem of food crisis management and consequent product recall, the  
103 problem of tracing bulk products, the issues related to quality and identity preservation, and  
104 the problem of fraud prevention and anti-counterfeiting. The second part of the paper,  
105 Section 4, reports the authors' viewpoint on the possible trends and perspectives in  
106 traceability-oriented food supply chain management. Finally, concluding remarks are  
107 reported in Section 5.

108  
109

## 110 **2. Traceability related legislations and standards**

111

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

117

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

124

125 International importing of food due to the global market has increased efforts to apply  
126 traceability strategies at the international level, and this issue was debated within the UN's  
127 joint Food and Agriculture Organization (FAO) and World Health Organization (WHO),

128 leading to the Codex Alimentarius, where traceability in the food sector is primarily defined  
129 as “*the ability to follow the movement of a food through specified stage(s) of production,*  
130 *processing and distribution*” (Codex Alimentarius Commission, 2006). Here it was  
131 recognised that, at the international level, methods are not harmonised and are often  
132 complicated, thus also leading to barriers to trade (Codex Alimentarius Commission, 2007).

133

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

137

## 138 2.1. European and US legislations

139

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

158

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

166

167 In the US, compulsory traceability was only recently introduced for the food sector  
168 (Donnelly and Thakur, 2010; Smith et al., 2005), and food safety was previously assured  
169 mainly by private companies in order to guarantee a good quality to the consumer (Kramer  
170 et al., 2005). Traceability first became mandatory only to react against bioterrorism (United  
171 States, 2002). The Food Safety Modernization Act (United States, 2011), signed on January  
172 2011 by the US President, introduces a system of preventive controls, inspections and  
173 compliance authorities, as a response to violations (recalls) on domestic as well as on foreign  
174 US food.

175

## 176 2.2. International standards

177

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

186

187 Several International Standards and European norms that are related to traceability in the  
188 food chain have been published (exhaustive discussions can be found in McEntire et al.,  
189 2010 and Schulze et al., 2008). These standards are in the following areas: quality  
190 management systems, food safety management systems, traceability of fish products, data  
191 capture techniques and electronic interchange of data elements and documents in commerce,

192 industry and administration. While standards in *internal traceability*, which refers to records  
193 kept inside the business unit, are not specifically requested, in *external traceability*, defined  
194 as the sharing of information among the different stakeholders of the supply chain (Moe,  
195 1998), standards and methods for data interchange are crucial.

196  
197 The International Organization for Standardization (ISO) has delivered, in the context of the  
198 ISO 9000 series for Quality Management Systems, a number of standards concerning  
199 traceability. ISO 22000:2005 specifies the requirements for food safety management  
200 systems. In particular, it addresses the establishment and application of TS “*that enables the*  
201 *identification of product lots and their relation to batches of raw materials, processing and*  
202 *delivering records*” (Int. Organization of Standardization, 2005). ISO 22005:2007  
203 introduces principles and basic requirements for the design and the implementation of a food  
204 (and feed) TS. Even if it does not specify how this should be achieved, it introduces the  
205 requirement that organisations involved in a FSC have to define information that should be,  
206 at each stage, obtained and collected from the supplier and then provided to customers, in  
207 addition to product and processing history data (Int. Organization of Standardization, 2007).  
208 In ISO 9001:2008 the concept of product identification is introduced, requiring that “*where*  
209 *appropriate, the organization shall identify the product by suitable means throughout*  
210 *product realization and where traceability is the requirement, the organization shall control*  
211 *the unique identification of the product and maintain records*” and that “*preservation shall*  
212 *also apply to the constituent parts of a product*” (Int. Organization of Standardization,  
213 2009). To this extent, a number of ISO Standards (e.g. ISO/IEC 15961, 15962, 24791,  
214 15459,15418, and 15434) have been delivered to regulate data encoding on radio frequency  
215 identification devices and their interoperability with barcode-based systems (see Chartier &  
216 Van Den Akker, 2008 for a complete report delivered by the Global RFID Interoperability  
217 Forum for Standards).

218  
219 Parallel to these, commercial standards have been delivered by organisations and  
220 associations to set traceability requirements, facilitate traceability data sharing and adopt  
221 product identification standards for commercial purposes. This is the case, for instance, for  
222 GS1 standards (GS1 US, 2010), GlobalGAP (GlobalGAP, 2013) and British Retail  
223 Consortium (BRC) Best Practice Guidelines for Traceability (British Retail Consortium,  
224 2013), where requirements for traceability, principles of effective TS design and guidelines

225 to undertake traceability tests are addressed. Satisfaction of these commercial standards,  
226 which usually corresponds to obtaining a specific certification, represents a necessary  
227 condition for a company to access a given market.

228

### 229 3. Traceability in food supply chain management

230

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

237

#### 238 3.1. Definitions

239

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

248

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

256

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

264

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

268

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

277

278 Bollen et al. (2007) further elaborated on this concept by introducing the notion of  
279 *identifiable unit* (IU), which represents the unit of product that must be uniquely identifiable  
280 within each system in which it is used. The size of the IUs is responsible for the *granularity*  
281 of the traceability system. Many definitions of granularity have been proposed in literature.  
282 Karlsen et al. (2012) defined granularity as a quantity “*determined by the size of a traceable*  
283 *unit and the number of the smallest traceable units necessary to make up the traceable unit*  
284 *at a specific granularity level.*” Granularity level is determined by the size and number of  
285 batches, and a finer granularity allows for adding even more detailed information about the  
286 product, and for acting at a more detailed and range-limited level in the case of a possible  
287 recall. The optimal granularity level is very difficult to determine, since it depends on  
288 product type and customer. Unfortunately, in most parts of current supply chains, the

289 granularity at which the products involved are traced does not come from the results of a  
290 formal analysis and optimisation study, but it is principally the consequence of a  
291 combination of tradition, short-term convenience and use of available facilities.

292

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

304

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

314

315 Finally, an important aspect of the TS is the definition of monitoring schemes to evaluate the  
316 effectiveness of the system. Whenever possible TS response should be validated by other  
317 methods (typically physicochemical, genetic, or microbiological) able to identify and  
318 discriminate products (see Peres et al., 2007 and the very recent papers by Galimberti et al.,  
319 2013 and Aceto et al., 2013). The correct functioning of ICT procedures should be  
320 periodically checked, as discussed by Randrup et al. (2008) in a Nordic fish supply chain

321 case study, simulating a food safety hazard, and by Mgonja et al. (2013). The importance of  
322 validation methods is also reported as a main requisite in ISO 22005:2007 (Section 5.1  
323 General design considerations) where it is stated that “*the traceability system should be*  
324 *verifiable*”.

325

### 326 3.2. Traceability-driven issues in food supply chain management

327

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

333

#### 334 3.2.1 Food crisis management

335

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

340

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

351

352 The management of a recall procedure has to be performed by the top management of the  
353 company, and involves many activities, ranging from risk assessment and the identification  
354 of the interested products to the notification of the measure to the actors of the supply chain  
355 (suppliers, distributors, buyers etc.) and, finally, the recall action. In this context, Wynn et al.  
356 (2011) identified common data requirements for traceability and data exchange, and  
357 analysed opportunities for the automation of the notification process in case of a recall.

358

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

364

365 Since this could be absolutely critical for a company, some studies for modelling and  
366 forecasting the effects of recall actions have been carried out (e.g. see Kumar and Budin,  
367 2006, Randrup et al., 2008 and Fritz and Schiefer, 2009). Most companies do not have  
368 reliable methods to manage a recall strategy, nor to estimate the real amount of product that  
369 has to be discarded in case of a recall.

370

371 The recall of a product typically follows two steps that need to be performed in a very short  
372 time: the backward identification of potentially deficient lots and then the forward  
373 identification of potentially affected products that have to be withdrawn (Fritz and Schiefer,  
374 2009). The performance of a traceability system can therefore be directly associated with its  
375 ability to hold down the amount and cost of the product to be recalled. Hence, a *recall cost*  
376 (*RC*) can be directly associated with the material that has to be recalled, which depends on  
377 different factors such as i) the size of the batches that have been individually tracked and  
378 managed by the traceability system, ii) the way the batches of the different materials have  
379 been processed and mixed to obtain the final product, and iii) the level of segregation  
380 adopted by the company to manage and maintain different batches of product separate.  
381 Direct costs associated with a recall action include the costs for the notification of the recall,  
382 the logistics to retrieve the product and lost sales. Resende-Filho and Buhr (2010) consider

383 all these cost components as directly proportional to the amount of product to be recalled,  
384 that is

$$RC = \alpha P_r Q_R$$

385 where  $P_r$  denotes the retail value of the product,  $Q_R$  the quantity of product to be recalled and  
386  $\alpha > 1$  is a coefficient accounting for notification, logistics etc. Similarly, Fritz and Schiefer  
387 (2009) express the overall cost of a traceability system as the sum

$$C(\text{overall}) = RC + C(tt) + C(e) + C(q)$$

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

391

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

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

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

404

405 However, it should be remarked that the typical interest of a company is to know the largest  
406 possible amount of product that it could be necessary to recall. For this reason, Dabbene and  
407 Gay (2011) introduced the *worst-case recall cost (WCRC)* index, defined as the largest  
408 amount of product that has to be recalled when a batch of raw material is found unsafe.  
409 Analogously, they defined the *average recall cost (ARC)* index, which represents the average  
410 mass of product to be recalled when one of the entering material is found inappropriate. The

411 formalism introduced by Dupuy et al. (2005) and also adopted in Dabbene and Gay (2011)  
412 stems from the consideration that, from a traceability viewpoint, the production process can  
413 be modelled as an interconnected graph, where the different lots of raw materials are  
414 represented as nodes, and the arrows represent the mixing operations that lead to the final  
415 products. A very simple example of this model is reported in Figures 1a and 1b, which  
416 depict two similar situations in which three different raw materials A, B, and C enter into a  
417 mixing/splitting process obtaining two intermediates (D and E) and three final products F, G,  
418 and H. The numbers on the arrows represent the quantity (mass) of material involved in the  
419 mixing. This example illustrates the meaning of the *BDC*, *WCRC* and *ARC* indices. Notice  
420 that, in two cases that differ only in the position of one link, the three costs can significantly  
421 differ. In particular, while the batch dispersion (which corresponds to the total number of  
422 links from raw materials and final product) does not vary in the two cases, the *worst-case*  
423 *recall cost* is rather different.

424

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

442

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

459

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

472

473 More generally, the literature on modelling and optimisation approaches to traceability  
474 systems design is very wide. For the sake of completeness, Table 1 presents a summarising

475 view of the different approaches and solutions to TS design. The table concentrates on the  
476 works where the managing and optimisation aspects, which represent the main focus of our  
477 review, are central.

478

### 479 3.2.2 Traceability of bulk products

480

481 Many industries use ingredients that are liquids (milk, vegetable oils, etc.), powders (cocoa,  
482 powdered milk, flour etc.), crystals (e.g. salt, sugar) or grains that are stored, in many cases,  
483 in huge silos which are very rarely completely emptied, so that many lots are  
484 contemporaneously kept in the same container. In the case of liquid food, Cocucci et al.  
485 (2002) stressed that cleaning between two product batches is “*of primary importance*” to  
486 allow distinct separated batch identities. In particular, *cleaning-in-place* procedures involve  
487 pumping water and detergent through the production equipment and, besides guaranteeing  
488 high hygienic standards and cleaning, are foreseen as the only way of strictly guaranteeing  
489 that the different batches cannot contaminate each other. However, these cleaning  
490 procedures usually represent a high cost for the firm, and become particularly undesirable for  
491 *continuous production systems* (such as, for instance, milk production in a dairy). In these  
492 processes, in which products are refined gradually and with minimal interruptions through a  
493 series of operations (Dennis and Meredith, 2000), a continuous flow of liquid/granular raw  
494 material is necessary to maintain the production and, as pointed out by Skoglund and  
495 Dejmek (2007), any interruption for cleaning would require stopping the production so that  
496 “*there is an incentive to clean as seldom as possible.*”

497

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

507 RFID-based traceability system would require the development of a technology for safely  
508 removing the tracing devices from the final product (e.g. before grain grinding). Recently,  
509 some solutions have been proposed by Liang et al. (2009), Lee et al. (2010), and Liang et al.  
510 (2013) for the specific case of grains, which involve inserting particular pill-sized food-grade  
511 tracer particles into the grains during harvest. These tracers carry identity information related  
512 to product origins, and are composed of materials that can be safely eaten such as sugar or  
513 cellulose. In particular, specialised ink-jet printers have been devised to print bar codes or  
514 data matrix (DM) code symbols on the particles with food-grade ink. Anyway, these  
515 solutions remain principally an off-line approach suitable for modelling and validation  
516 purposes, since collecting and identifying the tracers would usually still require interrupting  
517 production.

518

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

539 2011) to determine precise thermal conditions of fluid products processed in mixed  
540 continuous-discontinuous flow conditions.

541

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

553

### 554 3.2.3. Quality and identity-preservation concerns

555

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

570 validated an automated TS that integrates online traceability data and chill-chain conditions  
571 monitoring, applied to an intercontinental fresh fish logistics chain.

572

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

580

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

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

607

608 These attributes are not necessarily dependent on quality characteristics, but they increase  
609 the value of the product as perceived by the consumer (Niederhauser, 2008). As in many  
610 cases the consumer cannot directly verify the preserved attributes, these need to be  
611 guaranteed by certification along the whole supply chain. There are also cases, such as  
612 pharmaceutical-grade products, where a very high degree of purity is crucial (Elbeheri,  
613 2007).

614

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

618

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

625

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

634 discussed in several works regarding engineering and logistics of harvest planning and  
635 delivery (see e.g. Maier, 2006).

636

637 IP is also adopted to separate lots of products with particular traits or with particular known  
638 compositions that have to be used to mix with others to enhance the properties of the  
639 resulting mixed blend. This is the case, for instance, for balancing protein content in flour or  
640 acidity and ethanol content in wine. In some particular cases, for diet food, baby food or  
641 industrial needs, some components must be higher or lower than in the traditional product. In  
642 the case of corn, high contents of lysine, oil, amylose, and extractable starch are sometimes  
643 desired, while for soybeans, high (sucrose or isoflavone) and low (low saturate, low-  
644 linolenic) varieties have a different economic value (Elbeheri, 2007; Wilson and Dahl,  
645 2008).

646

#### 647 3.2.4. Fraud prevention and anti-counterfeit concerns

648

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

658

659 More specifically, fraud prevention and anti-counterfeiting can be performed by overt  
660 (visible) and covert (difficult or impossible to see with naked eyes) technologies for product  
661 authentication, which, in any case, are paired to methods for tracking and tracing movements  
662 through the supply chain (Li, 2012; Wang & Alocilja, 2012; Tin and Tsang, 2012; Sun et al.,  
663 2013). Machine-readable devices (barcodes, QR codes, data matrix) allow the number of  
664 checks to be enhanced and electronic data that can be shared on secured networks to be  
665 captured. RFID systems seem to be the most promising because of their unique features for

666 automatic, non-line-of-sight identification and tracking of objects. RFID authentication can  
667 be performed by “centralised database checking”, by “offline object authentication” or, more  
668 recently by “track and trace” methods. Centralised database checking relies on online  
669 product authentication in real-time by a plausibility check of the unique code performed over  
670 Internet. These systems are very efficient, but the cost of maintaining a back-end database is  
671 very high, and it is also difficult to establish appropriate privacy levels.

672

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

681

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

692

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

697

698

#### 699 **4. Trends and perspectives**

700

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

705

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

715

716 Moreover, to be really effective, a TS should be conceived and implemented at the entire  
717 supply chain level, going beyond the basic principle of "*one step back-one step forward*  
718 traceability" adopted to comply the EC Regulation 178/2002 (European Commission, 2002),  
719 where every actor in the chain handles only the data coming from his supplier and those sent  
720 to his client. One of the problems encountered by many companies in sharing information at  
721 supply chain level is the lack of widely accepted standards. Improving traceability in the  
722 whole supply chain and engaging all the stakeholders involved would allow the greatest  
723 benefit to be realised. Besides the opportunity to increase the depth of the TS (see, for  
724 instance, the cocoa case study in Saltini and Akkerman, 2012), the implementation of an  
725 inter-organisational communication and sharing information system between all  
726 organisations across the food supply chain can lead to fast and efficient data exchange  
727 (Anica-Popa, 2012). This allows for i) the reduction of the necessary time to identify, for a  
728 foodstuff, all the movements and the food processors involved along the chain, ii) the  
729 detection and elimination of possible traceability critical points (Karlsen and Olsen, 2011),  
730 iii) the adoption of more sophisticated management rules that take into account the whole

731 history of a product. These benefits can be achieved by extending optimal lot sizing and  
732 mixing policies from production to distribution, reducing the overall lot dispersion. To this  
733 end, the adoption, as proposed by Rong and Grunow (2010), of chain dispersion to optimise  
734 both the production, in terms of batch sizing, and distribution (i.e. batch sharing among  
735 retailers) strategies is envisaged, as the reduction of the overall dispersion limits the  
736 complexity in case of a possible recall.

737

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

742

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

751

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

759

760 This aspect has been partially considered in some recent works. For example Wang *et al.*  
761 (2009) proposed a *risk rating* parameter accounting for the possibility of a recall, which is  
762 estimated on HACCP-inspired criteria, but does not tackle the problem from a probabilistic

763 viewpoint. Analogously, Tamayo et al. (2009) proposed the measurement of the criticality of  
764 production as an estimate of its state of current risk. This index is computed by means of a  
765 neural network, on the basis of three parameters: i) the dispersion rate (the ratio between real  
766 dispersion and optimal dispersion of the lot), ii) some measure of the quality and reliability  
767 of the supplier, and iii) the remaining shelf life. Resende-Filho and Buhr (2010) used the  
768 probabilistic model proposed by Cassin et al. (1998) for *E. coli* O157:H7 contamination of  
769 ground meat to estimate the probability of recall in a hamburger supply chain, and finally to  
770 evaluate the effect of the TS and possible intervention on the quality control system to  
771 reduce the costs of a contingent recall.

772

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

787

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

795

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

804

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

814

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

818

819 Moreover, the fact that the supply chain is indeed a dynamic system impacts on other aspects  
820 of traceability management. For instance, even if modern industries comply with art.18 in  
821 EU Regulation N.178/2002, in many cases they are not fully prepared to quickly start the  
822 recall after the primary signals of potential injuries and then trace back their product along  
823 the supply chain. To this extent, Mgonja *et al.* (2013) introduced the concept of *rapidity* to  
824 evaluate the speed of TS in responding to information requests regarding the traded items.  
825 Note that the reduction of recall time is essential for several reasons: a delay in the recall can  
826 be perceived by the consumer as negligence on the part of the company and, what is worst, it

827 can increase the number of possible injuries and even deaths (Magno, 2012). Anyway, the  
828 recall process requires some time to effectively take place, and this introduces delays into the  
829 planning strategy, thus generating an implicit relationship between the rapidity in removing  
830 the products involved and the measure of their dispersion, now considered as a function of  
831 time also. Clearly, the earlier the contaminated product is removed from the production line,  
832 the smaller its dispersion will be. This intrinsic time-dependency cannot be captured by a  
833 static framework.

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## 835 **5. Concluding remarks**

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

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855

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1288 **Figure 1**

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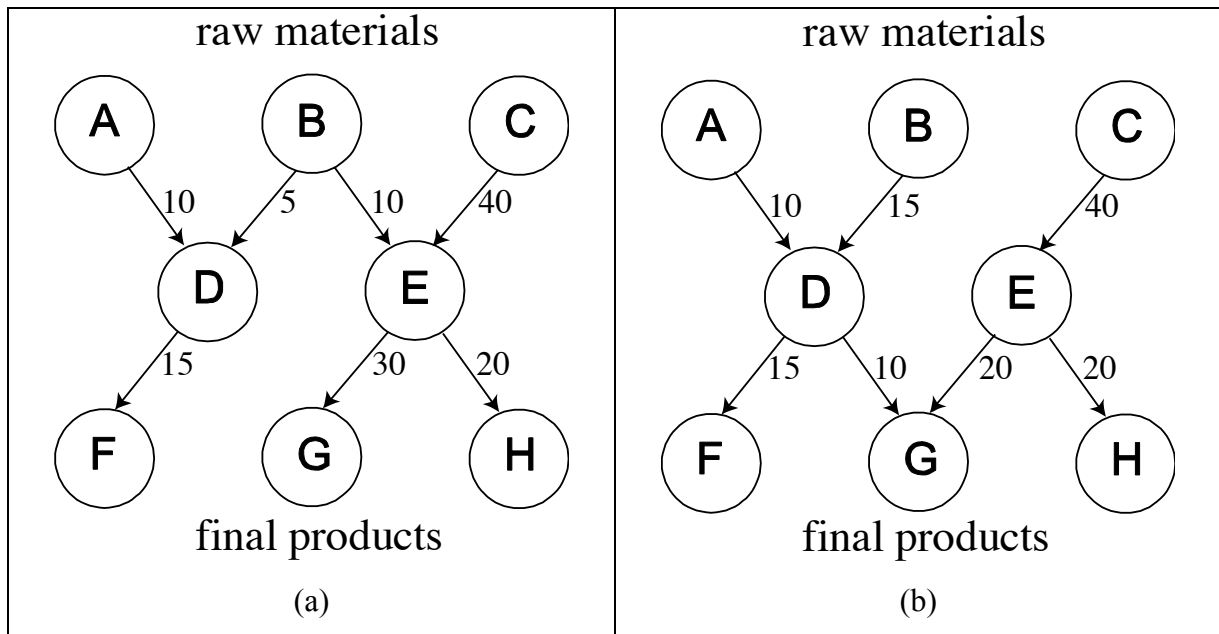


Figure 1: example of computation of different traceability performance indices. In both cases, the batch dispersion cost  $BDC$  is equal to six. The worst-case recall cost  $WCRC$  of (a) is 65, and it is relative to raw material B (if B is found defective, all the final products have to be recalled). 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.

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 1302 **Table 1** – Overview of modelling and optimisation approaches to traceability systems design. Method: (A) analysis; (M) modelling;  
 1303 (O) optimisation; (S) simulation; (V) validation of a TS; (MILP) Mixed Integer Linear Programming; (NL) Non-linear  
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	Method		Product	Characteristic
<b>Bollen et al. (2007a)</b>	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
<b>Bollen et al. (2007b)</b>	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.
<b>Dabbene &amp; Gay (2011)</b>	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 <i>worst-case</i> (or average) <i>quantity of product to be recalled</i> in the case of crisis; optimises the design of the TS on the base of this cost function
<b>Donnelly et al. (2009)</b>	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

<b>Dupuy et al. (2005)</b>	MO	MILP	General method, example on meat (sausage)	Introduces the measures of <i>batch dispersion</i> , <i>downward dispersion</i> , <i>upward dispersion</i> . Optimises mixing policies to minimise batch dispersion
<b>Karlsen et al. (2011)</b>	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
<b>Karlsen &amp; Olsen (2011)</b> <b>Karlsen et al. (2012)</b>	A	Qualitative methods	Fish (salmon and seafood)	Discusses the validity of qualitative methods for the determination of critical traceability points; introduces the <i>critical traceability point analysis</i> ; evaluates the effect of different granularity levels on the TS
<b>Li et al. (2006)</b>	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
<b>Mngonja et al. (2013)</b>	V	Qualitative methods	Fish	Diagnostic tool to validate performance of the TS
<b>Piramuthu et al. (2013)</b>	MO	MILP	Perishable food	Minimises a joint liability cost, introducing a time-exponential quality degradation function in the optimisation
<b>Randrup et al. (2008)</b>	V	-	Fish	Validation and performance evaluation of TS via simulated product recall in Nordic countries

<b>Resende-Filho &amp; Buhr (2010)</b>	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
<b>Rong &amp; Grunow (2010)</b>	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
<b>Saltini &amp; Akkerman (2012)</b>	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
<b>Tamayo et al. (2009)</b>	O	Genetic algorithms (GA) and Neural Networks (NN)	Meat (sausages, the same case study proposed by Dupuy et al. 2005)	Proposes GA methods for <i>batch dispersion</i> -type problems (Dupuy et al. 2005); uses NN to estimate a <i>criticality index</i> of the production
<b>Thakur &amp; Hurburgh, (2009)</b>	AM	DBMS	Bulk grain	Model the information exchange between actors in grain supply chain using relational databases formalism
<b>Thakur et al. (2010)</b>	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

<b>Thakur &amp; Donnelly (2010)</b>	AM	-	Soybean	Identifies a standardised list of information to be recorded for the traceability of a soybean value chain
<b>Wang et al. (2009)</b>	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