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Abstract

The agro-food industry is one of the largest parts of the European Union's economy and faces economic and environmental stresses. While food traceability systems (FTSs) inform supply chain actors of product and logistical attributes, large scale implementations are scarce and do not support active decision making. We present a framework developed for FUTUREMED project used to perform a data-driven analysis that considers both micro and macro aspects of a food supply chain (FSC). With its comprehensive multiple-depth data architecture incorporated within a tailored decision-support platform, this framework and the resulting decision-support tool is the first to move beyond simple traceability implementation to the sustainable planning of food logistics, bridging the gap between research techniques and real-world data availability. We define KPIs that measure a subset of economic and environmental factors to quantify the impact of logistical decisions. We validate the framework with the case study of an Italian fruit trader that is considering opening a new warehouse. We conclude by suggesting that this framework be applied to more complex case studies and be enhanced through including more dimensions of sustainability.

Keywords: *Food operations, Sustainable Planning, Traceability, Food Supply Chain, Data architecture, IoT*

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This project also gains some contributions, in any way, by some Engineering students at University of Bologna that contributed at gathering and manipulating data and hence deserve mention: Giulia Olivi, Simone Sassi, Federico Losappio, Elisabetta Pazzaglia, Giulia D'Addato, Simone D'Andrea, Andrea Degiorgis, Vanessa Catalano, Irene Ciliberto, Elisa Ciaccheri, and Vittoria Calfurini.

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1. Introduction

The agro-food industry is a leading component of the EU economy, and governments are increasingly concerned about the long term sustainability of this sector (Notarnicola et al., 2017^{a,b}). Others have addressed stressors of food system sustainability as follows. The exploitation of natural resources like water and soil (Kummu et al., 2012), resultant GHGs emissions (Sala et al., 2017), competition for land between food and biofuels (Rathmann et al., 2010; Fisher et al., 2010^{a,b}; Cobuloglu and Büyüktaktakın, 2015), use of genetically modified organisms (GMOs), pesticides and chemical fertilizers (Gerdes et al., 2012; Roy et al., 2009; Boye and Arcand, 2013; McLaughlin and Kinzelback, 2015) are just few of the environmental issues affecting the food ecosystems. Food sustainability has a social as well as environmental dimension: volatile prices, bottlenecks, and food waste, losses, or contamination influence negatively impact actors and stakeholders' economic wellbeing (Garrone et al., 2014; Lebersorger and Schneider, 2014; Aiello et al., 2014). Furthermore, food insecurity contributes to social problems such as hunger and obesity (Fan and Brzeska, 2016; Thomas, 2010; Sadler et al., 2016).

Although these issues independently affect the environmental, economic, and social dimensions of sustainability, they are each exacerbated by ignoring the role operations play throughout the food supply chain (FSC) and the resultant interdependencies and externalities. Better information is crucial for improving food sector sustainability, and others (Hu et al., 2013; Etemadnia et al., 2015; Gwanpua et al., 2015) have demonstrated how increased information can drive such improvements. Higher visibility and transparency of food operations would enable precise performance assessments, resulting in more accurate planning and control of the production and distribution activities to the benefit of all stakeholders (Aiello et al., 2015; Accorsi et al., 2018).

Food traceability systems (FTSs) inform consumers and other supply chain actors of product attributes, shelf-life, and logistics aspects (e.g., delivery time) (Dabbene and Gay, 2011). Although FTSs could enhance knowledge about the FSC, barriers limit their diffusion (Bosona and Gebresenbet, 2013). Implementing a traceability system is expensive and requires expertise beyond most FSC companies (Bottani and Rizzi, 2008). The food sector is comprised of

thousands of small actors that are neither horizontally nor vertically integrated. Lastly, information uncertainty couples with a lack of standardized data acquisition and communication protocols. Thus, effective implementations of FTSs are rare.

Encouraging the diffusion of FTSs to shed light on FSC ecosystems requires specifying which information to track (Tsolakis et al., 2014). This paper illustrates such a framework for FSC data collection that builds a structured knowledge on food processes and supports integrated, data-driven planning. The underlying work is from the European Union and Mediterranean Project FUTUREMED (MED/2007-2013 – FutureMED) under the grant of the European Regional Development Fund. Their goal is mapping and optimizing agro-food supply chains for generic food products (i.e. both raw and processed) in the Mediterranean region through adopting Information and Communications Technology (ICT) in the agro-food sector, connecting supply chains actors. Note the proposed framework is intended for generic food products but remain open to others. Indeed, the characteristic that makes food supply chains distinctive and challenging even more than perishability is the extreme fragmentation of the sector, which counts hundreds of thousands of small producers who supply tens of thousands of intermediate players, who, in turn, serve thousands of selling points and hundreds of retailers, each owning a distribution chain. Furthermore, this hierarchy couples with that of decision-makers and of macro-micro issues which reflects the strategic, tactical and operational nature of supply chain planning. In such highly spread and fragmented environment, typical approaches to FTS are infeasible without first providing a comprehensive and integrated data architecture to cope with different processes to track and decision levers to handle. This assumption motivated our research.

The remainder of this paper is organized as follows. Section 2 summarizes a literature review. Section 3 defines the framework and the associated database for FSC data collection, storage, and manipulation. Section 4 illustrates how the framework enables data-driven analysis and supports decision-making for a case study. Section 5 concludes the paper by discussing the obtained results and considers potential further applications for the framework.

2. Literature review

Considering the impact of the food industry on the European and Mediterranean economies and the associated externalities (Kucukvar and Samadi, 2015), operations researchers have contributed in supporting decision-making on FSC management (Ahumada and Villalobos, 2009). However, these contributions separately address various decisions (i.e. of strategic, tactical and operational nature), and the need for a more unified approach is highlighted (Akkerman et al., 2010).

Indeed, classic operations research approaches inherently have limitations in solving FSC issues. The first limitation is methodological: both optimization and simulation techniques build upon a conceptual model of the system to be analyzed. Such models simplify the real system through a subset of parameters and decision variables that are exclusive and localized rather than inclusive and systemic. Secondly, the micro (localized and short term) and macro (diffused and mid-long term) perspectives of planning are rarely integrated in the same decision problem (De Keizer et al., 2017, Manzini et al., 2014^a, Mason et al., 2015; Accorsi et al., 2015 and 2017^a, Soto-Silva et al., 2016). Thirdly, the dearth of information availability over wider spatial scales and multiple FSC stages and stakeholders impedes properly quantitative decision-support systems. These three factors contribute to a single-minded focus on sub-optimizing parts of these complex ecosystems without considering the whole FSC (Higgings et al., 2010).

The poor coordination among the food actors in the FSC (Handayati et al., 2015) and paucity of ICT infrastructures results in limited visibility of processes to control and prevents practical implementation of data-driven planning methodologies. Others (Aung and Chang, 2014; Ting et al., 2014) state the need for FTS frameworks for data tracking and manipulation at different stages of the FSC.

FTSs are implemented for different purposes: to comply with mandatory regulations, to attest product origin, to certify specific food properties, and to aid recall actions in case of sanitary outbreaks (Dabbene et al., 2014). Saak (2016) formulates an equilibrium model to investigate why and when a supply chain should invest in traceability systems to improve its reputation for high quality processes. Dai et al. (2015) build upon the axiomatic design method (Suh, 2001) to study the impacts of introducing a traceability system on the supply chain actors' economic interests. Aiello et al. (2015) introduce a mathematical approach to predict the profit of introducing an FTS in fruit and vegetable supply chains. Ascoli et al. (2014) define a model incorporating three indices of traceability and use regression analysis to test empirically how they affect a fish processor. Dabbene and Gay (2011) formulate an optimization model to maximize FTS performance to support recalls for sanitary outbreaks. The identification of the proper trade-off between the *depth* and *scale* of a data acquisition and communication infrastructure, the associated costs, and the resulting benefits, remains challenging (Badia-Melis et al., 2015). A better understanding how a FTS can impact the performance of the FSC is necessary (Bosona and Gebresenbet, 2013).

Other researchers have worked towards the definition of frameworks that support FTSs (Regattieri et al., 2007). A search on Web of Science – Scopus from 2000–2018 for articles mentioning *food supply chain* and *data* yields 371 records, of which 56 include the term *traceability* and 11 also include the term *framework*. These 11 papers are classified in Table 1 which indicates whether the framework focuses on IT architectures, records integration from different sources or tracking sensors, is concerned on safety control or standard compliance, or supports decision making on FSC operations and layers.

Table 1. Traceability frameworks on FSC from the literature

Some of these deserve mention. Bechini et al. (2008) introduce a data model for traceability that describes FCS assets and explore the behavioral patterns of a food lot throughout the distribution pipeline. Li et al. (2010) illustrate a framework for early warning systems using data mining methods applied to a case study of a chicken slaughterhouse. Storøy et al. (2013) present the TraceFood framework to facilitate data interchange through a non-proprietary standard and outline best practices for the implementation of a FTS. Manzini and Accorsi (2013) propose a framework to ensure the quality of products throughout logistical operations. Ting et al. (2014) incorporate data-mining approaches into a decision-support tool to address safety issues. Pizzuti et al. (2014) illustrate a food Track & Trace (T&T) ontology to aid the conceptualization, design, and implementation of FTSs, while Pizzuti and Mirabelli (2015) present a T&T system based on a comprehensive food value chain model.

Although FTSs track lot-specific details throughout the FSC, few tools are able to infer product flows along complex, large scale supply chain networks. Within the FRISBEE European project Gogou et al. (2015) and Gwanpua et al. (2015) both illustrate a web-based platform to collect and analyze the temperature conditions throughout chilled and frozen FSCs. Verdouw et al. (2016) demonstrate virtualizing a FSC according to the Internet-of-things paradigm and provide an enabling information system architecture. The main contribution documented is a national database (LeBlanc et al., 2015) and simulation tool aimed at analyzing food safety risk and controlling sanitary outbreaks along

FSCs. Compared to LeBlanc et al.'s work, this paper proposes a database and an integrated decision-support tool for the mapping, planning, and optimization of food production and distribution operations in the Mediterranean region. Given the properties of a traceability system defined by McEntire et al. (2010), the framework proposed in this paper is a flexible, large breadth, geo-referenced, and multiple-depth data architecture to enable data-driven analysis and planning of food logistics operations. It is flexible because it is not just a data repository for FTSs, but it also behaves as dataset to design, analyze, and optimize operations. It has large breadth since it refers to physical flows of products from farm-to-table and includes characteristics of entities involved at each stage including geo-referencing. Lastly, a multiple-depth approach integrates data layers (i.e., micro and macro) and granularities, and enables the linkage of different abstraction levels and records throughout the FSC system.

To our knowledge, this paper covers a gap in the literature that lacks of holistic decision-support systems addressing simultaneously to macro and micro issues on food supply chain planning and management. We propose an original ontological framework and a support-decision platform aimed beyond just traceability implementation to the data-driven planning of food production and distribution operations over a large scale environment.

3. Methodology and framework design

We build a framework in six steps:

1. *Step 1*: Modelling the FSC boundaries and the decision-makers;
2. *Step 2*: Analyzing the FSC's entities;
3. *Step 3*: Designing the data architecture and its database;
4. *Step 4*: Collecting and aligning data;
5. *Step 5*: Developing a decision-support tool and interfaces;
6. *Step 6*: Validating and applying the framework.

The first step conceptualizes the FSC operations by depicting the activities and associated actors necessary to process and distribute food from growers/farmers to the consumers. We identify the nodes/stages where tasks occur, the decision-makers involved, along with the information abstraction layers and system boundaries required for holistic planning. An information abstraction level represents a layer of analysis, while boundaries highlight which food processes or physical and information flows are mapped.

The second step defines the FSC's entities, identifying a panel of properties and features for each that characterize its role in the FSC's operations. This step assesses the relevance of each entity in accordance with its data abstraction level and determines the relational linkages. In our framework, such entities are the information holders or the physical objects to which data records are referred.

The third step designs a flexible database for the analysis of FSC operations. It allows for collection of localized micro FTS records at a low level of abstraction, and organization of information belonging to different abstraction levels through a multiple-depth integration. Integration between information layers is obtained through a hierarchical data architecture which combine the stages of the FSC and the related entities with the data tracked to support decision-making as illustrated in Fig. 1. Data integration follows two approaches: the *top-down inference* uses data available at an higher level (e.g. seasonal food consumption per province) to infer records at lower level (e.g. physical food flows handled by the nodes of different distribution channels within a province); the *bottom-up inference* uses records tracked

at lower lever (e.g. the environmental stresses measured along a shipment) to deduce the behavior of a process or an entity at higher levels (e.g. stresses experienced by food on a route and given season). The proposed data architecture results into a comprehensive database which links the stages of a generic FSC and collects records over European scale. The fourth step finalizes an extensive data collection from different and multiple-depth sources, including national and European statistics databases, existing Geographic Information Systems (GISs), Information Systems of the involved companies, handbooks, and websites. This step also aligns the space and time granularity of the available information. The resulting relational database is filled with primary and secondary data. The fifth step develops a decision-support platform and user interfaces for data-driven planning and analysis of FSC operations. The developed tool is intended to addressed to different planning targets in agreement with the purposes of different decision-makers as exemplified in Fig. 1. The tool virtualizes the physical flows of food throughout existing or new supply chains, then quantifies and assesses a panel of economic, environmental, and logistics KPIs, compares alternative network scenarios through what-if multi-scenario analysis, and runs optimization models. The final step validates the framework with a proof of concept used to address to a company's issue.

The resulting database and tool support the collection and organization of food related data at multiple abstraction levels, the mapping of the flows for a generic FSC over a large scale, the analysis of food operations and performances of involved nodes and actors, and the optimization of punctual processes rather than the overall pipeline from farm-to-table. The most important activities for each step are described in the following sections, while the conceptual framework with the data abstraction levels, entities, decision-makers, planning targets and boundaries is illustrated in Fig. 1.

Fig. 1. Framework targets, boundaries and decision-flows.

3.1. Modelling the FSC boundaries and decision-makers

A FSC involves all the stages from farmers to consumers. In order to understand the information to track and collect at each stage we adopted an approach known as Material Flow Analysis (MFA), aimed at drawing the physical food flows throughout the supply chain. The resulting key information to collect is the handled goods at each *stage*, the actors and *decision-makers* involved, the processes carried out, and the *node* where the process is performed. The goods flow is characterized by a food product and handled volume. The type of product ranges from raw food (e.g. fruits and vegetables) and agro-food commodities, semi-processed foods, bulk or packaged finish foods, and the proper unit of measure for the volume varies accordingly.

As illustrated in Fig. 1., the framework couples three different hierarchies. The first deals with the decision-makers and stakeholders involved in FSC planning which range from growers, distributors and retailer, to regulatory agencies and bureaus of agriculture, infrastructures and transportation. The second refers to the records and sets of data required by decision-makers to handle and take data-driven operational, tactical or strategic decisions. The classification that follows cross-references the first two hierarchies taking inspiration from others' taxonomies (Tsolakis et al., 2014; Pizzuti and Mirabelli, 2015; Accorsi et al., 2017^b):

- *Growers/farmers* refer to primary production and includes growers, farmers, or aquacultures devoted to cultivating and farming. To plan seeding, cropping, harvesting or farming operations the agro-climate profiles

(i.e. soil and weather features) of crop/farm nodes, the cost of fertilizers and nutrients, and the suppliers portfolio and demand need to be collected.

- *Suppliers/Producers/Packagers* collect and consolidate raw products from the growers behaving as consolidators or processors. These are less numerous than growers and more strategically located, and contribute to transform raw products into packed, finished food. Package features, products' seasonality and shelf life, retailer orders drive the design of the processing system layout, in agreement with the level of flexibility required by the production-mix, and the production volume fulfilled. As a result, processing plants assume the shape of continuous processing-lines for washing, grading, cutting and peeling, blanching or cooling, rather than of job-shops, necessary when the production mix explodes as in the food service industry (Farahani et al., 2013; Penazzi et al., 2017).
- *Packaging producers* supply processors or consolidators with packaging materials or provide pooling services for the whole network in the case of reusable packaging.
- *Carriers/distributors* transport food throughout the FSC via various modes and organize the distribution of food products from vendors to consumers. Distributors use networks of storage facilities to match supplies with the customers' orders in agreement with the storage capacity and fleet availability, the service level to achieve, and the product turn-over.
- *Consumers* consist of the final FSC stage, such as retailers' depots, grocery shops, gross markets, cantinas, and restaurants.
- *Port (-trans-modal hub) authorities* manage port/hub operations, rules and infrastructures and benefit from the awareness of the seasonal incoming flows of food and ports/hubs connectivity.
- *Regulatory agencies* represent stakeholders of FSCs aimed at define whether and how food products can circulate across national borders, and at which cost (*customs*).
- *Bureaus of Transport, Infrastructures and Agriculture* at the top of the pyramid represent the main strategic decisional organs for the planning of sustainable and large-scale FSCs. Their challenging role can be supported by synthetic but comprehensive KPIs resulting from the hierarchical data architecture of Fig. 1.

The places where the aforementioned decision-makers/actors operate represent logistics nodes or stages of the FSC network, and some of these identify physical points for tracking and allocating flows. The combination of the first two hierarchies of Fig. 1 is justified by the nature of planning: at bottom levels many operational decisions can be taken each fueled by wide sets of parameters and information; at top level, given the complexity and impact of decision-making, this should be supported by synthetic but comprehensive KPIs.

The vast number of actors involved in transnational geographic distribution typically discourages the implementation of T&T protocols and technologies. Thus, information on food flows is limited for some stages, actors, or nodes. Nevertheless, the planning of sustainable food operations requires integrated data-driven analysis fueled by a comprehensive dataset. The proposed framework identifies, in the third hierarchy, three *abstraction levels* for data collection and shows the links and interdependencies between information layers, allowing for inferring missing records though an integrated top-down and bottom-up approach for the analysis of the food operations over a large scale geography. These are represented in Fig. 1 and described as follows:

- *Geographical level* refers to the panel of high-level/strategic parameters describing the role of a geographical area, to assess its potential for the development of agro-food supply chains, and to compare this potential with those of other areas. This panel includes quantitative metrics that describe the economics, logistical

performances, level of maturity of the agricultural sector, available transport infrastructure, and environmental profile. The import-export balance, production volume, and flows of agro-food products distributed between the geographical areas are also collected at this level. This information describes the demographic and economic aspects of an area, the enabling levers for the development of sustainable FSCs (e.g., infrastructures, state of the agriculture sector), and the limiting factors such as climate or natural resources.

- *Logistics level* includes information provided by the actors operating along the FSC. The logistics network of the nodes and the operations for the supply, production and distribution of food products are mapped at this level. As example, this level records the flows of food supplied and delivered at each stage, the number of trucks travelling between the nodes, the throughput of processing facilities, thereby supporting the tactical planning of the operations.
- *On-field level* tracks punctual data regarding the FSC entities and processes as collected via FTSs or remote sensors to aid operational planning. This level also includes micro-climate parameters and soil profiles measured at a given producer's node, and the transportation profile of a given shipment in terms of suffered temperatures, departing and arrival time, load utilization.

The identification of these abstraction levels, which borrow the levels of planning i.e. strategic, tactical and operational, shows how traceability systems alone are not sufficient to support the systemic planning of FSC operations as they focus on a single process and do not integrate systemic information.

3.2. The FSC entities

The entities defined at *Step 2* represents physical objects, processes, and nodes. Each entity belongs to an abstraction level characterized by the set of parameters and data collected at that level. Fig. 2 illustrates the role of the main entities, their connections, and the knowledge hierarchy through the three abstraction levels via Object-Relational Mapping (ORM) notation,

The entity *Geoarea* represents a territory where parameters describing the climatic, socio-economic, infrastructural, agricultural, or logistical profiles are known. These quantitative properties couple with the flows between two *Geoareas*: demands, supply capacities, and the import-export balance for each food product. The granularity of *Geoareas* is not predetermined, ranging from a city to a country depending on information availability.

The entity *Node* represents a FSC node and is characterized by parameters describing its operational role. The connection between a couple of *Nodes* is given at the Logistics level via the *Shipment* entity and is typically characterized by origin and destination nodes, a departure date, a load to be delivered, and *Transport vehicle*. A *Shipment* is organized in response to an *Order* by a *Customer*.

The properties of these entities can be further explored On-field through use of sensors able to collect soil/climate features of a crop (i.e. soil and micro-climate profiles in Fig. 2), timely information on a single product or unit load (i.e., transportation profile in Fig. 2), or track primary production, processing activities, and distribution processes.

Fig. 2. Framework entities

3.3. Data architecture

The hierarchy of relevant entities and associated data and parameters identified in the framework defines the relational database tables for collecting, storing, and manipulating the records describing the characteristics and role of each entity role by using SQL scripts. The fields of the main tables follow. A record of the table *Node* identifies geographical

coordinates, the address, and binary parameters tracking the node's access to a specific transport mode. The last parameters indicate the node's potential for exploiting transshipments. The classification given in Section 3.1 results in defining different tables for separate roles, avoiding field redundancies and sustaining table normalization. The tables *Crop*, *Processing Plant*, *Storage Facility*, *Port*, *Multimodal hub*, and *Market* further define each node. For example, a *Crop* table record reports the number of hectares, the variety cultivated, the set of irrigation and harvesting systems applied, and at the On-field level the soil and the micro-climate profiles (Accorsi et al., 2016). A record from the table *Storage Facility* includes typical warehouse design parameters, storage equipment, the number of aisles, bays and storage level, and temperature set-points of cold rooms.

According to the hierarchy of Fig. 2, each node belongs to a *GeoArea*, which behaves as a collector of nodes. The framework organizes the set of import and export rules and certifications required to distribute different food categories among *GeoAreas* of different countries. The table *Flow* tracks physical flows of food distributed from a *GeoArea* to another over time. At a lower level, the table *Shipment* tracks physical deliveries among nodes by recording the origin and destination, departure date, shipped products, and transport mode. The *Product* table records properties of products: product category, variety, nutritional values, and links to shelf life profiles and conservation requirements. These tables permit tracking the environmental profile of a shipment in term of monitored temperature and humidity records, and the combination of package and product that have that profile at the On-field level. These records can be used for laboratory simulations testing the responsiveness of both product and package to transport conditions and measuring the impact of logistics processes on the product's quality and safety (Manzini et al., 2014^b; La Scalia et al., 2016; Ayyad et al., 2017; Valli et al., 2013). Table 2 shortlists the tables and their main fields and quantifies the number of records collected per table.

Fig. 3. Database E-R diagram.

While the framework is generalizable to all FSCs, we focus on fruit and vegetable supply chains. The data sources used to populate the tables of the geographical level include annual authorities' reports, whitepapers, websites, and a thesaurus of databases. The gathering of lower level records has been supported by a group of enterprises involved in the FutureMed project that provided primary data from ERP systems, questionnaires to managers at various nodes, and information from websites. The sources for On-field information are mainly storage and distribution processes of specific food companies that have been monitored via environmental sensors.

Table 2. Database fields, abstraction levels (AL), and records number.

3.4. Decision-support tool and interfaces

We developed a decision-support platform (DST) to address the following research goals (RGs) and planning targets. The DST works via desktop software developed in C# .NET and interfaces with a MS SQL Server database while reading other data sources such as MS Access databases or Excel files, and it uses MS Mappoint and OpenStreetMap to provide maps and retrieve point-to-point routing information.

- RG 1: Overviewing the information at different abstraction level with a GIS support, and performing queries to the database;
- RG 2: Inferring the missing information at lower (higher) levels through a top-down (bottom-up) approach;

- *RG 3*: Quantifying a panel of economic, logistics and environmental KPIs resulting by the food production and distribution scenario (as-is) throughout the FSC;
- *RG 4*: Setting different parameter-driven scenario (to-be) of a FSC and comparing the associated performances in what-if simulation analysis;
- *RG 5*: Creating and applying models to optimize production-distribution scenarios (optimized to-be) from a holistic perspective.

The list of *RGs* couples with some FSC planning targets as shown in Fig. 1. Some of the tools' Graphic User Interfaces (GUIs) follow. *RG 1* is met by the GUI that summarizes records collected at Geographical and Logistics levels by mapping FSC nodes and uses colors and size to compare and quantify the desired metrics, as shown in Fig. 4. By achieving *RG 1*, the decision-makers at different levels of the hierarchy can identify business opportunities (e.g. uncovered markets, production areas close to logistics infrastructures) or assess the utilization of existing logistics infrastructures (e.g. storage facilities, ports).

Fig. 4. Tool GUIs: Overviewing the high-level FSC records with a GIS.

A twofold approach is implemented for *RG 2*. Information at the higher abstraction level infers the shared behavior of the nodes that belong to a *GeoArea* via a top-down approach. For example, the physical flow of apples distributed from one region to another are tracked in the table *Flow* letting us assume that the storage facilities and ports located within those areas are responsible for such flows. Thus, this flow can be split among these nodes, and distribution records at logistics level can be estimated and appended to the *Shipment* table. The DST integrates records at all three levels to determine food flows throughout the FSC. The annual flow of a product among *GeoAreas* can be allocated to growers, processing facilities, ports, storage facilities, and market nodes of those areas. The more collected nodes, the more reliable flow allocations will be. The user can estimate a product's seasonal demand given a region's market nodes as illustrated in Fig. 5. Should *Shipment* profiles be available, the DST would use this information to infer the environmental conditions experienced during the distribution of food from one *GeoArea* to another. Thus, the DST provides a bottom-up approach for a risk assessment for product quality associated with a route.

Fig. 5. Tool GUIs: Inferring data across different abstraction levels

By achieving *RG 2*, the decision-maker deepen its knowledge of the FSC operations and also understand where gaps in data collection exist and which processes are hence out-of-monitoring.

RGs 3 and *4* are met though the GUIs illustrated in Fig. 6, which allow for: (1) assessing physical food flows between the nodes as recorded in the table *Shipment*; (2) analyzing an *as-is* distribution scenario in term of quantitative economic, logistics, and environmental metrics; (3) generating a set of to-be distribution scenarios for what-if comparisons; and (4) deciding location-allocations across the FSC by virtualizing parameter-driven to-be scenarios. A panel of KPIs compare distribution scenarios throughout the FSC. Fig. 6 shows the map of the food shipments through a selected network, the environmental GHGs associated with the trucks, and the frequency analysis of the distance travelled per shipment. Furthermore, the GUI uses colors to compare two distribution scenarios, orange for *as-is* and blue for *to-be*, plotting shipments in term of travelled distance and utilization. *RGs 3* and *4* address to several planning targets as transport cost reduction, to the assessment of environmental externalities of food operations, and to the re-design of the network infrastructure.

Lastly, *RG 5* aims at designing optimized to-be FSC scenarios through strategic, tactical and operational optimization models. For sake of brevity, the formulation of such models, as well as their application with the data architecture of the FUTUREMED project, is devoted to other and future papers.

Fig. 6. Tool GUIs: Distribution scenarios and KPIs assessment.

4. Proof of concept

The decision-support platform has been tested with industrial case studies, each addressing to different *RGs* and planning targets, some of which will be presented in future papers. One such case study concerns the distribution scenario of an Italian fruit trader that is assessed and improved by addressing to the *RGs* 1, 3 and 4. This Italian SME operating in the food import/export across the Mediterranean purchases fruit from consolidators and processors and then arranges distribution activities to customers. As the company is committed to daily negotiations of purchasing and selling prices, picking and delivery tours, and filing import-export documents, the proposed DST aids by providing information such as transport costs between nodes, country-specific rules, area food demand (See Fig. 8), and an overview of the opportunities for improving logistics costs. Indeed, we adopted the proposed framework and DST to virtualize the existing (as-is) distribution scenario and try the impact of a new storage facility located in Vignola (MO). “*Is that location convenient?*”, and “*which are the economic and environmental returns from the new facility?*” are two questions addressed by our framework. Fig. 7 summarizes the main company’s network features and characteristics and shows the nodes of the observed FSC on the map.

Fig. 7. Company’s network features and map.

The DST has been used to support the company’s decision to establish a storage facility as intermediate stage between the suppliers and the customers. The new facility would consolidate shipments, leading to better food conservation and decreasing food miles. The tool creates both *as-is* and *to-be* distribution scenarios, comparing them via a panel of economic, logistics and environmental metrics. Two destination markets, Germany and Unit Arab Emirates, are also considered, and new supply chains connecting these nodes with the existing suppliers’ network have been assessed with the tool.

Fig. 8. Customer demand for oranges, peaches and apples in German markets.

The *Flow* records at the geographical level estimate the demand per product and city for both customers’ markets (see Fig. 8). Data provided by the company virtualizes the network, calculates the routes, quantifies the seasonal volume of fruit retrieved by processors and delivered to customers, and then estimates the needed storage capacity of the new warehouse at the logistics level. The fruit volume varies by season but is equal in both scenarios that differ only by whether a new storage facility exists. A list of shipments over an annual horizon and a panel of KPIs are generated for each distribution scenario.

Fig. 9. Tool GUIs: Company testbed

The *as-is* scenario uses two storage facilities in Albenga and Verona to consolidate the shipments, while the *to-be* scenario includes a new warehouse located in Modena surroundings (i.e., Vignola as in Fig. 9) suggested by the company's managers. The distribution scenarios follow two stages: first from the producer to the storage facility and then to the customer. Starting from the annual orders profiles, the routes, from the suppliers to the warehouse and then to the consumers, have been virtualized by the DST and distances calculated to minimize travelling for each shipment. The new storage facility aims at consolidating the shipments and at reducing the travelling distance from suppliers to consumers' nodes.

Table 3. What-if analysis with the Company testbed.

Table 3 quantifies a panel of some economic, logistics and environmental KPIs (i.e. addressing to RG 3) and summarizes the results from the what-if comparison analysis between the *as-is* and *to-be* scenarios. The new warehouse in the *to-be* scenario would reduce the overall total travelled distance for food distribution, which consequently decreases both transport costs and resulting environmental externalities. The shipments in the *to-be* scenario are lower because the warehouse enhances the consolidation of demand orders. Dealing with logistics, the DST quantifies the economic saving per year between *as-is* and *to-be* scenario in almost 45 k€ as calculated from the average transport cost reduction multiplied the number of shipments. This benefit provided valuable information for deciding whether to invest in the new storage facility and how long payback would take, while the other changes in the environmental metrics quantifies the GHG emissions savings that would be possible (i.e., 8% reduction), which may be useful for cap-and-trade and emission mitigating systems as EU ETS or white certificates (Convery, 2009; Sorrell et al., 2009).

5. Discussion and future developments

Now that the framework and database have been developed and validated through a case study, we consider potential applications and avenues for future development. The most strategic level would entail the planning and optimization of the European and Mediterranean food production and distribution systems while considering long-term sustainability. One use-case could be assessing the environmental externalities from the distribution flows of food across the countries. Another analysis might entail investigating ports (Bartholdi et al., 2016), warehouses, transshipment hubs and other logistics infrastructures with respect to current utilization and the opportunities for improvement. Further down the hierarchy of decision levels the database and DSTs would be useful in identifying distribution bottlenecks and suggesting the most feasible and sustainable food routes given both economic and environmental aspects. Another use would be identifying new market opportunities given existing logistics connections, product shelf lives, availability of refrigerated infrastructure (Gallo et al., 2017), and distances between suppliers and consumers, based on aggregate purchasing power and market demand. At the most operational level, these tools could work within the Internet-of-Things paradigm as detailed by Accorsi et al., (2017^b) and yet exemplified by others (Yan et al., 2016; Zhang et al., 2017; Li et al., 2017), allowing for adjustments at the farm, processing and distribution levels, given based on a variety of micro data such rainfall patterns and vendor costs.

Thus, we anticipate using this framework to illustrate other more complex case studies such as the re-design of a retailer supply chain for fruit and vegetable products, the assessment of ready-to-eat vegetables' deliveries to tourism areas, and the optimization of shipping routes in the Mediterranean basin, according to the food seasonality and shelf-life. All of these studies would simultaneously provide a more detailed description of each DST and the related functionalities available in the tool set.

While many applications are possible with the current functionality of the database and supporting DST, we also consider future improvements. Table 3 addresses key logistical, economic, and environmental metrics, specifically greenhouse gas emissions. Of course, food system sustainability encompasses more than this subset of drivers. Extensions to the framework and supporting database should include other environmental factors such as land use issues, as is done in Accorsi et al. (2016), and social factors: for example, such extensions could support community planners' efforts to ensure citizens' access to quality food.

A future extension would entail using these results to educate supply chain actors and even ultimately consumers of the externalities associated with hidden operations from farm-to-table, thereby eliciting more sustainable choices (Cholette et al., 2013). For instance informed consumers' aversion to palm oil due to environmental externalities (The Guardian, 2015; Huffington, 2017), has resulted in Italian retailers stocking fewer such products.

6. Conclusion

This paper illustrates a framework for the design of a database aiding the assessment, planning and design of food production and distribution operations over a large scale area and strategic perspective. To the authors' knowledge, this framework and the resulting decision-support platform is the first to move beyond simple traceability implementation to the sustainable planning of food logistics operations over a large-scale environment that bridges the gap between research techniques and real-world data availability.

This database and the associated DSTs support researchers and practitioners alike in collecting and organizing the information necessary for a quantitative analysis and assessment. For example, in the aforementioned case study for the Italian SME importer/exporter, the economic savings associated with the logistics operations provided valuable information for deciding whether to invest in improving the logistic network and quantifying the resultant environmental benefits. The database and DSTs could be used as-is to inform decisions made at all levels in the FSC or could be further extended to consider additional dimensions of sustainability.

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References

- Accorsi, R., Cholette, S., Manzini, R., Pini, C., Penazzi, S., 2016. The Land-Network problem: Ecosystem carbon balance in planning sustainable agro-food supply chains. *Journal of Cleaner Production* 112(1), 158–171.
- Accorsi, R., Gallo, A., Manzini, R., 2017a. A climate-driven decision-support model for the distribution of perishable products. *Journal of Cleaner Production* 165, 917–929.
- Accorsi, R., Baruffaldi, G., Manzini, R., Tufano, A., 2018. On the design of cooperative vendors' networks in retail food supply chains: A logistics-driven approach. *International Journal of Logistics Research and Applications*, 21(1), 35–52.
- Accorsi, R., Bortolini, M., Baruffaldi, G., Pilati, F., Ferrari, E., 2017^b. Internet-of-things paradigm in food supply chains control and management. *Procedia Manufacturing* 11, 889–895.
- Accorsi, R., Manzini, R., Pini, C., Penazzi, S., 2015. On the design of closed-loop networks for product life cycle management: Economic, environmental and geography considerations. *Journal of Transport Geography* 48, 121–134.
- Ayyad, Z., Valli, E., Bendini, A., Accorsi, R., Manzini, R., Bortolini, M., Gamberi, M., Gallina Toschi, T., 2017. Simulating international shipments of vegetable oils: Focus on quality changes. *Italian Journal of Food Science* 29, 38–49.
- Ahumada, O., Villalobos, J.R., 2009. Application of planning models in the agro-food supply chain: A review. *European Journal of Operational Research* 196(1), 1–20.

- 1 Ahumada, O., Villalobos, J.R., 2011. Operational model for planning the harvest and distribution of perishable agricultural products. *International*
- 2 *Journal of Production Economics* 133(2), 677–687.
- 3 Aiello, G., Enea, M., Muriana, C., 2014. Economic benefits from food recovery at the retail stage: An application to Italian food chains. *Waste*
- 4 *Management* 34(7), 1306–1316.
- 5 Aiello, G., Enea, M., Muriana, C., 2015. The expected value of the traceability information. *European Journal of Operational Research* 244, 176–186.
- 6 Asioli, D., Boecker, A., Canavari, M., 2014. On the linkages between traceability levels and expected and actual traceability costs and benefits in the
- 7 Italian fishery supply chain. *Food Control* 46, 10–17.
- 8 Akkerman, R., Farahani, P., Grunow, M., 2010. Quality, safety and sustainability in food distribution: a review of quantitative operations
- 9 management approaches and challenges. *OR Spectrum* 32, 863–904.
- 10 Aung, M.M., Chang, Y.S., 2014. Traceability in a food supply chain: Safety and quality perspectives. *Food Control* 39, 172–184.
- 11 Badia-Melis, R., Mishra, P., Ruiz-Garcia, L., 2015. Food traceability: New trends and recent advances. A review. *Food Control* 57, 393–401.
- 12 Bartholdi, J.J. Jarumaneeroj, P., Ramudhin, A., 2016. A new connectivity index for container ports. *Maritime Economics* 18, 231–249.
- 13 Bechini, A., Cimino, M.C.G.A., Marcelloni, F., Tomasi, A., 2008. Patterns and technologies for enabling food supply chain traceability throughout
- 14 collaborative e-business. *Information and Software Technology* 50, 342–359.
- 15 Boye, J.I., Arcand, Y., 2013. Current trends in green technologies in food production and processing. *Food Engineering Reviews* 5(1), 1–17.
- 16 Bosona, T., Gebresenbet, G., 2013. Food traceability as an integral part of logistics management in food and agricultural supply chain. *Food Control*
- 17 33, 32–48.
- 18 Cholette, S., Ungson, G.R., Özlük, Ö., Özşen, L., 2013. Exploring purchasing preferences: Local and ecologically labelled foods. *Journal of*
- 19 *Consumer Marketing*, 30(7), 563–572.
- 20 Cobuloglu, H.I., Büyüktaktakın, I.E., 2015. Food vs. biofuel: An optimization approach to the spatio-temporal analysis of land-use competition and
- 21 environmental impacts. *Applied Energy* 140, 418–434.
- 22 Convery, F.J., 2009. Origins and development of the EU ETS. *Environmental and Resource Economics*, 43(3), 391–412.
- 23 Dabbene, F., Gay, P., 2011. Food traceability systems: Performance evaluation and optimization. *Computers and Electronics in Agriculture* 75, 139–
- 24 146.
- 25 Dabbene, F., Gay, P., Tortia, C., 2014. Traceability issues in food supply chain management: A review. *Biosystems Engineering* 120, 65–80.
- 26 Dai, H., Ge, L., Zhou, W., 2015. A design method for supply chain traceability systems with aligned interests. *International Journal of Production*
- 27 *Economics* 170, 14–24.
- 28 De Keizer, M., Akkerman, R., Grunow, M., Bloemhof, J.M., Haijema, R., van der Vorst, J.G.A.J., 2017. Logistics network design for perishable
- 29 products with heterogeneous quality decay. *European Journal of Operational Research* 262, 535–549.
- 30 Etemadnia, H., Goetz, S., Canning, P., Tavallali, M.S., 2015. Optimal wholesale facilities location within the fruit and vegetables supply chain with
- 31 bimodal transportation options: An LP-MIP heuristic approach. *European Journal of Operational Research* 244, 648–661.
- 32 Fan, S., Brzeska, J., 2016. Sustainable food security and nutrition: Demystifying conventional beliefs. *Global Food Security* 11, 11–16.
- 33 Fischer, G., Prieler, S., van Velthuisen, H., Lensink, S.M., Londo, M., de Wit, M., 2010. Biofuel production potentials in Europe: Sustainable use of
- 34 cultivated land and pastures. Part I: Land productivity potentials. *Biomass and Bioenergy* 34, 159–172.
- 35 Farahani, P., Grunow, M., Akkerman, R., 2013. Design and operations planning of municipal foodservice systems. *International Journal of*
- 36 *Production Economics* 144, 383–396.
- 37 Fischer, G., Prieler, S., van Velthuisen, H., Berndes, G., Faaij, A., Londo, M., de Wit, M., 2010. Biofuel production potentials in Europe: Sustainable
- 38 use of cultivated land and pastures, Part II: Land use scenarios. *Biomass and Bioenergy* 34, 173–187.
- 39 Gallo, A., Accorsi, R., Baruffaldi, G., Manzini, R., 2017. Designing sustainable cold chains for long-range food distribution: Energy-effective
- 40 corridors on the Silk Road belt. *Sustainability, A Journal* 2017, 9(11), 2044; doi:10.3390/su9112044.
- 41 Gerdes, L., Busch, U., Pecoraro, S., 2012. GMOfinder – A GMO screening database. *Food Analytical Methods* 5, 1368–1376.
- 42 Gwanpua, S.G., Verboven, P., Leducq, D., Brown, T., Verlinden, B.E., Bekele, E., Aregawi, W., Evans, J., Foster, A., Duret, S., Hoang, H.M., van
- 43 der Sluis, S., Wissink, E., Hendriksen, L.J.A.M., Taoukis, P., Gogou, E., Stahl, V., El Jabri, M., Le Page, J.F., Claussen, I., Indergård, E., Nicolai,
- 44 B.M., Alvarez, G., Geeraerd, A.H., 2015. The FRISBEE tool, a software for optimising the trade-off between food quality, energy use, and global
- 45 warming impact of cold chains. *Journal of Food Engineering* 148, 1–12.
- 46 Handayati, Y., Simatupang, T.M., Perdana, T., 2015. Agri-food supply chain coordination: the state-of-the-art and recent developments. *Logistics*
- 47 *Research* 8(5), 1–15.
- 48 Higgins, A.J., Miller, C.J., Archer, A.A., Ton, T., Fletcher, C.S., McAllister, R.R.J., 2010. Challenges of operations research practice in agricultural
- 49 value chains. *Journal of the Operational Research Society* 61(6), 964–973.
- 50 Hu, J., Zhang, X., Moga, L.M., Neculita, M., 2013. Modeling and implementation of the vegetable supply chain traceability system. *Food Control* 30,
- 51 341–353.

- Huffington Post, 2017. Palm oil products are being pulled from some stores in Italy after a report linking it to cancer. Available online at: https://www.huffingtonpost.com/entry/italy-nutella-cancer_us_58792c3de4b0e58057feac94
- Kucukvar, M., Samadi, H., 2015. Linking national food production to global supply chain impacts for the energy-climate challenge: the cases of the EU-27 and Turkey. *Journal of Cleaner Production* 108, 395–408.
- Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J., 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertilizer use. *Science of the Total Environment* 438, 477–489.
- La Scalia, G., Aiello, G., Miceli, A., Nasca, A., Alfonzo, A., Settani, L., 2016. Effect of vibration on the quality of strawberry fruits caused by simulated transport. *Journal of Food Process Engineering* 39, 140–156.
- LeBlanc, D.I., Villeneuve, S., Hashemi Beni, L., Otten, S., Fazil, A., McKellar, R., Delaquis, P., 2015. A national produce supply chain database for food safety risk analysis. *Journal of Food Engineering* 147, 24–38.
- Li, Y., Kramer, M.R., Beulens, A.J.M., van der Vorst, J.G.A., 2010. A framework for early warning and proactive control systems in food supply chain networks. *Computers in Industry* 61, 852–862.
- Li, Z., Liu, G., Liu, L., Lai, X., Xu, G., 2017. IoT-based tracking and tracing platform for prepackaged food supply chain. *Industrial Management & Data Systems* 117(9), 1906–1916.
- Manzini, R., Accorsi, R., 2013. The new conceptual framework for food supply chain assessment. *Journal of Food Engineering* 115(2), 251–263.
- Manzini, R., Accorsi, R., Bortolini, M., 2014^a. Operational planning models for distribution networks. *International Journal of Production Research* 52(1), 89–116.
- Manzini, R., Accorsi, R., Ayyad, Z., Bendini, A., Bortolini, M., Gamberi, M., Valli, E., Gallina Toschi, T., 2014^b. Sustainability and quality in the food supply chain. A case study of shipment of edible oils. *British Food Journal* 116, 2069–2090.
- Mason, N., Flores, H., Villalobos, J.R., Ahumada, O., 2015. Planning the planting, harvest, and distribution of fresh horticultural products. *International Series in Operations Research and Management Science* 224, 19–54.
- McLaughlin, D., Kinzelback, W., 2015. Food security and sustainable resource management. *Water Resources Research* 51, 4966–4985.
- Notarnicola, B., Sala, S., Assumpció, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017^a. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production* 140 (2), 399–409.
- Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2017^b. Environmental impacts of food consumption in Europe. *Journal of Cleaner Production* 140 (2), 753–765.
- Penazzi, S., Accorsi, R., Ferrari, E., Manzini, R., Dunstall, S., 2017. Design and control of food job-shop processing systems: A simulation analysis in the catering industry. *International Journal of Logistics Management* 28(3), 782–797.
- Pizzuti, T., Mirabelli, G., Sanz-Bobi, M.A., Gomez-Gonzalez, F., 2014. Food Track & Trace ontology for helping food traceability control. *Journal of Food Engineering* 120, 17–30.
- Pizzuti, T., Mirabelli, G., 2015. The Global Track&Trace System for food: General framework and functioning principles. *Journal of Food Engineering* 159, 16–35.
- Rathmann, R., Szklo, A., Schaeffer, R., 2010. Land use competition for production of food and liquid biofuels: An analysis of the arguments in the current debate. *Renewable Energy* 35, 14–22.
- Regattieri, A., Gamberi, M., Manzini, R., 2007. Traceability of food products: general framework and experimental evidence. *Journal of Food Engineering* 81, 347–356.
- Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering* 90, 1–10.
- Saak, A.E., 2016. Traceability and reputation in supply chain. *International Journal of Production Economics* 177, 149–162.
- Sadler, R.C., Gilliland, J.A., Arku, G., 2016. Theoretical issues in the ‘food desert’ debate and ways forward. *GeoJournal* 81 (3), 443–455.
- Sala, S., Assumpció, A., McLaren, S.J., Notarnicola, B., Saouter, E., Sonesson, U., 2017. In quest of reducing the environmental impacts of food production and consumption. *Journal of Cleaner Production* 140 (2), 387–398.
- Sorrell, S., Harrison, D., Radov D., Klevnas, P., Foss, A., 2009. White certificate schemes: Economic analysis and interactions with the EU ETS. *Energy Policy*, 37(1), 29–42.
- Soto-Silva, W.E., Nadal-Roig, E., González-Araya, M.C., Pla-Aragones, L.M., 2016. Operational research models applied to the fresh fruit supply chain. *European Journal of Operational Research* 251, 345–355.
- Storoy, J., Thakur, M., Olsen, P., 2013. The TraceFood framework – Principles and guidelines for implementing traceability in food value chains. *Journal of Food Engineering* 115, 41–48.
- Suh, N.P., 2001. *Axiomatic design: Advances and application*. Oxford University Press, New York.
- The Guardian, 2015. The Italians fighting against an “invasion” of palm oil. Available online at: <https://www.theguardian.com/sustainablebusiness/2015/dec/09>.

- 1 Thomas, B.J., 2010. Food deserts and the sociology of space: Distance to food retailers and food insecurity in an Urban American neighborhood.
2 World Academy of Science, Engineering and Technology 43, 19–28.
- 3 Ting, S.L., Tse, Y.K., Ho, G.T.S., Chung, S.H., Pang, G., 2014. Mining logistics data to assure the quality in a sustainable food supply chain: A case
4 in the red wine industry. *International Journal of Production Economics* 152, 200–209.
- 5 Tsolakis, N.K., Keramydas, C.A., Toka, A.K., Aidonis, D.A., Iakovou, E.T., 2014. Agrifood supply chain management: A comprehensive
6 hierarchical decision-making framework and a critical taxonomy. *Biosystems Engineering* 120, 47–64.
- 7 Valli, E., Manzini, R., Accorsi, R., Bortolini, M., Gamberi, M., Bendini, A., Lercker, G., Gallina Toschi, T., 2013. Quality at destination: Simulating
8 shipment of three bottled edible oils from Italy to Taiwan. *Rivista Italiana delle Sostanze Grasse* 90, 163–169.
- 9 Yan, B., Yan, C., Ke, C., Tan, X., 2016. Information sharing in supply chain of agricultural products based on the Internet of Things. *Industrial*
10 *Management & Data Systems* 116(7), 1397–1416.
- 11 Zhang, Y., Zhao, L., Qian, C., 2017. Modeling of an IoT-enabled supply chain for perishable food with two-echelon supply hubs. *Industrial*
12 *Management & Data Systems* 117(9), 1890–1905.
- 13

Reference	IT Architecture	Data Integration & Alignment	Regulation & standard compliance	Tracking Technologies	Food Safety	Supply Chain Design & Management	Support to decision-making
Bechini et al., 2005	●	●	○	○	○	○	○
Shanahan et al., 2009	○	○	●	●	○	○	○
Lenton, 2010	○	○	●		●	○	○
Costa et al., 2013	●	○	○	●	○	○	○
Storøy et al, 2013	●	●	○	○	○	○	○
Zhang et al., 2014	○	○	●	○	●	○	○
Solanki et al., 2014	●	○	○	○	○	●	○
Brofman et al. 2014	○	○	○	●	○	○	●
Yang et al., 2014	○	○	○	●	○	○	○
Pant et al., 2015	○	●	○	○	○	●	○
Pizzuti et al., 2015	○	○	○	○	○	●	●
<i>This paper</i>	○	●	●	○	●	●	●

Table 1. Traceability frameworks on FSC from the literature

Table	Attributes	AL	No. Of Records
GeoArea	Country, Region, Province, Area, Latitude, Longitude, SocioEconomicProfile, AgroProfile, LogisticProfile, InfrastructureProfile, ClimateProfile, EnvironmentalProfile, InfrastructureCostProfile, EnergyCostProfile, LaborCostProfile		1210
SocioEconomicProfile	GeoArea, Period, AgricultureValueAdded, CashSurplus, CurrentAccountance, CentralGovernmentDebt, ExportsOfGoodsAndServices, GDPperCapita, GDPGrowth, GrossCapitalFormation, ImportOfGoodAndServices, IndustryValueAdded, Inflation, PortfolioEquity, ServicesValueAdded, TradeInServices		72
AgroProfile	GeoArea, Period, %AgriculturalIrrigatedLand, %AgriculturalLand, AgriculturalValueAdded, AgriculturalValueAddedForWorker, ArableLand, EmploymentInAgriculture, ForestArea, ImprovedWaterSource, LandArea, PermanentCropland, LandUnderCereal, RuralPopulation, CerealYield, LivestockProductionIndex		98
LogisticProfile	GeoArea, Period, FoodExport, FuelExport, TransportServices, TravelServices, AgriculturalRawMaterialImports, TariffRates, MerchandiseTrade, AbilityToTrackAndTraceConsignments, CompetenceAndQualityOfLogisticsServices, EaseOfArrangingCompetitivelyPricedShipment, TimeToExport, TimeToImport, EfficiencyOfCustomsClearanceProcess, FrequencyConsigneeWithExpectedTime		40
InfrastructureProfile	GeoArea, Period, AirTransportRegisteredCarriers, AnnualFreshWaterAgriculture, AnnualFreshWaterTotal, ContainerPortTraffic, ElectricPowerConsumption, ICTGoodsExport, ICTGoodsImport, InternetUsers, PassengerCars, RailLines, RenewableInternalFreshWater, RoadSectorFuelConsumption, RoadSectorEnergyConsumption, RoadsPaved, Vehicles		95
ClimateProfile	GeoAreaCode, Period, CO2Emissions, EnergyUse, MethaneEmissions, MortalityRateUnder5, NitrousOxideEmissions, OtherGreenhouseGasEmissions, PopulationGrowth, PopulationPrimaryCompletionRate, RatioOfGirlsToBoyInSchool, UranPopulation, AccessToElectricity, PovertyHeadcountRatio, PopulationInUrbbanAgglomerationOfMoreThanOneMillion, LandAreaWhereElevationIsBelow5m	Geographic	111
EnvironmentalProfile	GeoAreaCode, Period, AgriculturalMethaneEmissions, AgriculturalNitrousOxideEmissions, FishSpecies, MammalSpecies, CO2Emissions, ForestArea, MarineProtectedAreas, OrganicWaterPollutant, PlantSpecies, MethaneEmissions, NitrousOxideEmissions, OtherGreenhouseGasEmissions, WaterPollutionFoodIndustry, WaterPollutionMetalIndustry, WaterPollutionPaperAndPulpIndustry, WaterPollutionTextileIndustry, WaterPollutionOtherIndustry		92
InfrastructureCostProfile	GeoAreaCode, AgricultureCost, LicenseCost, ProductionBuildingCost, DistributionBuildingCost, EnergyInfrastructureCost, WoodlandCost		25
EnergyCostProfile	GeoAreaCode, KWhElectricityCostDomestic, KWhElectricityCostIndustrial, KWhGasCostIndustrial, KwhSolarCost, KwhWindCost, KwhCarbonCost, KwhGasCost, FuelCost		20
LaborCostProfile	GeoAreaCode, OperatorCost, FarmerCost, WorkerCost, WarehouseWorkerCost, EmployeeCost, DriverCost		25
DemandGeoArea	GeoArea, Period, Product, Demand, ChannelGDO, ChannelGrossMarket, ChannelGroceryShop, ChannelGroceryMarket		82324
Expense	GeoArea, Period, Product, ExpensePerFamily		20
ImportRules	GeoAreaImporter, GeoAreaExporter, National tax, Import rules		1929
ExportRules	GeoAreaImporter, GeoAreaExporter, Export rules		1200
ImportExport	GeoAreaCode, ImportExportProfile, ProductCode, Period, TypeProduct, ImportFlow, InternalDemand, InternalProduction, ExportFlow		900
Supply	NodeCode, ProductCode, Period, NodeType, Country, ProductionQty, ProductionCost, PackagingCost, StorageCapacity, ProductionArea, LandfillCost, ProductionEmissions, TransformationEmissions, SupplierEmissions, LandfillEmissions		12358
Flow	NodeCodeFrom, NodeCodeTo, FlowCount, GeoAreaFrom, GeoAreaTo, WeeklyConnections, Lines, Product, NominalCapacity, MaxCapacity, OverallFlow, LiquidBulk, DryBulk, AgroLiquidBulk, AgroDryBulk, GeneralCargo		1874
Node	EnterpriseCode, NodeCode, NodeType, Enterprise, ZipCode, Address, City, Province, Nation, Region, Continent, RoadAccess, RailAccess, SeaAccess, AirAccess, GeoArea		12234
Crop	EnterpriseCode, NodeCode, NodeType, NodeName, Enterprise, ZipCode, RoadAccess, ThroughputCapacity, Power, EnergyReq, WaterReq, CO2, Turnover, AgroProfile, SoilProfile, ClimateProfile, GeoArea	Logistic	> 1000
ProcessingPlant	EnterpriseCode, NodeCode, NodeType, NodeName, Enterprise, ZipCode, RoadAccess, RailAccess, ThroughputCapacity, Power, EnergyReq, WaterReq, CO2, Turnover, WHProfile, LayoutProfile, GeoArea		> 100
StorageFacility	EnterpriseCode, NodeName, Enterprise, Zipcode, RoadAccess, RailAccess, StorageCapacity, HandlingCapacity, Power, EnergyReq, WaterReq, CO2, Turnover, WHProfile, LayoutProfile, PlantProfile, BmHeight, BmDepth, BmLayer, UIBmLayer, RackLevel, BeamCode, ColumnCode, CrossCode, FwLevel, UICode, GeoArea		> 500

Market	EnterpriseCode, NodeCode, NodeType, NodeName, Enterprise, ZipCode, RoadAccess, TotalDemand, GrossMarket, Market, ConsumptionPoint, GeoArea	> 10000
Port	NodeCode, NodeName, NodeType, City, Province, Country, Region, Continent, TotalArea, RailLength, QuayLength, Cranes, Employees, Vessels, Capacity, Throughput, MaxDraught, StorageArea, Totalterminals, Cruises, DryBulk, LiquidBulk, GeneralCargo, Oilpipe, DryAgroBulk, LiquidAgroBulk, TransshipmentFraction, EUNorthernArea, EUSouthernArea, MediterraneanArea, ConnectionRail, ConnectionRoad, ConnectionMatirime	214
Terminal	NodeCode, PortCode, TerminalCode, Type, Name, ProductCategory, Throughput, Period, Cranes, StraddleCarriers, Forklift, PortTruck, PipePlugs, ReeferPlugs, VesselBerths, RailTerminal, Reachstakers, VesselCapacity, Area, StorageCapacity, throughputRate, LoadingRate, UnloadingRate, Temperatresotrage, CoolStorage, FrozenStorage	241
Multimodal Hub	NodeCode, Nodename, NodeType, City, TotalArea, RailLemgth, Employees, StorageArea, StorageAreaTemp, TotalTerminals, DryBulk, LiquidBulk, GeneralCargo, OilPipe, DryArgoBulk, EUNorthernArea, EUSouthernArea, MediterraneanArea, ConnectionRail, ConnectionRoad, ConnectionMaritime, FixedCranes, MobileCranes, FloatingCranes	48
Rail Connection	ConnectionCode, Destination, Enterprise, Frequency, TravelHours, NodeCode, NodeName	259
Order	OrderCode, Category, ShipmentCode, NodeCode, NodeCodeTo, DeliveryDate, PdkQuantity, PdkWeight, PalletQuantity, Parts, TransportationModeCode, Load, Description, ShipmentCode, UnitloadCode	>> 300000
Product	ProductCode, ScientificaName, FoodCode, Category, Name, Variety, Brand, Enterprise, DOP, IGP, IGT, DOC, DOCG, Energy, Edibility, Water, Protein, Lipid, Cholesterol, Carbohydrates, Amid, Sugar, Fibre, Alcol, Sodium, Potassium, Iron, Calcium, Selenium, Tiamin, Riboflavin, VitaminA, VitaminB, VitaminC, VitaminE, EthyleneProduction, EthyleneSensibility, ColdSensibility, HarvestPeriod, Certification, OptimalStorageTemperature, OptimaleStorageRh, MaximumShelflife, PackageCode	525
DemandNode	ProductCode, NodeCode, Period, Quantity, Udm	1663340
Shelflife	ProductCode, TempMin, TempMax, Name, Type, RhMin, RhMax, ShelfLifeMin, ShelfLifeMax	614
Price	ProductCode, Node, Period, Type, ProductName, Variety, Country, region, City, PriceGrossMarket, Udm, Week, BeginDate, EndDate, Month, Market, ShopVariance, DiscountVariance, LargeRetailerVaiancy, PublicMarketVariance, RetailerVariance	42474
Shipment	TransportationCode, ShipmentCode, NodeName, NodeCode, NodeCodeTo, ProducerCode, ShipperCode, CarrierCode, ImporterCode, CustomerCode, ContainerType, ContainerSize, ProductCode, CartonQty, UnitLoadQty, OriginPort, DestinationPort, DepartureDate, ArrivalDate	78
TransportationMode	TransportationCode, TransportationName, TransportationType, VehicleName, Description, Class, LicenceRequired, VehicleLenght, VehicleWidth, LoadHeight, WeightCapacity, GrossTonnage, Co, Hc, Nox, Pm, Ch4, N2O, Nh3, SO2, CO2, CO2Eq, FuelConsumption, EnergyConsumption, TransportationCost, ContainerQuantity, VehicleQty, AvgSpeed, MaxDistance	40
Package	PackageCode, ProductCode, PackageName, PackageType, PackageLevel, Firm, Shape, ProductWeight, PackageLength, PachageWidth, PAckageHeight, Udm, Cork, Sleever, Material, color, Weight, Barcode, PackagePrimary	30
UnitLoad	UnitLoadCode, UnitLoadLenght, UnitLoadWidth, UnitLoadHeight, unitLoadWeight, Material	25
Enterprise	EnterpriseCode, NodeName, Group, Enterprise, NodeType, Importer, Exporter, Grower, Distributor, Address, Zipcode, City, Province, Region, Nation, Continent	9601
ShipmentProfile	ShipmentCode, Ibutton, DatePeriod, Position, Temperature, ThermalKit, ContainerCode, Sampling, ShipmentCode, NodeName, NodeCode, NodeCodeTo, TransportationCode, EnterpriseCode	78
Analysis	SimulationCode, ShipmentCode, ProductCode, TotalSulphurousDioxide, FreeSulphurousDioxide, OpticDensity420nm, TotalAcidity, VolatilAcidity, PhenolicAcid, SO2Free, SO2Total, ColorIntensity, SmellIntensity, TasteIntensity, Shipment, Ibutton, DatePeriod	4
Simulation	SimulationCode, ShipmentCode, Product, SimStart, SimEnd, SmplingPeriod, Samplingtime, TempOffset, RhOffset, TempCurrent, RhCurrent, Shipment, Ibutton, DatePeriod	12
ClimateProfileMonitoring	GlobalRadiation, Precipitation, RelativeHumidity, StationInfo, SunshineFraction, SunshineHours, TempAver, TempDayTime, TempMeanMax, TempMeanMin, TempNihtTime, VapourPressure, WindSpeed	12456
SoilProfileMonitoring	Demand, DewPoint, Distance, Ea_ed, EnergyCost, Eta, GeoArea, InfrastructureCost, LaborCost, Land, LandUse, LogisticsCost, Node, OutputFlow, OutputLand, PET, Product, Rse, Soil, Transportation, Use, UseProductLimit, UseProductPercentage, UseProductRate, WaterRetention, ym	19978

On-field

Table 2. Database fields, abstraction levels (AL), and collected records.

Type of metric	KPIs	Unit of measure	Distribution Scenarios		Change
			As-is	To-be	$\Delta\%$
Logistics	Number of Shipments	(shipments/year)	2,867	2,665	-7%
	Total travelling	(km/year)	2,167,702.76	1,938,336.77	-11%
	Average Travel Time	(hour/shipment)	22.17	21.88	-1%
Economic	Average Transport Cost	(€/shipment)	466.16	449.47	4%
	Fuel consumption	(kg/year)	29,516,592.60	26,894,936.30	-9%
Environmental	Equivalent CO ₂ (GWP ₁₀₀)	(kg/year)	900,470.15	823,989.13	-8%
	HC	(kg/year)	237.005	165.073	-30%
	NO _x	(kg/year)	11,828.91	11,492.32	-3%
	PM	(kg/year)	384.591	365.924	-5%
	CH ₄	(kg/year)	39.990	37.847	-5%
	N ₂ O	(kg/year)	37.833	30.257	-20%
	NH ₃	(kg/year)	3.87	2.75	-29%
	SO ₂	(kg/year)	3432.387	3431.876	n.s.
	CO ₂	(kg/year)	892,037.37	817,939.70	-8%

Table 3. What-if analysis with the Company testbed.

Reference	IT Architecture	Data Integration & Alignment	Regulation & standard compliance	Tracking Technologies	Food Safety	Supply Chain Design & Management	Support to decision-making
Bechini et al., 2005	●	●	○	○	○	○	○
Shanahan et al., 2009	○	○	●	●	○	○	○
Lenton, 2010	○	○	●		●	○	○
Costa et al., 2013	●	○	○	●	○	○	○
Storøy et al, 2013	●	●	○	○	○	○	○
Zhang et al., 2014	○	○	●	○	●	○	○
Solanki et al., 2014	●	○	○	○	○	●	○
Brofman et al. 2014	○	○	○	●	○	○	●
Yang et al., 2014	○	○	○	●	○	○	○
Pant et al., 2015	○	●	○	○	○	●	○
Pizzuti et al., 2015	○	○	○	○	○	●	●
<i>This paper</i>	○	●	●	○	●	●	●

Table 1. Traceability frameworks on FSC from the literature

Table	Attributes	AL	Number Of Records
GeoArea	Country, Region, Province, Area, Latitude, Longitude, SocioEconomicProfile, AgroProfile, LogisticProfile, InfrastructureProfile, ClimateProfile, EnvironmentalProfile, InfrastructureCostProfile, EnergyCostProfile, LaborCostProfile		1210
SocioEconomicProfile	GeoArea, Period, AgricultureValueAdded, CashSurplus, CurrentAccountance, CentralGovernmentDebt, ExportsOfGoodsAndServices, GDPperCapita, GDPGrowth, GrossCapitalFormation, ImportOfGoodAndServices, IndustryValueAdded, Inflation, PortfolioEquity, ServicesValueAdded, TradeInServices		72
AgroProfile	GeoArea, Period, %AgriculturalIrrigatedLand, %AgriculturalLand, AgriculturalValueAdded, AgriculturalValueAddedForWorker, ArableLand, EmploymentInAgriculture, ForestArea, ImprovedWaterSource, LandArea, PermanentCropland, LandUnderCereal, RuralPopulation, CerealYield, LivestockProductionIndex		98
LogisticProfile	GeoArea, Period, FoodExport, FuelExport, TransportServices, TravelServices, AgriculturalRawMaterialImports, TariffRates, MerchandiseTrade, AbilityToTrackAndTraceConsignments, CompetenceAndQualityOfLogisticsServices, EaseOfArrangingCompetitivelyPricedShipment, TimeToExport, TimeToImport, EfficiencyOfCustomsClearanceProcess, FrequencyConsigneeWithExpectedTime		40
InfrastructureProfile	GeoArea, Period, AirTransportRegisteredCarriers, AnnualFreshWaterAgriculture, AnnualFreshWaterTotal, ContainerPortTraffic, ElectricPowerConsumption, ICTGoodsExport, ICTGoodsImport, InternetUsers, PassengerCars, RailLines, RenewableInternalFreshWater, RoadSectorFuelConsumption, RoadSectorEnergyConsumption, RoadsPaved, Vehicles		95
ClimateProfile	GeoAreaCode, Period, CO2Emissions, EnergyUse, MethaneEmissions, MortalityRateUnder5, NitrousOxideEmissions, OtherGreenhouseGasEmissions, PopulationGrowth, PopulationPrimaryCompletionRate, RatioOfGirlsToBoyInSchool, UranPopulation, AccessToElectricity, PovertyHeadcountRatio, PopulationInUrbanAgglomerationOfMoreThanOneMillion, LandAreaWhereElevationIsBelow5m	Geographic	111
EnvironmentalProfile	GeoAreaCode, Period, AgriculturalMethaneEmissions, AgriculturalNitrousOxideEmissions, FishSpecies, MammalSpecies, CO2Emissions, ForestArea, MarineProtectedAreas, OrganicWaterPollutant, PlantSpecies, MethaneEmissions, NitrousOxideEmissions, OtherGreenhouseGasEmissions, WaterPollutionFoodIndustry, WaterPollutionMetalIndustry, WaterPollutionPaperAndPulpIndustry, WaterPollutionTextileIndustry, WaterPollutionOtherIndustry		92
InfrastructureCostProfile	GeoAreaCode, AgricultureCost, LicenseCost, ProductionBuildingCost, DistributionBuildingCost, EnergyInfrastructureCost, WoodlandCost		25
EnergyCostProfile	GeoAreaCode, KWhElectricityCostDomestic, KWhElectricityCostIndustrial, KWhGasCostIndustrial, KwhSolarCost, KwhWindCost, KwhCarbonCost, KwhGasCost, FuelCost		20
LaborCostProfile	GeoAreaCode, OperatorCost, FarmerCost, WorkerCost, WarehouseWorkerCost, EmployeeCost, DriverCost		25
DemandGeoArea	GeoArea, Period, Product, Demand, ChannelGDO, ChannelGrossMarket, ChannelGroceryShop, ChannelGroceryMarket		82324
Expense	GeoArea, Period, Product, ExpensePerFamily		20
ImportRules	GeoAreaImporter, GeoAreaExporter, National tax, Import rules		1929
ExportRules	GeoAreaImporter, GeoAreaExporter, Export rules		1200
ImportExport	GeoAreaCode, ImportExportProfile, ProductCode, Period, TypeProduct, ImportFlow, InternalDemand, InternalProduction, ExportFlow		900
Supply	NodeCode, ProductCode, Period, NodeType, Country, ProductionQty, ProductionCost, PackagingCost, StorageCapacity, ProductionArea, LandfillCost, ProductionEmissions, TransformationEmissions, SupplierEmissions, LandfillEmissions		12358
Flow	NodeCodeFrom, NodeCodeTo, FlowCount, GeoAreaFrom, GeoAreaTo, WeeklyConnections, Lines, Product, NominalCapacity, MaxCapacity, OverallFlow, LiquidBulk, DryBulk, AgroLiquidBulk, AgroDryBulk, GeneralCargo		1874
Node	EnterpriseCode, NodeCode, NodeType, Enterprise, ZipCode, Address, City, Province, Nation, Region, Continent, RoadAccess, RailAccess, SeaAccess, AirAccess, GeoArea		12234
Crop	EnterpriseCode, NodeCode, NodeType, NodeName, Enterprise, ZipCode, RoadAccess, ThroughputCapacity, Power, EnergyReq, WaterReq, CO2, Turnover, AgroProfile, SoilProfile, ClimateProfile, GeoArea		> 1000
ProcessingPlant	EnterpriseCode, NodeCode, NodeType, NodeName, Enterprise, ZipCode, RoadAccess, RailAccess, ThroughputCapacity, Power, EnergyReq, WaterReq, CO2, Turnover, WHPProfile, LayoutProfile, GeoArea		> 100
StorageFacility	EnterpriseCode, NodeName, Enterprise, Zipcode, RoadAccess, RailAccess, StorageCapacity, HandlingCapacity, Power, EnergyReq, WaterReq, CO2, Turnover, WHPProfile, LayoutProfile, PlantProfile, BmHeight, BmDepth, BmLayer, UIBmLayer, RackLevel, BeamCode, ColumnCode, CrossCode, FwLevel, UICode, GeoArea		> 500
Market	EnterpriseCode, NodeCode, NodeType, NodeName, Enterprise, ZipCode, RoadAccess, TotalDemand, GrossMarket, Market, ConsumptionPoint, GeoArea	Logistic	> 10000
Port	NodeCode, NodeName, NodeType, City, Province, Country, Region, Continent, TotalArea, RailLength, QuayLength, Cranes, Employees, Vessels, Capacity, Throughput, MaxDraught, StorageArea, Totalterminals, Cruises, DryBulk, LiquidBulk, GeneralCargo, Oilpipe, DryAgroBulk, LiquidAgroBulk, TransshipmentFraction, EUNorthernArea, EUSouthernArea, MediterraneanArea, ConnectionRail, ConnectionRoad, ConnectionMatirime		214
Terminal	NodeCode, PortCode, TerminalCode, Type, Name, ProductCategory, Throughput, Period, Cranes, StraddleCarriers, Forklift, PortTruck, PipePlugs, ReeferPlugs, VesselBerths, RailTerminal, Reachstackers, VesselCapacity, Area, StorageCapacity, throughputRate, LoadingRate, UnloadingRate, Temperatresotrage, CoolStorage, FrozenStorage		241
Multimodal Hub	NodeCode, Nodename, NodeType, City, TotalArea, RailLength, Employees, StorageArea, StorageAreaTemp, TotalTerminals, DryBulk, LiquidBulk, GeneralCargo, OilPipe, DryArgoBulk, EUNorthernArea, EUSouthernArea, MediterraneanArea, ConnectionRail, ConnectionRoad, ConnectionMaritime, FixedCranes, MobileCranes, FloatingCranes		48
Rail Connection	ConnectionCode, Destination, Enterprise, Frequency, TravelHours, NodeCode, NodeName		259
Order	OrderCode, Category, ShipmentCode, NodeCode, NodeCodeTo, DeliveryDate, PdkQuantity, PdkWeight, PalletQuantity, Parts, TransportationModeCode, Load, Description, ShipmentCode, UnloadCode		>> 300000
Product	ProductCode, ScientificaName, FoodCode, Category, Name, Variety, Brand, Enterprise, DOP, IGP, IGT, DOC, DOCG, Energy, Edibility, Water, Protein, Lipid, Cholesterol, Carbohydrates, Amid, Sugar, Fibre, Alcol, Sodium, Potassium, Iron, Calcium, Selenium, Tiamin, Riboflavin, VitaminA, VitaminB, VitaminC, VitaminE, EthyleneProduction, EthyleneSensibility, ColdSensibility, HarvestPeriod, Certification, OptimalStorageTemperature, OptimalStorageRh, MaximumShelflife, PackageCode		525
DemandNode	ProductCode, NodeCode, Period, Quantity, Udm		1663340
Shelflife	ProductCode, TempMin, TempMax, Name, Type, RhMin, RhMax, ShelfLifeMin, ShelfLifeMax		614
Price	ProductCode, Node, Period, Type, ProductName, Variety, Country, region, City, PriceGrossMarket, Udm, Week, BeginDate, EndDate, Month, Market, ShopVariancy, DiscountVariancy, LargeRetailerVaiancy, PublicMarketVariancy, RetailerVariancy		42474
Shipment	TransportationCode, ShipmentCode, NodeName, NodeCode, NodeCodeTo, ProducerCode, ShipperCode, CarrierCode, ImporterCode, CustomerCode, ContainerType, ContainerSize, ProductCode, CartonQty, UnitLoadQty, OriginPort, DestinationPort, DepartureDate, ArrivalDate		78
TransportationMode	TransportationCode, TransportationName, TransportationType, VehicleName, Description, Class, LicenceRequired, VehicleLenght, VehicleWidth, LoadHeight, WeightCapacity, GrossTonnage, Co, Hc, Nox, Pm, Ch4, N2O, Nh3, SO2, CO2, CO2Eq, FuelConsumption, EnergyConsumption, TransportationCost, ContainerQuantity, VehicleQty, AvgSpeed, MaxDistance	On-field Data	40
Package	PackageCode, ProductCode, PackageName, PackageType, PackageLevel, Firm, Shape, ProductWeight, PackageLength, PachageWidth, PAcageHeight, Udm, Cork, Sleever, Material, color, Weight, Barcode, PackagePrimary		30
UnitLoad	UnitLoadCode, UnitLoadLenght, UnitLoadWidth, UnitLoadHeight, unitLoadWeight, Material		25
Enterprise	EnterpriseCode, NodeName, Group, Enterprise, NodeType, Importer, Exporter, Grower, Distributor, Address, Zipcode, City, Province, Region, Nation, Continent		9601
ShipmentProfile	ShipmentCode, Ibutton, DatePeriod, Position, Temperature, ThermalKit, ContainerCode, Sampling, ShipmentCode, NodeName, NodeCode, NodeCodeTo, TransportationCode, EnterpriseCode		78
Analysis	SimulationCode, ShipmentCode, ProductCode, TotalSulphurousDioxide, FreeSulphurousDioxide, OpticDensity420nm, TotalAcidity, VolatilAcidity, PhenolicAcid, SO2Free, SO2Total, ColorIntensity, SmellIntensity, TasteIntensity, Shipment, Ibutton, DatePeriod		4
Simulation	SimulationCode, ShipmentCode, Product, SimStart, SimEnd, SmplingPeriod, Samplingtime, TempOffset, RhOffset, TempCurrent, RhCurrent, Shipment, Ibutton, DatePeriod		12
ClimateProfileMonitoring	GlobalRadiation, Precipitation, RelativeHumidity, StationInfo, SunshineFraction, SunshineHours, TempAver, TempDayTime, TempMeanMax, TempMeanMin, TempNihfTime, VapourPressure, WindSpeed		12456
SoilProfileMonitoring	Demand, DewPoint, Distance, Ea_ed, EnergyCost, Eta, GeoArea, InfrastructureCost, LaborCost, Land, LandUse, LogisticsCost, Node, OutputFlow, OutputLand, PET, Product, Rse, Soil, Transportation, Use, UseProductLimit, UseProductPercentage, UseProductRate, WaterRetention, ym		19978

Table 2. Database fields, abstraction levels (AL), and collected records.

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	NO _x	(kg/year)	11,828.91	11,492.32	-3%
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	SO ₂	(kg/year)	3432.387	3431.876	n.s.
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Table 3. What-if analysis with the Company testbed.

Conceptual
Framework

Fig. 1. Framework goals, boundaries and decision-flow

Geographical level

Logistics level

On-field level

Fig. 2. Framework entities

Fig. 3. Database E-R diagram.

Fig. 4. Tool GUIs: Overviewing the high-level FSC records with a GIS.

Fig. 5. Tool GUIs: Inferring data across different abstraction levels

Entities	Values	UoM	Network Map	Legenda
Network nodes	28			<p>Supplier</p> <p>Distributors storage facility</p> <p>Customer</p>
Supplier	9			
Multimodal hubs	3			
Products	10			
Orders/Time horizon	2074			
Time horizon of analysis	12 Months			
Avg distance between ports	4730 km			
Avg distance between hubs	2120 km			
Avg travelling distance per route	670 km/route			
Avg Emission CO2 eq per shipment	279 kg/shipment			
Total travelling (roadway)	761,994 km			
Total km (seaway)	1,405,709 km			

Fig. 7. Company's network features and map.

Fig. 8. Customer demand for oranges, peaches and apples in German markets.

Fig. 9. Tool GUIs: Company testbed

Highlights

This paper:

- is developed within the European Union and Mediterranean Project FUTUREMED;
- presents a framework for the implementation of data-driven analyses in sustainable food operations planning and management;
- addresses micro and macro aspects of the FSC and provides a hierarchical data architecture, incorporated within a tailored decision-support platform;
- supports the design and planning of sustainable food production and distribution activities;

The illustrated database and tool:

- are validated with a case study of an Italian fruit trader considering opening a warehouse to serve new markets.