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Fresh food sustainable distribution: cost, delivery time and carbon footprint three-objective optimization

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ABSTRACT

This paper presents a three-objective distribution planner to tackle the tactical optimization of fresh food distribution networks considering operating cost, carbon footprint and delivery time goals. The developed expert system overcomes the widely adopted methodologies mainly focused on the cost minimization only. These three independent goals are jointly included in a unique tool, called Food Distribution Planner, to support the tactical planning of multi-modal distribution networks of perishable produces.

This expert system implements a three-objective linear programming model, considering the typical food distribution constraints, i.e. the food quality dependence on the delivery time, the geographically distributed market demand and the farmer production capacities.

This paper further applies the proposed system to a real case study dealing with the distribution of fresh fruits and vegetables from a set of Italian producers to several European retailers. The most effective distribution network is studied best balancing the economic, environmental and delivery time objective functions. Such a tactical network planning leads to 9.6% CO_2 emission reduction with 2.7% cost increase compared to the correspondent single-objective configurations. Finally, the delivery time allows no produce waste due to the food quality preservation during shipment.

1. Introduction

The aim of distribution network (DN) optimization is to study the most effective way to ship products from the supply centers to the demand points facing the related decisions (Manzini et al., 2008), e.g. the allocation of the market demand to the producers considering their production capacity (Apaiah and Hendrix, 2005), the shipment mode choice (Eskigun et al., 2005) and the distribution center utilization (Cheng and Tsai, 2009; Ioannou, 2005).

Traditional DN optimization goal is to design and plan the network minimizing its total cost (Amiri, 2006; Goetschalcks and Fleischmann, 2008). In the last fifteen years, an increasing number of Authors suggested the environmental sustainability as a further relevant DN feature, proposing the so-called sustainable supply chain pattern (Chaabane et al., 2012; Dekker et al., 2012; Seuring and Müller, 2008). Several indicators quantify the DN sustainability level (Jain et al., 2013). Among them, the carbon footprint measures the amount of *equivalent* carbon dioxide ($CO_{2\,EQ.}$) emissions directly and indirectly caused by a certain activity. The previous term *equivalent* refers to the amount of carbon dioxide with the same global warming potential of the mixture of greenhouse gases (GHG) emitted by the considered activity (Solomon et al., 2007). Rizet et al. (2012) use this indicator to estimate the emissions related to the transport activities of different DNs in three European countries. Cholette and Venkat (2009) estimate the carbon emissions from the wine distribution in the United States, whereas Roy et al. (2008) consider tomato distribution in Japan.

The latest DN trends suggest the delivery time as a third relevant aspect for the DN design (Cheng and Tsai, 2009; Cheshmehgaz et al., 2011). Delivery time is affected by both the shipment mode and the DN configuration. The faster the shipment mode and the shorter the DN chain, the lower such a value is (Chopra, 2003).

Cost, environmental sustainability and delivery time are fundamental criteria for the DN strategic design, tactical planning and operational management. Nevertheless such criteria frequently diverge so that effective trade-offs become necessary. To face the DN configuration issue, considering more than one performance driver, multi-objective optimization (MO) is of help (Moncayo-Martínez and Zhang, 2011).

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Several Authors adopt MO DN models proposing economic and environmental objective functions (OFs). Ramudhin et al. (2009) and Chaabane et al. (2011) propose a MO mixed integer linear programming (MILP) model to estimate the cost and the GHG emitted by both the delivery and the production phases. Concerning the produce shipment from the suppliers to the demand points, Paksoy et al. (2010) evaluate different shipment modes to reduce the delivery cost and the related emissions. Finally, Xifeng et al. (2013) firstly join cost, environmental impact and delivery time OFs in the same tri-objective DN model and recommend further studies in such a direction.

Fresh food DNs (FFDNs) differ from the traditional DNs because of the peculiarities of the food produces toward manufacture goods (Manzini and Accorsi, 2013). The fresh food quality is not constant over the produce lifetime. It frequently decreases rapidly reaching a value of zero after the so-called shelf life (Osvald and Stirn, 2008). Thus, fresh food quality assessment necessitates produce traceability (Regattieri et al., 2007). Traceability is the ability to follow a produce through all the stages of production and distribution (Bevilacqua et al., 2009; Thakur et al., 2010). Tracing food quality requires a set of information to be evaluated (Storøy et al., 2012), e.g. the visited DN nodes, the used transport modes and the related transport duration.

Presenting an in-depth review of the literature, Ahumada and Villalobos (2009) note that several papers deal with the modeling of FFDNs. As example, Rong et al. (2011) develop a MILP model aimed at guaranteeing the produce quality for consumers. Ahumada and Villalobos (2011) include the perishability in the of their revenue maximizing model. Produce selling price is discounted by a factor proportional to the produce residual shelf life. Furthermore, Vanek and Sun (2008) suggest an energy minimizing model that considers both the shipment and the perishable produce production. These Authors propose to ship an additional produce quantity to guarantee the consumer demand satisfaction, due to the produce deterioration.

In parallel, wide research is done on the analysis of the food consumption trends and the food choice decisions. The most recent evidences highlight a rising attention to the food supply chain environmental management close to the preference to safety and healthy food (Sobal and Bisogni, 2009; Kearney, 2010). Consumer behavior while shopping food includes the collection of a wide range of information. High attention is paid on the shelf life, the origin, production and distribution standard and the nutritional properties, next to the price, driving the final choice. Food package is among the key source to collect such data (Eldesouky et al., 2015).

Due to the relevance of the topic, several Authors propose innovative software tools to help the practitioners with the DN design and tactical planning (Figueira et al., 2015; Hu et al., 2009; Kengpol, 2008; Moynihan et al., 1995). These decision support system aim is to integrate a wide set of decisions that typically have to be handled by the distribution planners (Manzini, 2012). The traditional DN criteria included in these tools deal with the market demand allocation to the producers, the transport mode choice and the vehicle routing (Manzini et al., 2011a; Manzini et al., 2011b). No decision support system proposed by the literature considers the product perishability during the transport. A distribution planning tool customized to FFDNs has to consider both the traditional DN design criteria as well as the food produce specific features (Manzini et al., 2014).

Starting from this background, this paper proposes an innovative expert system, called Food Distribution Planner (FDP), based on a three-objective linear programming (LP) model for the FFDN tactical planning considering both the perishability of fresh food and the possibility of multi-modal transports. The FDP aims to minimize the operating cost, the carbon footprint and the delivery time. Its distinctive features are the following.

- *Food perishability*: a quality function describes the produce shelf life to evaluate the quality decrease over the transport time and the related market purchase probability;
- *Multi-modal transport*: the system manages three possible transport modes (truck, train and airplane) for both mono- and multi-modal shipments;
- *Multi-level distribution network*: the considered FFDN includes producers, first stage and second stage intermodal hubs (IHs) and retailers as possible network nodes;
- *Multi-product*: a mix of produces with their own features is considered (shelf life, production costs and environmental emissions).

According to the introduced topic, the remainder of this paper is organized as follows. The next Section 2 presents the FDP system architecture. Section 3 describes the DN for food produces, while Section 4 applies the proposed FDP system to plan a European FFDN. Section 5 illustrates the key results and, finally, Section 6 ends the paper with key conclusions and it suggests further research opportunities.

2. Food distribution planner system architecture

FDP is an expert system whose aim is to support the tactical planning of FFDNs to transport perishable produces within a multimodal network. Its architecture is made of three functional modules (see Fig. 1).

- *INPUT*: the user describes the food distribution problem with information about the produce features (perishability, production cost and environmental impact), the food producers

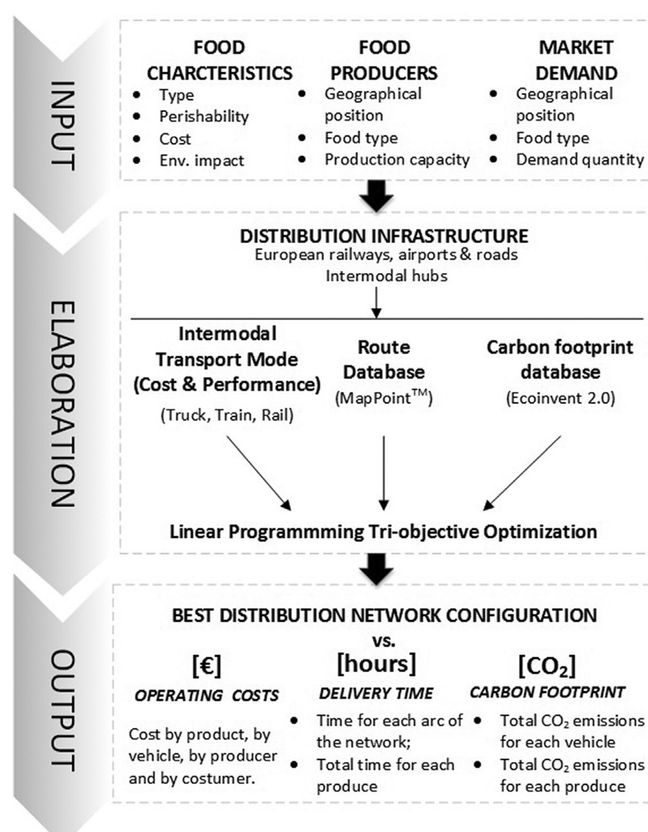

Fig. 1. FDP architecture.