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Modelling food logistics networks with emission considerations: The case of an international beef supply chain

M. Soysal *, J.M. Bloemhof-Ruwaard, J.G.A.J. van der Vorst

Operations Research and Logistics Group, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands

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ABSTRACT

Intrinsic characteristics of food products and processes along with growing sustainability concerns lead to the need for decision support tools that can integrate economic considerations with quality preservation and environmental protection in food supply chains. In this study, we develop a multi-objective linear programming (MOLP) model for a generic beef logistics network problem. The objectives of the model are (i) minimizing total logistics cost and (ii) minimizing total amount of greenhouse gas emissions from transportation operations. The model is solved with the ε-constraint method. This study breaks away from the literature on logistics network models by simultaneously considering transportation emissions (affected by road structure, vehicle and fuel types, weight loads of vehicles, traveled distances), return hauls and product perishability in a MOLP model. We present computational results and analysis based on an application of the model on a real-life international beef logistics chain operating in Nova Andradina, Mato Grosso do Sul, Brazil and exporting beef to the European Union. Trade-off relationships between multiple objectives are observed by the derived Pareto frontier that presents the cost of being sustainable from the point of reducing transportation emissions. The results from the pie chart analysis indicate the importance of distances between actors in terms of environmental impact. Moreover, sensitivity analysis on practically important parameters shows that export ports' capacities put pressure on the logistics system; decreasing fuel efficiency due to the bad infrastructure has negative effects on cost and emissions; and green tax incentives result in economic and environmental improvement.

1. Introduction

The progressive increase of food consumption due to growing world population and wealth stimulates higher food production. A recent way for managing the increased production is globalization of food supply chains (FSCs) with the help of improvements in transport technologies, cheaper transportation, reductions in tariffs and other barriers to trade. Globalization has improved the chance of profitability from cross-border operations as well; however it has led to increased distances between partners in supply chains (Elhedhli and Merrick, 2012). The increased distances have enhanced the strategic importance of logistics network decisions such as selection of suppliers, distribution channels and transportation modes, determining production and inventory amounts at each plant and allocation of products (Cordeau et al., 2006; Harris et al., 2011). The need for a well organized logistics network thus has increased in the food sector, which is producing more than ever on a global scale.

Traditional logistics management considers mainly two key logistical aims, cost reduction (efficiency) and improved responsiveness, while dealing with the logistics network problem. However, intrinsic characteristics of food products and processes such as product perishability and food quality, and a growing sustainability trend require extension of the key logistical aims with quality and environmental considerations. This necessity leads to the need for decision support tools that can integrate economic considerations with quality preservation as well as environmental protection in FSCs. Accordingly, literature review shows that there is a need for models that are able to deal with the key challenges in managing quality and sustainability (Akkerman et al., 2010; Soysal et al., 2012). The need in practice and in research forms our main motivation to develop a model that allows to consider perishability of goods and emissions from transportation operations along with cost concerns in food logistics network.

We take the beef sector as a representative of a food supply chain that has both food and environment related challenges. Shelf life for beef that includes several quality factors (e.g. juiceness, tenderness, nutritive value, appearance and palatability) puts an additional pressure on logistics decisions, since the product may become undesirable, even it is not unsafe (Delmore, 2009). Apart

* Corresponding author.
E-mail address: mehmet.soysal@wur.nl (M. Soysal).

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from quality concerns, appreciation grows for the idea of a carbon-constrained economy in the livestock sector with the growing awareness towards environment conservation (Robinson et al., 2011). Especially, transportation is one of the main sources of livestock related carbon dioxide (CO_2) emissions (Delgado et al., 1999) and increasing global beef trade results in more fuel consumption for beef related transportation. Therefore, it is wise to address product perishability and emissions from transportation while managing beef logistics chains.

We develop a multi-objective linear programming (MOLP) model for a generic beef logistics network problem. The objectives of the model are (i) minimizing total logistics cost and (ii) minimizing total amount of greenhouse gas (GHG) emissions from transportation operations. Duration of inventory keeping is limited due to the perishability nature of the product. The environmental effect of freight transportation is measured in CO_2 emissions. We provide a case study of the international beef logistics chain operating in Nova Andradina, Mato Grosso do Sul, Brazil and exporting beef to the European Union (EU) to illustrate the applicability of the proposed model for real logistics systems. The rationales for the selected beef chain are the following: (1) Brazil ranks as the largest beef exporter in the world by holding an approximately 21% share of the global beef trade in 2011 (Abiec, 2012d), (2) Brazil has potential to keep its position in the global market, and (3) Beef trade relationship exists (47,693 ton for fresh-chilled beef in 2010) between Brazil and the EU (Abiec, 2012a, 2012b). In this case study, we put the main focus on road transportation, which is the only delivery option till the export ports, as rail, inland ship or air need infrastructure that is not available yet. The logistical challenges in the case of Brazil are mainly related to usage of old trucks, inefficient road infrastructure or deficiency of available trucks.

The structure of the remaining paper is as follows. Section 2 presents a literature review on logistics models that take product perishability and/or emissions into account. Section 3 presents a formal definition of the generic problem, the methodology used for emission estimations and the proposed MOLP model for the generic beef logistics network problem. Section 4 presents the case study description, data gathering and the computational analysis of the model. The last section presents conclusions and directions for further research.

2. Literature review

The logistics network problem that has transportation and inventory decisions under capacity constraints for a multi-period planning horizon has been widely studied in the literature (see Ahn et al., 1994; Bilgen and Gunther, 2010; Verderame and Floudas, 2009). However, quality degradation of products puts additional challenges on logistics decisions in food sector. Literature review studies present the state of the art in product perishability consideration in FSCs (Ahumada and Villalobos, 2009; Akkerman et al., 2010; James et al., 2006; Soysal et al., 2012). As pointed out in these studies, the number of proposed decision support tools which are able to control products according to their quality levels has been increasing in recent years (e.g. Bosona and Gebresenbet, 2011; Rong et al., 2011; Wang et al., 2010; Ahuja, 2007). Ahuja (2007) controls the quality of products by constraining the number of periods that a good is stored at a facility. In this study, we use this approach to account for the perishable nature of beef.

Similar to raising awareness on quality decay, sustainability is an emerging area in FSCs (Akkerman et al., 2010; Seuring and Muller, 2008). The main reasons for the growing interest are stakeholder pressure and the need for adopting increasing environmental regulations. GHG emissions reduction, the most prominent environmental issue in practice, is one of the most significant sustainability objectives considered in logistics management literature (Soysal et al., 2012). Researchers have developed quantitative logistics models that can manage economic issues along with emission controls in response to the need for practice. Literature search is carried out within Thomson Reuters (formerly ISI) Web of Knowledge and followed by reference and citation analysis to find related contributions that have quantitative models with emission consideration for logistics management. We investigate the models with respect to main characteristics (Table 1) summarized below:

- *Model type*: Mixed Integer Linear Programming and Multi-Objective (Non)Linear Programming approaches are the most used modelling types.
- *Decisions*: The main logistical drivers in a supply chain are production/processing, transportation and inventory management decisions (Chopra and Meindl, 2010). The reviewed models manage one or more of the aforementioned decisions. All models aim to reduce emissions from transportation. Additionally, some studies consider emissions from production/processing and/or inventory holding together with transportation emissions.
- *GHG emissions calculation approaches:* The crucial stage during model development is calculating emissions from predetermined emission sources. Researchers employ basically two approaches to measure the emissions from transportation operations. First approach, which is preferred most, is using fixed emission or environmental impact factors per distance unit and/or per weight unit (e.g. Chaabane et al., 2008; Wang et al., 2011), per product (e.g. You et al., 2012), per vehicle (e.g. Paksoy et al., 2011b), which are obtained through other environmental studies. The second approach is estimating emissions indirectly by calculating total energy consumed from transportation operations while considering the aforementioned parameters such as distance, speed or weight (e.g. Bektas and Laporte, 2011; Bauer et al., 2010). For production and inventory related emissions, either fixed emission factor per unit produced or stocked (e.g. Oglethorpe, 2010) or energy consumption from production and/or inventory related operations is considered (e.g. Abdallah et al., 2012).
- *GHG consideration*: Studies in the literature either take only CO_2 gas emissions (e.g. Bauer et al., 2010) or group emissions of different GHG gases, such as CO_2, CH_4, and NO_x, together in a single indicator in terms of carbon dioxide equivalent (CO_2eq) emissions (e.g. You et al., 2012).
- *Application area*: Researchers implement the proposed models on different areas such as automotive, steel and plastic waste.

We found three quantitative models that manage product perishability while considering GHG emissions (Akkerman et al., 2009; Van der Vorst et al., 2009; You et al., 2012). Among these studies only You et al. (2012) propose a MOLP model that can be used to gain insight in the trade-off between multiple objectives. In contrast to that study, we also consider the effects of return hauls on transportation cost and emissions. Furthermore, we adopt a different methodology based on a distance-based formulation, Defra (2005), to estimate road transport emissions. Under this methodology, road structure, vehicle and fuel types, weight loads of vehicles and traveled distances are taken into account. This approach has been also used by Harris et al. (2011), who integrated the approach into a simulation model without considering perishability and return hauls (see Table 1). Therefore, this study breaks away from the literature on logistics network models by simultaneously considering the aforementioned issues.