Yakavenka, Volha

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Volha Yakavenka, Ioannis Mallidis, Ioannis Siamas, Dimitrios Vlachos
Mechanical Engineering Department
Aristotle University of Thessaloniki, Greece
olgushaya@gmail.com, siamasgr@hotmail.com, imallidi@auth.gr, vlachos1@auth.gr

Eleftherios Iakovou
Engineering Technology and Industrial Distribution Department,
Texas A&M University, Texas, US
eiakovou@tamu.edu

Abstract
The economic modifications along with the rapid demographic growth of the last century have led to the increased significance of effective supply chain management strategies for ensuring food security and safety. Due to the fact that 50% of food produced annually is perishable, the growing and geographically dispersed consumers' demand can only be served through well-designed cold supply networks that manage perishable commodities. The consideration of product perishability in the design of multi-echelon supply chain adds additional complexity to the decision-making process, as time now plays an important role in the preservation of the product's quality. In this respect, responsive supply chains should be developed that employ fast and reliable transportation modes. At the same time, the consideration of the supply chain's environmental impact and economic viability should be also incorporated in the decision-making process. Under this perspective the purposes of this paper are: (i) to identify the parameters, and the distinctive characteristics of supply chains of perishable goods that differentiate them from classical supply networks and raise the need for special managerial capabilities, (ii) to propose a modelling methodology employed for the cost and CO_2 emissions optimal design of multi-echelon supply chains, while incorporating the shelf life of the chain's products in the decision-making process. The applicability of the proposed model is illustrated in the realistic case of a supply chain connecting the South-Eastern with the North-Eastern European regions.

Keywords: cold supply chain, perishable goods, network design, methodology

JEL classifications:

1. Introduction

According to the World Health Organization, the demand for basic foodstuffs doubles every 30 years and a significant part of the world's population receives only 75% of the daily dietary norm. Therefore, food security is one of the biggest problems that humanity faces now and will face in the future. Moreover, the supply of the population with food products rich in vitamins is an important task. The satisfaction of the population's demand in fruits and vegetables is carried out by local agricultural production and imports. The second way is particularly relevant for countries that are geographically located in the north of the tropics. Their climatic conditions do not allow to cultivate many kinds of fruits. The attempts to grow them lead to multiple increases in energy consumption requirements, greater amounts of fertilizers that can cause irreversible degradation of natural resources, soil depletion and serious environmental pollution. Therefore, the imports of fruit for the majority of countries located in the middle and northern latitudes, has become one of the main sources of vitamins' replenishment in the national diet.

Nevertheless, distances between the different regions of the world still play a crucial role in logistics of temperature sensitive products where time and delivery conditions are an issue of special importance. The minimization of delivery time is one of the main problems in the transport of fresh fruits since their prices decrease over time that has a negative economic impact on all the participants of supply chain. In order to partially address this issue, refrigerated carrier units (trucks, containers, wagons) are employed which along with the appropriate facilities (refrigerated warehouses, distribution centers, loading/unloading units) aim at sustaining the perishable product's freshness. However, the rising transportation volume is associated with the growing level of environmental externalities such as: CO_2 emissions of transport modes, emission from electricity usage by refrigerators and refrigeration units, coolant leakages, waste from expired items etc. It is widely known that refrigeration is the biggest contributor of carbon emission in cold supply chain. According to (FAO, 2011) shipping can account for up to 45 percent of the energy consumed to export fresh fruit while refrigerated storage and during transportation can account for up to 10 percent of the total food supply carbon footprint (Cleland, 2010). Numerous studies in recent years focus on the emissions generated in different echelons of the supply chain (James & James, 2010; Dekker et al., 2012; Chaabane et al., 2012). James & James (2010) identified a mutual effect of cold chain and climate change: climate change influences the cold chain through rising in average world temperature, which increases the energy consumption for refrigeration systems. On the other hand, the generation of this energy and loss of refrigerant contribute to CO_2 production and global warming. Thus, climate change increases linkages between energy and temperature controlled supply chain where different transport modes have their own performance levels and represent a compromise between speed and energy consumption per unit of mass being transported.

Therefore, cold supply chain network design decisions along with the traditional problem of the identification of the optimum configuration of the network based on its total cost minimization should also consider the environmental aspect and products' expiration date limitation. Under this context, the purpose of this paper is to propose a modelling methodology for the optimal design of multi-echelon sustainable supply chains while incorporating the shelf life duration limitations of the supply chain's products in the decision-making process. The consideration of the product's shelf life duration is regarded by the identification and the further exclusion of the network's routes and associated modes from the network's structure at stake. While the design process itself is accomplished through the development of the classical Mixed Integer Linear Programming methodology.

The rest of the paper is organized as follows. In Section 2 we present the literature review. Section 3 presents the proposed methodological framework for designing cold supply chain networks, while Section 4 presents the Mixed Integer Linear Programming methodology. Section 5 illustrates the applicability of the model through a specific case study in the South-Eastern and North-Eastern European regions. Section 6 discusses the outcomes. Finally, Section 7 sums up the findings of this research.

2. Literature Review

Over the past few years a plethora of studies concerning the supply chain distribution network design problems have been conducted. A lot of them elaborate on issues regarding the number, location, capacity and operation of distribution centers/production facilities in a generalized form

(Mallidis et al., 2012) and do not consider specific characteristics and conditions for transportation, storage and processing of perishable products within the network. However, it is impossible to devise a solution suitable for all kinds of supply chains and products. Not in vain a phrase "Chain of Thought" is applied for food supply chain and cold supply chain in particular (Estrada-Flores, 2008). Therefore, consideration of perishability in the supply chain management has received increased attention in research works (Govindan et al., 2014).

Transportation scheduling and routing decisions as well as allocation and inventory decisions have some differences in the cold chain and traditional supply chain. Consequently, some modification and changes in the current models, or development new models is required (Bozorgi et al., 2014), where one of the significant features of the cold chain models particularly the expiration date limitation should be considered (Voughan, 1994). Meanwhile, Apte (2010) underlines the great significance of time in the management of food supply chain. The author concludes that decision-makers should consider time in order to minimize fresh product supply chain network's vulnerability to disruption. Hence, transportation routing and modes selection decisions in relation to time windows are of high importance (Lemma et al., 2014).

Despite a considerable number of works regarding distribution networks that deal with the transportation and storage of temperature-sensitive products (Hsu et al., 2007; Broekmeulen et al., 2009; Minner et al., 2010; Jia et al., 2011) many of the proposed network design models ignore time limitations for distribution of such specific products within the network.

In this direction, Ahumada et al. (2011) propose an operational model with the objective of maximizing the revenues of the producer of perishable agricultural products. In this contest, the decision of using efficient transportation modes that provide the best trade-off between time to reach the market and cost are restricted by the product's shelf life constraint. Rong et al. (2011) present an MILP model that aims to minimize the total costs for the planning of food production and distribution with a focus on product quality, introducing the maximum planned transport lead time and storage time limits. Zhou et al. (2015) provide a multi-objective scheduling model aiming at maximizing the mean fractional remaining shelf life, minimizing total logistics cost and the fractional remaining shelf life deviation under given delivery time constraints for small volume perishable products. Firoozi et al. (2013) formulate and solve an integrated inventory location model for perishable commodities by investigating the effect of lifetime on the objective function that minimizes the total annual costs. The authors solve the model using a heuristic Lagrangian relaxation algorithm and setting a time constraint for the remaining of the product in the distribution center. Different other research works that focus on inventory and routing problems in addition to, or instead of, the cost function with respect to temperature-sensitive products and taking into account limited time window are conducted by Osvald et al. (2008), Olsson et al. (2010), Amorim et al. (2012), Kouki et al. (2013). Nevertheless, the environmental issues have been considered along with the cost for the supply chain and especially cold supply chain management research quite recently.

Actually, the work by James and James (2010) is the most recent comprehensive paper addressing cold supply chains and emissions specifically. A methodological framework for the design of green agrifood supply chains is presented by Iakovou et al. (2012), while a comprehensive critical review on sustainability issues in designing and operating of agrifood supply chain is studied by Tsolakis et al. (2014), as well as a literature review on sustainable supply chain management practices and their interlinks to dynamic capabilities in the food industry are conducted by Beske et al. (2014). The consideration of the environmental function as an objective function has been applied for different echelons of the cold supply chain including storage and transportation in recent studies. Specifically for cold items, Bozorgi[2] et al. (2014) develop a non-linear inventory model that considers holding and transportation unit capacities for the cost and emissions objective functions but neglects time limit conditions. Govindan et al (2014) propose a multi-objective optimization model to design a multi-objective sustainable supply chain network of perishable food with the dual aims of minimizing costs and environmental effects. For this purpose, a two-echelon multiple-vehicle location–routing problem with time windows is utilized.

Despite the fact that there are plenty of studies that examine the impact of time parameters on various supply chain management policies, there is a lack of integrated systemic approaches for the design of sustainable supply chains that incorporate the shelf lives of their products in their decision-making proves. Under this context, the contribution of this paper hinges upon the development of a two stage optimization approach, which captures the impact of the perishable products low shelf durations in the design of multi-echelon cold supply chains. In the first stage, the proposed methodology determines routes that lead to supply chain times higher than or equal to the supply chain's product shelf life duration. These routes are then excluded in the second stage design process of the examined network

3. System Description

We consider a multinational company that supplies a Market with products that are characterized by low shelf life durations (i.e. fruits, vegetables, etc.). We assume that the Market consists of a number of Regional Markets where the demand is allocated in the region's capital. All cargo is transported from one distant loading point in refer containers, into the market through a number of Entry Points located in the Market's borders, and then to centralized Distribution Centers established within the market's premises. Transportation from the loading point to the entry points, can occur by ship, rail and truck transportation, while from the entry points to the distribution centers and then to the retail stores by truck and rail transportation.

However, the design of such supply chains is constrained by the shelf life duration of the products distributed, leading to an increased complexity of the whole design process. To address this issue we propose a methodology that consists of a two-stage supply chain network design process. The first stage determines the routes of the supply chain, along with the associated transportation modes employed, which lead to total transportation and storage times that are higher than or equal to the examined products shelf life. These routes are then excluded from the examined network structure. In the second stage, the classical network design problem is addressed which decides on: (i) the selection of the entry points; (ii) the choice of transport means; (iii) the selection of the distribution centers; and (iv) the determination of the associated flows between the nodes of the supply chain under study. The optimization criteria are the supply chain's total transportation and DC operating costs and the network's total transportation and DC operating CO_2 emissions.

4. Optimization Model

The multi-echelon cold supply chain under study runs from a Loading Point (0) to an Entry Point $i \in EP$. From there to a Distribution Center $j \in DC$, onto a retail store $r \in RM$ with a mode of transport $m \in M$ (note that m can also incorporate a predetermined mode configuration, i.e. ship plus truck). The strategic design of such a supply chain is undertaken through a two stage optimization process summarized as follows:

Stage 1: Pre-process evaluation of time-infeasible routes

The first stage of the optimization process involves the identification of the routes, and associated transportation modes employed, that lead to a total transportation and storage time per container which is higher than or equal to the container's product shelf life. In order to tackle this, an algorithm is designed (i.e. in Matlab), that numerically determines the container's door-to-door transportation and storage time per route (from LP-EP-DC-RM) for each $(i \in EP)$, $(j \in DC)$, $(r \in RM)$, and $(m \in M)$. The routes that lead to a total door-to-door transportation time that is higher than or equal to the container's product shelf life are excluded from examined supply chain structure, leading to the following second stage optimization process.

Stage 2: Application of a Mixed Integer Linear Programming Model

The second stage involves the application of a Mixed Integer Linear Programming model, which investigates: (i) potential entry points i, (ii) locations of operating distribution centers j, (iii) employment of transportation modes m, and (iv) the number of container flows transported between the various nodes of the network under study. The optimization criteria involve the transportation, DC operating and pipeline inventory holding costs, and the transportation and DC operating CO_2 emissions.

Table 1: Decision Variables

Variable	Description
x_{0i}^{m}	Number of TEUs transported from node 0 (Loading Point) to node i (Entry Point) using transportation mode m=1,…,M.
x_{ij}^{m}	Number of TEUs transported from node i to node j (Distribution Center) using transportation mode m=1,…,M.
x_{jr}^{m}	Number of TEUs transported from node j to node r (Retail Store) using transportation mode m=1,…,M.

Table 2: Model Parameters

Parameters	Description
D_r	Total demand at regional market r.
C_{0i}^{m}	Cost of transporting a refer TEU from node 0 to node i using transportation mode m.
C_{ij}^{m}	Cost of transporting a refer TEU from node i to node j using transportation mode m.
C_{jr}^{m}	Cost of transporting a refer TEU from node j to node r using transportation mode m.
C_{j}^{dc}	Cost per refer TEU for refrigerated storage and deconsolidation/consolidation services at a distribution center (at node j).
e_{0i}^{m}	CO_2 emissions generated from transporting a refer TEU from node 0 to node i using transportation mode m.
e_{ij}^{m}	CO_2 emissions generated from transporting a refer TEU from node i to node j using transportation mode m.
e_{jr}^{m}	CO_2 emissions generated from transporting a refer TEU from node j to node r using transportation mode m.
e_{j}^{dc}	Emissions generated from refrigerated storage per TEU at a distribution center.

Tables 1 and 2 provide the nomenclature for the decision variables and the parameters of the model respectively. All data are expressed in a common time unit, unless specified differently.

Minimize Expected Total Cost per planning horizon:

$$\min \sum_{i\in EP}\sum_{m=1}^{M} c_{0i}^{m} \cdot x_{0i}^{m} + \sum_{i\in EP}\sum_{j\in DC}\sum_{m=1}^{M}(c_{ij}^{m} + c_{j}^{dc}) x_{ij}^{m} + \sum_{j\in DC}\sum_{r\in RM}\sum_{m=1}^{M} c_{jr}^{m} \cdot x_{jr}^{m} \quad (1)$$

Minimize Expected Total CO_2 Emissions per planning horizon:

$$\min \sum_{i\in EP}\sum_{m=1}^{M} e_{0i}^{m} \cdot x_{0i}^{m} + \sum_{i\in EP}\sum_{j\in DC}\sum_{m=1}^{M}(e_{ij}^{m} + e_{j}^{dc}) x_{ij}^{m} + \sum_{j\in DC}\sum_{r\in RM}\sum_{m=1}^{M} e_{jr}^{m} \cdot x_{jr}^{m} \quad (2)$$

Subject to
Flow Constraints:

$$\sum_{m=1}^{M} x_{0i}^{m} = \sum_{j\in \mathbf{DC}}\sum_{m=1}^{M} x_{ij}^{m}, \quad \forall i \in \mathbf{EP} \quad (3)$$

$$\sum_{i\in \mathbf{EP}}\sum_{m=1}^{M} x_{ij}^{m} = \sum_{r\in \mathbf{RM}}\sum_{m=1}^{M} x_{jr}^{m}, \quad \forall j \in \mathbf{DC} \quad (4)$$

$$\sum_{j\in DC}\sum_{m=1}^{M} x_{jr}^{m} = D_r, \quad \forall r \in \mathbf{RM} \quad (5)$$

Non Negativity Constraints:

$$x_{0i}^{m}, x_{ij}^{m}, x_{jr}^{m} \geq 0 \quad (6)$$

The Flow Constraints (3)-(5) guarantee the balance of inbound and outbound flows for each Entry Point, Distribution Center and Regional Market respectively. The developed model is an extension of a two-level (Entry Points and DCs) facility location problem, extended with extra objective functions and different transportation mode options. The model can be solved with most standard MIP solvers, e.g. Lingo_ depending on its size.

5. Case Study

In this Section, we implement the proposed methodology in the realistic case of a cold supply chain for the distribution of fruit (peaches) produced in South-East Europe and exported to the North-East Europe. This kind of perishable cargo is transported in refrigerated carrier units (trucks, containers, wagons) through a distribution network which consists of one Loading Point (LP) in Port of Piraeus (Athens, Greece), five potential Entry Points (EP) located in the suitable Market’s points that can be international ports or other major transportation nodes (namely Riga (Latvia), Klaipeda (Lithuania), Gdansk (Poland), Brest (Belarus) and Chornomorsk (Ukraine)). For carrier units deconsolidation purposes one large central Distributional Center in Minsk (Belarus) is considered. From there trucks transport the orders to the retail stores that is established in capital cities of the four Regional Markets (RM) (namely Riga (Latvia), Vilnius (Lithuania), Warsaw (Poland) and Regions of Belarus). Figure 1 illustrates the cold supply chain network under study. The filled circle represents the Loading Point in Athens, the triangles represent the Entry Points in Riga, Klaipeda, Gdansk, Brest, Chornomorsk, the square represents the Distribution Center in Minsk, the hollow circles represent the Regional Markets in Riga, Vilnius, Warsaw and Regions of Belarus.

Figure 1: The Cold Supply Chain Network Under Study

6. Results

The developed model consists of 43 variables, 12 constraints and 114 non zeros and was solved via the Lingo 9 Solver. The solution methodology initially encompasses the pro-process that excluded the following routes, which lead to a total supply chain time which is higher than or equal to the product's shelf life. These routes are summarized in the following Table 3.

Table 3: Excluded Routes Through the Pre- Process

LP	EP	DC	Mode LP-EP	Mode EP-DC
Athens	Riga	Minsk	Ship	Truck
Athens	Gdansk	Minsk	Ship	Truck

- Note that all the RMs are served by Minsk DC by truck solely.

The next step in the solution methodology involves the implementation of the Mixed Integer Linear Programming model for deriving the optimal distribution structures with respect to cost and CO_2 emissions minimization objectives. These distribution structures are summarized in Table 4.

The cost efficiency of the first distribution network in Table 4 is mainly due to the relatively cheaper ship transportation from Athens LP to Klaipeda EP while the CO_2 emissions efficiency of the second distribution structure, is due to the CO_2 emissions efficient rail transportation employed from Chornomorsk EP to the operating DC in Minsk. Finally, the time efficiency of the third distribution structure is due to the employment of truck transportation both from the LP to the EP and from the EP to the DC.

Table 4: Optimal Cost and CO2 Emissions Distribution Structures

Optimiz. Criterion	LP	EP	DC	Mode LP-EP	Mode EP-DC
Cost	Athens	Klaipeda.	Minsk	Ship	Truck
CO_2	Athens	Chornom.	Minsk	Truck + Short Sea Shipping	Rail
Faster Route	Athens	Brest	Minsk	Truck	Truck

The final step of our analysis involves the identification of the total supply chain (SC) costs, CO2 emissions and times under the three optimization criterions.

Table 5: Optimal SC Cost, CO2 emissions and Time under the three Optimization Criterions.

Optimization Criterions	Cost mil. €/year	CO_2 emissions thousands of tons/year	Average Time (Days/shipment)
Distr. Network #1	143.6	125.7	17.4
Distr. Network #2	166.3	120.8	9.4
Distr. Network #3	179.2	163.8	7.3

The results depicted in Table 5 indicate that even though the traditional distribution structures in these areas employ truck transportation and enter the market through the EP of Brest, there seems to be an alternative distribution structure, the CO_2 emissions optimal, which balances cost and time efficiency.

7. Conclusions

This paper deals with design of the multi-echelon supply chain structure of products with low shelf lives, by proposing a two stage optimization process for incorporating the products shelf life restrictions in the supply chain's design process. The first stage involves a pre-process evaluation of the routes that lead to total supply times that are higher than or equal to the products shelf lives. These routes will be then excluded from the supply chain structure under study which we aim to optimally design. In stage 2, we propose the classical Mixed Integer Linear Programming methodology which decides on:(i) the selection of the entry points; (ii) the choice of transport means; (iii) the locations of the operating DCs (iv) the determination of the associated flows between the nodes of the supply chain, under total supply chain cost and CO_2 emissions minimization objectives. The proposed methodology was employed in the case of a fruits importer in the North-Eastern European region, and the main outcome derived indicates that the CO_2 emissions optimal solution also provides time and cost efficient solutions.

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