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GREENING SUPPLY CHAINS: IMPACT ON COST AND DESIGN

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Abstract

The consideration of environmental issues has emerged as a topic of critical importance for today's globalized supply chains. The purpose of this paper is to develop a strategic-tactical decision-support methodology to assist managers in evaluating the impact of environmental issues, related to transportation emissions, on the transport geography of a region. Specifically we provide a tool that addresses: (i) supply chain network design, including port of entry and transportation mode, and (ii) decisions on leasing vs. outsourcing of transportation and distribution centers. The applicability of the proposed methodology is examined through the development of a sustainable supply chain network in the South-Eastern Europe region. The results indicate that in most cases outsourcing distribution centers to Third Party Logistics operators improves both the cost and the environmental performance of a company. In all cases outsourcing of transportation operations minimizes the amount of CO_2 and PM emissions generated, while leasing minimizes costs.

Keywords: Supply Chain Sustainability, Carbon Footprint, Supply Chain Design.

1. Introduction

Liberalization of international trade has altered significantly the traditional landscape of global trade. It has resulted in the development of extensive and complex supply chain networks that connect distant production points with various demand points around the world, transforming therefore the geographical attributes of freight. Cost minimization of supply chain operations is undeniably the most important objective for supply chain network design today. Large container vessels, port facilities, distribution centers, as well as block trains and barges, are utilized in order to minimize transportation and storage costs per unit through the exploitation of economies of scale. However intense supply chain activities have resulted in the release of large amounts of greenhouse gasses and Particulate Matters (PM, also called fine dust) emissions affecting climate change and human health. Governmental initiatives such as the Kyoto protocol, and numerous European Union action plans, such as (i) Freight Transport Logistics Action Plan, (2007), (ii) Greening Transport, (2008), (iii) Strategy for the internalization of external costs, (2008), (iv) A sustainable future for transport: Towards an integrated, technology led and user friendly system, (2009), etc., promote environmentally friendly transportation modes or the application of economic instruments such as fuel taxes and road tolls.

Therefore supply chain network design specialists that traditionally deal with the problem of selecting the optimum location of entry ports and distribution centers based on total network cost minimization should also consider environment aspects. Accordingly, the purpose of this paper is to examine the effect of environmental parameters on the geography of transportation systems. To this end we provide a detailed modelling methodology of a supply chain network design taking into account both cost and emissions minimization objectives. The employed tool is based on multi-objective mixed integer linear programming. The proposed methodology assists in identifying the cost-environmental tradeoffs, from either leasing or outsourcing distribution centers and transportation operations. The methodology also allows for utilizing alternative transportation routes, transportation means, and potential establishment of deconsolidation/consolidation nodes. The applicability of the proposed methodology is shown through an application in a specific supply chain of white goods in South Eastern Europe.

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 supply chain networks, while Section 4 presents the multiple objective decision making model. Section 5 illustrates the applicability of the model through a specific case study. Section 6 discusses the outcomes. Finally, section 7 sums up the findings of this research.

2. Literature Review

Supply chain network design incorporates strategic decisions on the number, location, capacity and operation of distribution centers/production facilities as also tactical decisions on the selection of the intermediate counterparties (suppliers, freight forwarders etc.) required, for a company to meet its goals regarding product delivery times and costs. Facility location decisions play a decisive role in supply chain network design. They affect significantly a company's choice regarding transportation modes and cargo volumes transported. To be more specific a company may exploit economies of scale in the transportation of inbound flows to the distribution centers through the utilization of block trains or barges, which can transport large cargo volumes per trip, minimizing the systems total cost. As a consequence many Facility Location Models see, Daskin et al., (2005), Melo et al., (2009), Drezner and Hamacher (2002), Klibi et al. (2010), have been proposed within the supply chain.

However, the incorporation of environmental aspects in supply chain design has only started recently. Below we list the most relevant contributions, being Li et al. (2008), Neto et al. (2008) and Ramudhin et al., (2009). Li et al., (2008) propose a bi-objective (profit maximization and emissions minimization objectives) mathematical programming methodology to optimize distribution center locations taking into consideration transportation costs and transportation/production carbon emissions. They investigate the impact of crude oil price changes on location decisions. Neto et al., (2008) propose a multi-objective programming model that optimizes both objectives (cost and environmental impact) simultaneously, identifying the trade-off between cost and environment. The environmental impact (from global warming, eco-toxidicity, photo-chemical oxidation, acidification, nitrification, and solid waste) is expressed as a single weighted measure and not as an absolute value, while the examined supply chain formulation does consider optimum locations of nodes involved. Finally, Ramudhin et al., (2009) develop a comprehensive framework for sustainable supply chain network design. They propose a multi–objective mixed integer linear programming model as a decision support tool for the selection of suppliers and sub-contractors, product allocations to sites, capacity utilization and transportation configuration as also decisions regarding the reduction of their supply chains carbon emissions on one hand or the purchase of carbon credits on the other.

Although numerous publications propose integer programming tools for supply chain network design, the novelty of our proposed methodology is the inclusion of (a) the emissions oriented objective, (b) the leasing or outsourcing decision process for transportation and facilities and (c) the inclusion of alternative routes for imports. Moreover, we provide a realistic case giving insight into the geographical changes by introducing environmental aspects in supply chain design.

3. Supply Chain Description

We consider a multinational company that aims to serve a specific geographical area (Market) trading various products with similar characteristics (e.g. white goods, furniture, 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 in containers originating from one Major Loading Point far away. The Market can be accessed through a number of Entry Points located in the Market's borders that may be international ports or other major transportation nodes and therefore their capacity has no limitation. For container deconsolidation purposes a number of Distributions Centers can be established within the Market. Figure 1 depicts a simplified realization of the supply chain under study with two entry points, two distribution centers and four regional markets.

The critical decisions for managing the above supply chain network involve all decisions regarding: (a) network design such as (i) the selection of entry points (ii) the choice of transport means (iii) the selection of the distribution centers (iv) the determination of the associated flows, and (b) either leasing or outsourcing of transportation modes as well as distribution centers.

The optimization criteria are (i) the total costs including (a) transportation/handling costs per TEU, (b) rental and operational costs of distribution centers (c) holding costs per TEU, and (ii) the total amount of emissions generated from the above supply chain operations separately for each type of emission.

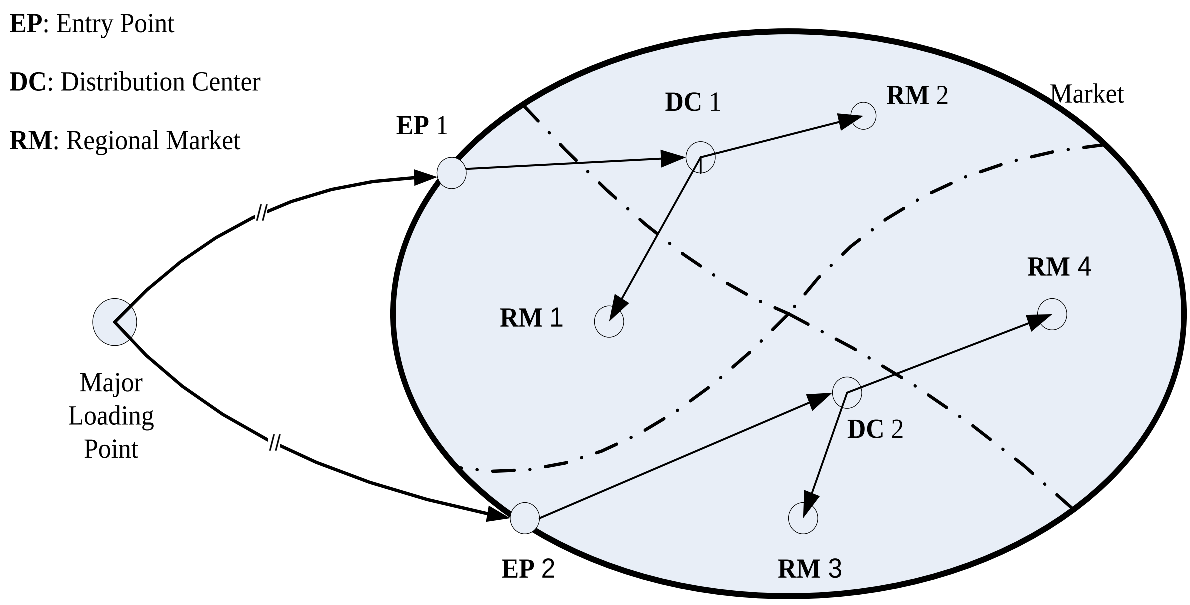

Figure 1: Supply Chain Network under Study

We consider four realistic options typical for supply chain designs. The first option involves the outsourcing of transportation as also distribution centers to a third party logistic provider (3PL). The second option involves the outsourcing of transportation services only, while distribution centers are leased through medium time-horizon contracts. The third option assumes leasing of transportation services and outsourcing of distribution centers while option four involves the leasing of both transportation modes and space as also personnel in distribution centers. Table 1 presents these four options.

Table 1: Design Options for Transportation (TR) and Distribution Center (DC) operations (O – Outsourcing, L – Leasing).

Option	Transportation	Distribution Center
A	O	O
B	O	L
C	L	O
D	L	L

To model the supply chain operations, we make the following assumptions: (i) rail services utilize the public railway network. The latter implies that rail transportation services are provided by each country's national railway company so the option of leasing rail transportation services is not considered valid. When the quantity transported exceeds a specific number of TEUs, a block train is utilized, resulting in a discount cost per TEU transported. (ii) the outsourced transportation and storage as also deconsolidation/consolidation services are charged per TEU by the 3PL and are based on spot market prices, (iii) the cost of leasing a distribution center for a specific time period is a fixed value that depends on the location of the center and its size, (iv) the trucks of the 3PL company (outsourcing transportation option) will transport cargo flows of other customers in the return haul of the trip, while in the leasing option trucks are exclusively utilized and thus return empty or almost empty (e.g. carrying commercial returns**,** and/or packaging material). Therefore, emissions generated in the return haul of the trip are charged in a different way in the outsourcing and leasing options, (v) the options that involve leasing of distribution centers require a minimum cargo volume to be feasible. To be more specific and considering the fixed leasing cost per period, it would not be economically viable for a company to utilize a distribution center when small cargo volumes are handled. Thus, for options B and D we set such a lower bound of TEU flows required for a distribution center to operate, which is calculated based on leasing and operational costs. Such a restriction does not hold for the option of outsourcing, and (vi) supply to distribution centers is typically full truck load (FTL), while thereafter it is often less-than-truckload (LTL) using milkruns. Thus, smaller delivery trucks are used from the distribution centers to the regional markets.

4. Model Development

The problem under study is formulated as a Mixed Integer Linear Programming Problem. The model investigates potential Entry Points (that belong to the set **EP**), locations of Distribution Centers (set **DC**) and transportation modes in order to transport TEUs to demand points, located in Regional

Markets (set **RM)** retail stores. Two types of objective functions are developed. The first one minimizes the total logistics costs and the second, the amount of different types of emissions, namely CO_2, CO, PM, SO_2, NOx, (the set **EG** includes these emissions types). The total logistics costs incorporate (a) the outsourced or leased transportation and the associated handling costs per TEU, which are differentiated for alternative transportation modes (even and for the various echelons of the supply chain, namely from the sourcing Major Loading Point to the Entry Points, from the Entry Points to the Distribution Centers and from the Distribution Centers to the Regional Markets) (b) the custom formalities expenses per TEU (c) the holding costs for the cycle stocks per TEU (d) the costs per TEU for outsourcing storage and deconsolidation/consolidation services to a 3PL or the fixed cost of leasing space in a distribution center. The model allows for leasing distribution centers of various sizes (capacities) that incorporate different leasing costs. Differences in leasing costs are also observed for distribution centers located in different countries.

Tables 2 and 3 provide the nomenclature for the decision variables and the parameters of the model respectively

Table 2: Decision Variables

Variable	**Description**
x_{ij}^{m}	number of TEU transported from node i to node j using transportation mode m =1,..,M.
z_{ij}	binary variable which indicates whether a block train is utilized or not in the route from node i to node j.
y_{j}^{w}	binary variable which indicates whether a distribution center of size w is leased at node j or not.

Table 3: Model Parameters

Parameters	**Description**
D_r	total demand at regional market r.
c_{ij}^{m}	cost of transporting a TEU from node i to node j using transportation mode m (node 0 is the major loading port).
c_{ij}^{bt}	block train transportation cost from node i to node j per TEU.
f_{j}^{w}	leasing cost (during planning horizon) of a distribution center of size w at node j (this cost includes all operational costs of the leased distribution center and is equal to zero in the option of outsourcing).
c_{j}^{dc}	deconsolidation/consolidation cost per TEU at a distribution center at node j (only in the option of outsourcing).

Parameters	Description
${}^{g}e_{ij}^{m}$	emissions of type g generated from transporting a TEU from node i to node j using transportation mode m.
${}^{g}e_{ij}^{bt}$	emissions of type g generated during a block train trip from node i to node j.
S_j^w	minimum TEU flow (break even) for feasible leasing of a distribution center of size w at node j ($S_j^w = 0$ for the option of outsourcing).
L^w	capacity of a distribution center of size w (L^w is considered infinite for the option of outsourcing).
t_{ij}^m	transportation time from node i to node j using transportation mode m.
h	holding cost per TEU.
N	represents the minimum TEU volume for charging a block train.
M_0	represents a very large constant.

Consequently the following integer programming model is proposed:

Minimize total cost (TC):

$$\sum_{i\in \mathbf{EP}}\sum_{m=1}^{M} c_{0i}^m \cdot x_{0i}^m + \sum_{i\in \mathbf{EP}} c_{0i}^{bt}\cdot x_{0i}^{bt} + h\cdot\sum_{i\in \mathbf{EP}}\left(t_{0i}^{bt}\cdot x_{0i}^{bt} + \sum_{m=1}^{M} t_{0i}^m \cdot x_{0i}^m\right)$$
$$+\sum_{i\in \mathbf{EP}}\sum_{j\in \mathbf{DC}}\sum_{m=1}^{M}\left(c_{ij}^m + c_j^{dc}\right)x_{ij}^m + \sum_{i\in \mathbf{EP}}\sum_{j\in \mathbf{DC}}\left(c_{ij}^{bt} + c_j^{dc}\right)\cdot x_{ij}^{bt} + h\cdot\sum_{i\in \mathbf{EP}}\sum_{j\in \mathbf{DC}}\left(t_{ij}^{bt}\cdot x_{ij}^{bt} + \sum_{m=1}^{M} t_{ij}^m\cdot x_{ij}^m\right) \quad (1)$$
$$+\sum_{w}\sum_{j\in \mathbf{DC}} f_j^w\cdot y_j^w + \sum_{j\in \mathbf{DC}}\sum_{r\in \mathbf{RM}}\sum_{m=1}^{M} c_{jr}^m\cdot x_{jr}^m + \sum_{j\in \mathbf{DC}}\sum_{r\in \mathbf{RM}} c_{jr}^{bt}\cdot x_{jr}^{bt} + h\cdot\sum_{j\in \mathbf{DC}}\sum_{r\in \mathbf{RM}}\left(t_{jr}^{bt}\cdot x_{jr}^{bt} + \sum_{m=1}^{M} t_{jr}^m\cdot x_{jr}^m\right)$$

or Minimize total emissions (TE$_g$) of type g:

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

Subject to

Flow Constraints

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

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

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

Capacity Constraints

$$\sum_{i\in \mathbf{EP}}\sum_{m=1}^{M} x_{ij}^{m} + \sum_{i\in \mathbf{EP}} x_{ij}^{bt} \geq \sum_{w} S_j^{w} \cdot y_j^{w},\quad \forall j \in \mathbf{DC} \quad (6)$$

$$\sum_{i\in \mathbf{EP}}\sum_{m=1}^{M} x_{ij}^{m} + \sum_{i\in \mathbf{EP}} x_{ij}^{bt} \leq \sum_{w} L^{w} \cdot y_j^{w},\quad \forall j \in \mathbf{DC} \quad (7)$$

$$\sum_{w} y_j^{w} \leq 1,\ \forall\ j \in \mathbf{DC}$$

Block train constraints

$$x_{0i}^{bt} - M_0 \cdot z_{0i} \leq 0\ \forall i \in \mathbf{EP} \quad (8)$$

$$x_{0i}^{bt} - N \cdot z_{0i} \geq 0\ \forall i \in \mathbf{EP} \quad (9)$$

$$x_{ij}^{bt} - M_0 \cdot z_{ij} \leq 0,\ \forall i \in \mathbf{EP}\ ,\forall j \in \mathbf{DC} \quad (10)$$

$$x_{ij}^{bt} - N \cdot z_{ij} \geq 0,\ \forall i \in \mathbf{EP}\ ,\forall j \in \mathbf{DC} \quad (11)$$

$$x_{jr}^{bt} - M_0 \cdot z_{jr} \leq 0,\ \forall j \in \mathbf{DC}, \forall r \in \mathbf{RM} \quad (12)$$

$$x_{jr}^{bt} - N \cdot z_{jr} \geq 0,\ \forall j \in \mathbf{DC}, \forall r \in \mathbf{RM} \quad (13)$$

Non Negativity Constraints

$$x_{ij}^{m} \geq 0 \quad (14)$$

The Flow Constraints are set in order to guarantee that there is no product surplus or shortage in the examined supply chain. More specifically, constraints (3), (4) and (5) guarantee the balance of inbound and outbound flows for each Entry Point, Distribution Center, and Regional Market respectively. Capacity constraint (6) guarantees that the activated distribution centers will handle at least the minimum TEU flows required for their leasing to be economically feasible. Thus, this constraint is used only for options B and D. Constraint (7) guarantees that when a distribution center is activated, its capacity (size) will be adequate to handle the cargo flow that will pass through it. Finally constraints 8-13 guarantee that a block train will be deployed given a specific number of TEUs (N).

The developed model is an extension of a two-level (entry points and DC's) capacitated location problem, extended with extra objective functions and different transportation mode options, with block train requirements. The model can be solved with a standard MIP solver, eg. CPLEX(R).

5. Case Study

In this section we present a case study to show the trade-offs allowed by the model. We consider a multinational company’s supply chain for transporting white goods in a South Eastern European market that includes Bulgaria, Romania and FYROM (also called Macedonia) with a planning horizon of one year. The replenishment orders are set on a monthly basis. We assume a 20% market share of the annual sales of white goods (specifically kitchens, ovens, refrigerators, and other electrical devices). The Loading Point is the Port of Shanghai and the Entry Points may be the Ports of Thessaloniki, Varna, and Constanta. We consider 15 Regional Markets, in the capital city of which a retail store will be established, satisfying the demand of the entire region. We allow for 16 potential Distribution Centers located on Entry Points (Thessaloniki Port, Varna Port, and Constanta Port) and Regional Market’s capitals. Figure 2 depicts the chain network under study. The triangles represent distribution centers while the circles represent entry points (ports). It must be stated in this point that all potential Distribution Centers besides that of Thessaloniki are also Regional Markets.

Figure 2: Map of the Region with major Supply Chain Nodes

The shipping network utilized in this case study involves Gioia Tauro (in Calabria, Italy) as transshipment hub and the 3 examined Entry Points. We assume that a typical mother vessel (6000TEU) is deployed in order to transport TEU flows from Shanghai to Gioia Tauro. The associated flows are then transshipped onto feeder vessels that call at the examined Entry Points.

The estimated annual demand for the examined products (kitchens, micro devices, ovens and refrigerators) in FYROM, Bulgaria and Romania is based on (i) the estimated annual demand for the examined products in Greece (ii) the ratio of each country's regions GDP to that of Greece.

Inbound flows to the Distribution Centers are transported either with (i) electric trains in the Bulgarian and Romanian rail routes, as also in the route of Thessaloniki to Skopje and (ii) diesel trains in the route of Thessaloniki to Kulata/Promachon (National Border) or (iii) heavy duty trucks in all routes (Euro III, IV, V, VI truck types are examined), to a number of Distribution Centers that correspond to the three countries under study. We assume that each heavy duty truck carries a 40ft container since the products under study are volume intensive. Considering (i) weight and volume characteristics of typical white appliances, refrigerators, micro ovens, kitchens and (ii) the volume of a 40ft container ($67m^3$), we estimated that the average weight of a container equals 7 tons. This gives an average gross weight of 11 tons per 40ft container (considering the approximately 4 ton weight of an empty 40ft container). When the load in a single trip exceeds 30TEUs or 15x40ft containers, a block train is used and a 20% cost discount is applied. Supply to the Regional Markets Retail stores is Less than Full Truck Load (LTL), and therefore outbound flows to the Regional Markets are transported with typical 10 ton delivery trucks with an approximately $31m^3$ platform loading. Following the same methodology with that of heavy duty trucks we have estimated that the net weight of the cargo capacity transported is approximately 3.2 tons.

There are insignificant differences in transportation times since the major part of total lead time that of maritime transportation is almost the same for all network realizations. Thus holding costs per cycle stocks are not included in the case. In the following paragraphs we will explain the steps followed in order to derive the results. All details can be found in an accompanying report Mallidis et al. (2010b).

5.1 Calculation of transportation costs

In the following paragraphs we explain the way of calculating the transportation costs. The latter consist of the truck, rail and shipping costs per 40ft container.

Truck costs

Studying the available charges for specific routes, obtained from Orphee Beinoglou S.A. and V.CH. Kampakis Group, that operate in the region, we derived the following regression equations for calculating truck transportation cost y in euro per 40ft container for various distances x.

Euro III heavy duty truck regression equation:

$$y = 1.92x + 241.87 \qquad 100\text{ Km} \le x \le 1100\text{ Km}$$

Euro III delivery trucks the regression equation is:

$$y = 1.953x + 1948 \qquad 50\text{ Km} \le x \le 600\text{ Km}$$

Notice the high offset value of 1948 euro for the delivery trucks. This can be explained from the fact that we have to upscale the results for 3.2 tons to the standard load of 7 tons we use in our calculations. For the option that involves leasing of transportation services though, Euro III heavy duty and delivery truck freight rates per 40ft container are estimated to decrease by 20% compared to the option that involves outsourcing. The latter may be justified by the fact that (i) they are charged based on a fixed long term contract and not on a spot market basis as in outsourcing and (ii) no agency fees are included since the examined company has direct communication with the truck owners.

Euro IV, V, VI heavy duty truck transportation freight rates in the options of outsourcing and leasing, are estimated with Euro III as the base. To be more specific we consider that 75% of all Euro type truck costs incorporate the truck drivers wages and other operational expenses, such as order costs, truck maintenance costs etc, while the 25% parts reflect the truck depreciation cost. Since the latter is proportional to the trucks purchase costs the 75% of the freight rate is the same for all trucks, independently of their engines Euro norm and the rest 25% of the freight rate changes, according to the truck purchase costs that depends on the engines Euro norm.

Table 4 shows the purchase costs (tractors only) of the examined Euro trucks along with their percentage freight rate differences, retrieved from S.Savvatis LTD (Personal Communication). The purchase costs for EURO VI trucks in table 4 represent estimates, since they are not yet in production.

Table 4: Euro truck purchase costs

Truck Types	Purchase cost (€)	Increase (%)	Freight rate increase (%)
Euro III (Heavy Duty Truck)	30,000	0.0	0.0
Euro IV (Heavy Duty Truck)	40,000	33.3	8.3
Euro V (Heavy Duty Truck)	55,000	83.3	20.8
Euro VI (Heavy Duty Truck)	100,000	233.3	58.3
Euro III (Delivery Truck)	15,000	100.0	100.0
Euro IV (Delivery Truck)	20,000	33.0	8.3
Euro V (Delivery Truck)	25,000	67.0	16.8
Euro VI (Delivery Truck)	60,000	300.0	75.0

Rail costs

The rail costs per 40ft container incorporate (i) a rail freight rate for transporting a 40ft container to its destinations rail depot (ii) a rail freight rate for returning the empty 40ft container (iii) a fixed discharge from wagon and a loading on truck cost per 40ft container (50€) at the rail freight depot as also the loading of the returning empty 40ft container on the wagon and (iv) a city limit expense of 100€ for transporting a 40ft container by truck from the rail depot to its final destination and returning the empty.

The parameters required for calculating the rail freight rates per 40ft container incorporate (i) size and weight classification coefficients based on different gross weights and types of containers and (ii) distance coefficients set by each country's national rail network. For returning the empty 40ft container, we consider the same distance coefficient while the weight and size classification coefficient selected is the one that corresponds to the lowest container gross weight category.

Shipping costs

The shipping costs per 40ft container have been retrieved from Orphee Beinoglou S.A. They incorporate (i) the fixed sea freight rates per 40ft container from Shanghai to the examined Ports (ii) the local charges (discharge, demurrage, pilotage costs, loading on a truck or wagon costs e.t.c.) at the examined Ports and (iii) the custom clearance documentation costs at each Port. The following table shows a breakdown of the shipping costs, from Shanghai to the examined EPs.

Table 5: Shipping cost breakdown (per 40ft container in euros)

Entry points / Cost	Thessaloniki Port	Varna Port	Constanta Port
Freight rates	1898	2076	2136
Local charges	219	279	271
Custom formalities	200	266	200
Total costs	**2,317**	**2,621**	**2,607**

5.2 Calculation of transportation emissions

Below we indicate how we calculated the emissions of all transport modes.

Ship Emissions

The examined container vessels emissions are calculated based on a fixed amount of CO_2 and PM emissions per ton/km (Ebert, 2005). The distance considered between Shanghai to Gioia Tauro and then to Thessaloniki, Varna and Constanta has been calculated with the use of the Port to Port distance calculator, searates.com (http://www.searates.com/reference/portdistance/). The choice of Entry Points thus only matters the feeder transports from Gioia Tauro.

Truck Emissions

Euro III, heavy duty and delivery truck CO_2 and PM emissions are calculated based on fixed CO_2 and PM emission amounts produced per ton/kilometer (Boer et al., 2008). The same CO_2 emissions amounts will be also considered for Euro IV, V, and VI heavy duty and delivery trucks since different Euro-type engines have no effect in terms of CO_2 emissions generated. Regarding PM emissions significant reductions are observed between Euro III and IV heavy duty and delivery truck engines while no differences are observed between Euro IV and V. Between Euro V and VI though, Euro VI engines are twice more cleaner compared to Euro V (http://www.dieselnet.com/standards/eu/hd.php).

In the options that involve outsourcing of transportation services the company is not accountable for the PM and CO_2 emissions generated in the return trips of the heavy duty and delivery trucks, since the latter are typically utilized to transport cargo for other companies returning. Therefore, the amount of emissions generated in the return haul of the trip is not considered. On the other hand though, the leased heavy duty and delivery trucks are dedicated to serve the examined company. Therefore the amount of emissions generated by the empty truck on the return trip will be added. For heavy duty trucks and given specific payloads, their fuel consumption is estimated to decrease by approximately 30% (Coyle 2007). For delivery trucks we assume a 40% decrease since the tonnage of the cargo transported represents a higher percentage of the empty trucks weight compared to heavy duty trucks.

Rail Emissions

Rail CO_2 and PM emissions are calculated based on a fixed amount of CO_2 and PM emissions produced per ton/km transported and incorporate the amount of emissions generated from the Entry point to the Distribution Centers. In case of electric trains it depends on how the electricity is generated. As it is difficult to obtain good values for the region, we used the published data from Ebert (2005). Table 6 provides an overview of the cost and emissions of the examined transportation modes.

Table 6: Overview of estimated average cost and emissions per transportation mode (40ft container, 200km)

Mode	**Cost (€)**	**CO_2 emissions (kg)**	**PMs (gr)**
Ship (6000TEU)	37.04	24.4	63.8
Ship (feeder)	n.a.	28.4	72.6
Euro III heavy duty truck	626.0	169.4	64.0
Euro IV heavy duty truck	678.0	169.4	12.8
Euro V heavy duty truck	756.2	169.4	12.8
Euro VI heavy duty truck	991.0	169.4	6.4
Rail (Diesel)	654.0	87.1	55.0
Rail (Electric)	556.0	61.4	19.8
Euro III delivery truck	2338.6	188.8	123.2
Euro IV delivery truck	2532.7	188.8	24.6
Euro V delivery truck	2731.5	188.8	24.6
Euro VI delivery truck	4092.5	188.8	12.3

Remark – shipping costs exclude customs costs, but rail costs include the additional costs of loading and unloading at the begin and endpoint.

Notice that in terms of reducing CO_2 emissions we want to use ships as much as possible, next rail and then heavy duty trucks. This coincides with the cost preferences. In terms of PM emissions we however prefer EURO VI heavy trucks, next EURO VI delivery trucks and thereafter trains. Ships are in that case the one-to-worst solution.

Warehouse costs

The cost for warehousing were obtained from V.CH Kampakis Group. The outsourcing warehousing cost is about €120 per 40ft container handled in Greece. For Bulgaria and Romania these costs are approximately 20% lower and for FYROM, 40% lower. Table 7 shows the estimated dedicated warehouse leasing costs as function of maximum capacity. For low capacities the cost per container are higher than in case of outsourcing, but for high capacities they are lower.

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Table 7: Warehouse Leasing costs (euro/ month)

Regions \ Capacity (in 40ft cntrs)	60	80	100	200
Greece (Thes/niki)	10000	13000	16500	20000
Bulgaria	8000	10400	13200	16000
Romania	8000	10400	13200	16000
FYROM (Skopje)	6000	7800	9900	12000

5.3 Model development and results

The developed model consists of some 547 variables, 80 integers, 67 constraints, 1542 nonzero's and it was solved on a Pentium 4 computer with 3.6 GHz CPU, and 1 GB RAM, via the LINGO 9 solver. We solved 12 instances of the model by combining the four leasing/outsourcing options of Table 1 with the three optimization criteria. Table 7 summarizes the optimal networks.

Table 8: Optimal Network Configurations of the Examined Problem Instances

	Optimization Criterion					
	Cost		**CO_2**		**PMs**	
Options (TR/DC)	**Entry Points**	**Distribution Centers**	**Entry Points**	**Distribution Centers**	**Entry Points**	**Distribution Centers**
A (O/O)	3	15	3	14	1	14
B (O/L)	3	6	3	6	1	6
C (L/O)	3	15	3	14	1	14
D (L/L)	3	6	2	6	1	6

All three Entry Points, viz. Thessaloniki, Varna and Constanta, are used in the cost optimal supply chain for all options. This result also holds for the CO_2 emissions optimal supply chain for options A,B, and C, while in option D the associated flows are channeled only via two Entry Points, namely Thessaloniki and Varna. On the other hand, the PM emission optimal network configuration only includes the Port of Thessaloniki in all options A, B, C and D. The reason for the latter is the higher PM emissions of the ship compared to hinterland transportation modes that makes the Entry Point with the shortest ship distance preferable, which is Thessaloniki in our case.

As far as the number of distribution centers in the optimal solution, we observe two cases. In case we outsource storage and consolidation/deconsolidation operations almost all potential distribution centers (except those of Thessaloniki in the cost optimal supply chains and Thessaloniki, Prahova in the CO_2 and PM emissions optimal supply chains) are included in the optimal solution. However, in case of leasing only few distribution centers are utilized since a lower bound has been set on the throughput.

Table 9 depicts the cost, CO_2 and PM emissions performance of the examined problem instances. The relative values in parentheses are the percentage increases from the reference case which is the best instance for the particular performance measure (instance 3 with option C for the cost, instances 5 and 9 with option A for the CO_2 and PM emissions respectively). The values in black denote for each optimization criterion, the best option in terms of one of the performance criteria. For all optimization criteria, option C, leasing transport and outsourcing warehouses, gives the lowest costs compared to the other options. The cost increases for the other options vary from 1.9% to 49.9% (instance 10 versus 11). On the other hand the adoption of option A, both outsourcing transportation and warehousing, leads to minimum emissions (the emission increases for the other options vary from 0.5% to 17.2% for CO_2 and from 0.1% to 3.2% for PM).

Table 9: Cost, CO_2 and PM emissions for the optimal solutions of the 12 problem instances

Instance	Optimization Criterion	Option (TR/DC)	Cost [thousand €/yr]		CO_2 [tn/yr]		PM [Kg/yr]	
1	Cost	A (O/O)	874.1	(2.9%)	**540.3**	(0.9%)	**1313.8**	(3.4%)
2	Cost	B (O/L)	1122.2	(32.1%)	561.3	(4.8%)	1323.4	(4.2%)
3	Cost	C (L/O)	**849.2**	(0.0%)	573.2	(7.0%)	1326.2	(4.4%)
4	Cost	D (L/L)	1052.5	(23.9%)	609	(13.7%)	1355.4	(6.7%)
5	CO_2	A (O/O)	910.7	(7.2%)	**535.5**	(0.0%)	**1310.6**	(3.2%)
6	CO_2	B (O/L)	1141.3	(34.4%)	553.2	(3.3%)	1333.4	(5.0%)
7	CO_2	C (L/O)	**893.8**	(5.3%)	538.2	(0.5%)	1312.2	(3.3%)
8	CO_2	D (L/L)	1089.1	(28.3%)	569.4	(6.3%)	1334.9	(5.1%)
9	PM	A (O/O)	1340.7	(57.9%)	**630.5**	(17.7%)	**1270.0**	(0.0%)
10	PM	B (O/L)	1805.8	(112.6%)	644.1	(20.3%)	1271.0	(0.1%)
11	PM	C (L/O)	**1204.5**	(41.8%)	732.2	(36.7%)	1274.0	(0.3%)
12	PM	D (L/L)	1501.7	(76.8%)	739.1	(38.0%)	1275.4	(0.4%)

Another interesting finding is the low cost increase in case a company adopts the policy that minimizes CO_2 emissions compared to the outcome of a cost minimization. If you change for a given option the optimization criterion from costs to CO_2 then the cost increases are only marginally (4.2%, 1.7%, 5,3% and 3.5%). The increases for the PM optimization compared to a cost, however, are much higher, viz. 54.9%, 80.5%, 41.8% and 52.9% since the expensive Euro VI trucks are solely applied in the PM instances.

Table 10 presents the total cost breakdown into ship, rail, truck, and delivery truck costs for the optimal networks. Under the cost optimization instances, rail is preferred, when the company outsources transportation services while heavy duty trucks when it leases transportation means. Under the CO_2 emissions optimization instances, rail is preferred in all options. Finally under the PM optimization the results indicate that Euro VI heavy duty trucks exhibit the best environmental performance compared to other Euro type heavy duty trucks and electric rail transportation. Moreover, leasing of distribution centers leads to a lower number of distribution centers and thus increases the utilization and the percentage cost of delivery trucks.

Table 10: Percentage cost breakdown per transportation mode for each problem instance

Instance	Optimization Criterion	Option (TR/DC)	Ship	Rail	Truck	Delivery Truck	Distribution Centers
1	Cost	A (O/O)	72.23	13.62	5.24	6.21	2.70
2	Cost	B (O/L)	55.46	12.76	0.41	27.10	4.27
3	Cost	C (L/O)	73.88	8.40	9.83	5.12	2.77
4	Cost	D (L/L)	59.97	3.31	8.10	24.07	4.55
5	CO_2	A (O/O)	69.08	17.47	0.90	9.97	2.58
6	CO_2	B (O/L)	54.23	9.62	0.69	31.36	4.10
7	CO_2	C (L/O)	70.00	19.13	0.25	8.00	2.62
8	CO_2	D (L/L)	58.30	13.52	0.31	23.47	4.40
9	PM	A (O/O)	42.11	0.00	44.45	11.70	1.74
10	PM	B (O/L)	31.70	0.00	29.30	36.35	2.65
11	PM	C (L/O)	47.41	0.00	40.41	10.36	1.82
12	PM	D (L/L)	36.18	0.00	26.71	34.06	3.05

6. Discussion

The results shown in the case obviously depend on the input assumptions, which may be debated. Yet they do reflect actual companies' behavior (like from UPS, TNT), in the sense that these are reducing kms driven and hence also costs and CO_2 emission. Moreover, it is an obvious conclusion that CO_2 emissions and costs can be reduced by having more consolidation and applying larger ships, larger trucks and intermodal transport. The latter is however, poorly developed in SE Europe, hence the case study does not further stress it. Our paper does stress the importance of using trucks more efficiently and that can be done by using more distribution centers as well as outsourcing. Today, in real life there are still too many empty truck kms and the kms that are driven are not always fully loaded. To reduce PM emissions however, one has to take expensive actions. On one hand the EURO V norms are already compulsory for new trucks in the EU, but considering the present deplorable economic position of trucking companies, it is way too costly to change the present (mostly EURO III) trucks for cleaner ones, unless someone else is going to pay for it.

7. Conclusions

Incorporating environmental issues in strategic and operational decisions affects considerably the design of supply chains. The geography of production facilities, transportation nodes and distribution centers will change.

We used a region in the South-Eastern Europe as a background for presenting the methodology proposed in this study. Although it was difficult to obtain exact emission and cost estimates, it is possible to obtain realistic values. Given these we determined the optimal network configurations for all optimization criteria and compared the optimal solutions to identify the tradeoffs between environment protection and cost. From the results we observed that the optimization of the supply chain based on CO_2 emissions does not increase substantially the supply chain network costs since cost and CO_2 emissions objectives often align. This implies that by adopting a CO_2 emissions minimization policy a company could achieve a satisfactory balance between costs and environmental efficiency. Looking into the PM emissions minimization objective though, the generated costs are very high. A proposed solution that could minimize the high costs of the PM emissions based supply chain is the deployment of electric rail transportation on more routes, but that requires large infrastructural investments.

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