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A Decision Support Model for Capturing the Impact of Energy Savings and Pollution Legislation on Supply Chain Network Design

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The EU's commitment to reduce the environmental impact of supply chain operations was initiated through the white paper proposal of 2001. Since then, several regulatory interventions have been proposed for costing the CO_2 emissions produced from supply chain operations. These costs should be taken under serious consideration by supply chain stakeholders when designing their supply chain networks. This paper proposes a strategic/tactical decision support model that will assist supply chain stakeholders in evaluating the impact of incorporating CO_2 emissions cost parameters in their networks design decision-making process. Specifically, we propose a model that addresses: (i) supply chain network design, including the determination of port of entry and transportation modes, and (ii) decisions on using dedicated versus shared warehouses and transportation. The applicability of the proposed methodology is illustrated through the development of a green supply chain network in the South-Eastern European region. The results indicate that: (i) dedicated transportation and shared DC operations minimize supply chain network design costs, and (ii) the potential implementation of a Maritime Emissions Trading Scheme (METS) could significantly affect strategic supply chain network design decisions.

1. Introduction

Global supply chains are significant contributors of greenhouse gasses, which are mainly generated through the transportation of the large streams of goods around the world. Between 1990 to 2007 global CO_2 emissions from transport have grown by 45 % (OECD/ITF, 2010), resulting in various external costs, the internalization of which could be achieved indirectly through the implementation of market-based instruments. To that effect, the two most important regulatory interventions proposed by the EU, are the Emissions Trading Scheme (ETS) (European Comission, 2003) and the Energy Taxation (European Commission, 2011). The ETS has been implemented in three periods (the third one, from 2013 to 2020, is currently active). Under the scheme and emissions cap are assigned to each operator of an installation. If the operator does not surrender an equivalent, to the cap amount of CO_2 emissions allowances, he would have to pay an excess emissions penalty of € 100 per excess t of CO_2 emissions produced. Payment of the excess emissions penalty would not however release the operator from the obligation to buy and then surrender an amount of allowances equal to those excess emissions produced during the preceding calendar year (European Commission, 2009). The ETS has been partially implemented for the airline sector since 2012 (European Commission, 2012), but not yet for the shipping sector. However a proposal has been made for the development of a Maritime Emissions trading Scheme in 2009 (CE Delft, 2009). Under the proposed scheme, the responsible entity for monitoring on the ship emissions in all voyages to EU ports is the ship operator while the accounting entity is the ship. The difference compared to the currently active EU ETS is that no penalty cost is charged in the case of non-compliance but rather there is a provision of a denial for port entry to the ship. Currently the EU is moving ahead with its regulatory intervention, pending a relevant action plan by the International Maritime Organization (IMO), in the fall of 2013. The purpose of this paper is to provide a detailed cost modelling methodology of a supply chain network design problem under a METS. The employed tool is based on multi-objective mixed integer linear

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programming methodology (MILP). It allows for utilizing all alternative transportation routes, modes, and potential establishment of deconsolidation/consolidation nodes taking into account alternative operating options with exclusive or not, utilization of facilities and modes. There are other research papers that aim to address issues related to transportation emissions (Sellitto, et al., 2011). The novelty of this paper hinges however, upon the inclusion of green regulatory interventions in supply chain network design.

2. System Description

We consider a multinational company that aims to serve a specific 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 containerized cargo is transported by vessels assumed to be originating from one Major Loading Point far away. We assume that a cap is assigned to the ship owner for each vessel at the beginning of each year. This cap is determined by the EU, based on a verified CO_2 emissions projections methodology, conducted by the ship owner. In the case that the ship produces more CO_2 emissions than the cap, in the routes of the network under study, he would have to purchase a number of allowances equal to the verified emissions during that year exceeding the cap, and also pay a penalty cost for that quantity. In the opposite case, the owner sells the remaining allowances up to the cap. In the first case, the extra cost is passed on the consignee and therefore, the freight rates per TEU from the distant loading point to the entry ports increase, while in the second case, the earnings from selling the remaining allowances are deducted from the freight rates charged on the consignee. 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 with no capacity limitation. For container deconsolidation purposes a number of Distributions Centres (DCs) can be established within the Market. The DCs order from the distant loading point under predefined order cycles which are determined by the shipping schedule from the distant loading point. Transport from the Entry Points to the DCs can occur by train, block train or truck. Finally, the replenishment orders of the Regional Markets from the DCs are also predefined and determined by the company's transportation planning schedule. These orders are transported by two types of trucks (small or large) or both, depending on the demand magnitude of the Regional Market during its replenishment cycle. Following the work of (Mallidis, et al., 2012), we examine four realistic options related to Shared/Dedicated use of transportation modes as well as DC services, in order to model the low/high equipment and facilities utilization, respectively. Table 1 summarizes these options.

Table 1: Design Options for Transportation and DC operations (Shared, Dedicated)

Option	Transportation	Distribution Centre
Tr-Sh/DC-Sh	Shared	Shared
Tr-Sh/DC-Ded	Shared	Dedicated
Tr-Ded/DC-Sh	Dedicated	Shared
Tr-Ded/DC-Ded	Dedicated	Dedicated

The critical decisions for managing the above supply chain network include: (a) network design such as the selection of entry points, the choice of transport modes, the selection of the DCs, the determination of the associated flows, and (b) shared or dedicated use of transportation modes (where applicable) as and of DCs. The optimization criterion is the total logistics cost that comprises of the transportation/handling costs per TEU, the rental and operational costs of DCs, the penalty cost per excess CO_2 shipping emissions and the cost per CO_2 emissions shipping allowance. To model the supply chain operations, we assume that dedicated use of rail services (either public or private) is not considered as an option as the capacity of railways is much larger than the transportation needs of a single manufacturer and one or two trips per month are usually sufficient. Additionally, when the quantity transported per train exceeds a specific number of TEUs, we assume that a block train is utilized resulting in a lower transportation cost per TEU. Moreover, shared transportation and storage as also deconsolidation/consolidation services are charged per TEU by the Third Party Logistics provider (3PL) and are decided based on spot market prices, while the cost of a dedicated DC for a specific time period is fixed, depending on the location of the distribution centre and its size. As the trucks of the 3PL company (in the shared transportation option) can transport cargo flows of other customers in the return haul of the trip, while trucks, in the dedicated option, are exclusively utilized and thus they often return empty or almost empty (e.g. carrying commercial returns, and/or packaging material), the transportation costs are charged differently in the shared and dedicated use options. Finally, for the options that involve the dedicated use of DCs, we assume that a minimum cargo volume is required for their use to be considered feasible. Thus, for the options that involve the dedicated use of DCs, a lower bound of TEU flows for a DC to operate is enacted.

3. Model Development under METS

The problem under study is formulated as a MILP Problem. The model investigates potential Entry Points ($i \in$ **EP),** locations of DCs ($j \in$ **DC)** and transportation modes, m=1,…,M in order to transport TEUs to demand points, located in Regional Markets ($r \in$ **RM)** retail stores. The supply chain runs from a point of origin, 0, to an entry point i, from there to a distribution centre j and on to a retail store r. Specifically, from the distribution centre j to the retail store r the associated flows can be transported by a delivery truck, and if the cargo volume is larger than the capacity of the delivery truck, by one or more heavy-duty trucks or with a combination of small and large trucks. A total logistics cost minimization function is developed comprised of: (a) the shared or dedicated transportation and the associated handling cost 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 DCs and from the DCs to the Regional Markets), (b) the custom related expenses per TEU, (c) the penalty cost per ton of excess shipping CO_2 emissions, (d) the cost per CO_2 emissions allowance, and (e) the costs per TEU for shared storage and deconsolidation/consolidation services to a 3PL or the dedicated use cost of the DCs. The model allows for dedicated use of DCs of various sizes (capacities) that incorporate different fixed costs. Tables 2 and 3 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.

Table 2: Decision Variables

Variable	Description
x_{ij}^{m}	Number of TEUs transported from node i to node j using transportation mode m=1,…,M during the planning horizon.
${}^{p}x_{0i}^{s}$	Number of TEUs transported from the distant loading point to node i using ship, during the planning horizon when the total CO_2 emissions from the distant loading point to the EPs are higher than the cap.
${}^{e}x_{0i}^{s}$	Number of TEUs transported from the distant loading point to node i using ship, during the planning horizon when that the total CO_2 emissions from the distant loading point to the EPs are less or equal to the cap.
x_{ij}^{bt}	Number of TEUs transported from node i to node j using a block train during the planning horizon.
x_{jr}^{st}	Deconsolidated cargo capacity (expressed in mean TEU load capacity) transported by a delivery truck from node j to node r.
x_{jr}^{lt}	Deconsolidated cargo capacity (expressed in mean TEU load capacity) transported by a heavy duty truck from node j to node r.
z_{ij}	Binary variables which indicate whether a block train is utilized or not in the route from node i to node j.
y_{j}^{w}	Binary variables which indicate whether a distribution center of size w is dedicated at node j or not.
K_{jr}	Binary variables which indicate whether a delivery truck is utilized or not in the route from node j to node r.
P_{Jr}	Binary variables which indicate whether a heavy duty truck is utilized or not in the route from node j to node r.
a	Binary variable which indicates whether the CO_2 emissions cap of the maritime company is reached or not.

Consequently the following MILP model is proposed

Minimize Expected Total Cost (TC) per planning horizon:

$$\textbf{Min} \sum_{i \in \mathbf{EP}} c_{0i}^{s} \cdot \left({}^{e}x_{0i}^{s} + {}^{p}x_{0i}^{s} \right) + \left(p + c^{ea} \right) \cdot \left(\sum_{i \in \mathbf{EP}} \left(e_{0i}^{s} \cdot {}^{p}x_{0i}^{s} \right) - cap \right) - c^{ea} \cdot \left(cap - \sum_{i \in \mathbf{EP}} e_{0i}^{s} \cdot {}^{e}x_{0i}^{s} \right) + \sum_{i \in \mathbf{EP}} \sum_{j \in \mathbf{DC}} \sum_{m=1}^{M} \left(c_{ij}^{m} + c_{j}^{dc} \right) \cdot x_{ij}^{m}$$

$$+\sum_{i\in \mathbf{EP}}\sum_{j\in \mathbf{DC}}(c_{ij}^{bt}+c_{j}^{dc})\cdot x_{ij}^{bt}+\sum_{w}\sum_{j\in \mathbf{DC}} f_j^w \cdot y_j^w+\sum_{j\in \mathbf{DC}}\sum_{r\in \mathbf{RM}}\left(c_{jr}^{st}\cdot x_{jr}^{st}+c_{jr}^{lt}\cdot x_{jr}^{lt}\right) \qquad (1)$$

Subject to:

Flow Constraints

$$^{e}x_{0i}^{s}+{}^{p}x_{0i}^{s}=\sum_{j\in \mathbf{DC}}\sum_{m=1}^{M}x_{ij}^{m}+\sum_{j\in \mathbf{DC}}x_{ij}^{bt},\ \forall\ i\in \mathbf{EP} \qquad (2)$$

$$\sum_{i\in \mathbf{EP}}\sum_{m=1}^{M}x_{ij}^{m}+\sum_{i\in \mathbf{EP}}x_{ij}^{bt}=\sum_{r\in \mathbf{RM}}\left(x_{jr}^{st}+x_{jr}^{lt}\right),\forall j\in \mathbf{DC} \qquad (3)$$

$$\sum_{j\in DC}\left(x_{jr}^{st}+x_{jr}^{lt}\right)=D_r,\forall r\in \mathbf{RM} \qquad (4)$$

Emissions Trading Constraints

$$^{p}x_{0i}^{s}-M\cdot a\le 0,\quad \forall i\in \mathbf{EP} \qquad (5)$$

$$^{e}x_{0i}^{s}-M\cdot (1-a)\le 0,\ \forall i\in \mathbf{EP} \qquad (6)$$

$$\sum_{i\in \mathbf{EP}}{}^{p}x_{0i}^{s}\cdot e_{0i}^{s}-cap>0 \qquad (7)$$

$$cap-\sum_{i\in \mathbf{EP}}{}^{e}x_{0i}^{s}\cdot e_{0i}^{s}\ge 0 \qquad (8)$$

Block Train Constraints

$$x_{ij}^{bt}/R_j-M\cdot z_{ij}\le 0\ \ \forall i\in \mathbf{EP},\ \forall j\in \mathbf{DC} \qquad (9)$$

$$x_{ij}^{bt}/R_j-N\cdot z_{ij}\ge 0\ \ \forall i\in \mathbf{EP},\ \forall j\in \mathbf{DC} \qquad (10)$$

Capacity Constraints

$$\sum_{i\in \mathbf{EP}}\sum_{m=1}^{M}x_{ij}^{m}/R_j+\sum_{i\in \mathbf{EP}}x_{ij}^{bt}/R_j\ge\sum_{w}S_j^w\cdot y_j^w,\forall j\in \mathbf{DC} \qquad (11)$$

$$\sum_{i\in \mathbf{EP}}\sum_{m=1}^{M}x_{ij}^{m}/R_j+\sum_{i\in \mathbf{EP}}x_{ij}^{bt}/R_j\le\sum_{w}L^w\cdot y_j^w,\forall j\in \mathbf{DC} \qquad (12)$$

$$\sum_{w}y_j^w\le 1,\forall\ j\in \mathbf{DC} \qquad (13)$$

Truck Constraints

$$x_{jr}^{st}/R_r-C_{st}\cdot K_{jr}\le 0,\ \forall j\in \mathbf{DC},\ \forall r\in \mathbf{RM} \qquad (14)$$

$$x_{jr}^{st}/R_r-S\cdot K_{jr}\ge 0,\ \forall j\in \mathbf{DC},\ \forall r\in \mathbf{RM} \qquad (15)$$

$$x_{jr}^{lt}/R_r-C_{lt}\cdot P_{jr}\le 0,\forall j\in \mathbf{DC},\ \forall r\in \mathbf{RM} \qquad (16)$$

$$x_{jr}^{lt}/R_r-C_{st}\cdot P_{jr}>0,\forall j\in \mathbf{DC},\ \forall r\in \mathbf{RM} \qquad (17)$$

Non negativity Constraints

$$x_{ij}^{m}\ge 0 \qquad (18)$$

Table 3: Model Parameters

Parameter	Description
D_r	Mean deterministic demand per planning horizon 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 per TEU from node i to node j
c_{0i}^{s}	Cost of transporting a TEU by ship from the distant loading point to the entry port i
c^{ea}	Cost per t CO_2 emissions (cost of purchasing a CO_2 emissions allowance)
p	Penalty cost per t of CO_2 of non-compliance to the cap
c_{jr}^{st}	Delivery truck transportation cost per TEU load from node j to node r
c_{jr}^{lt}	Heavy duty truck transportation cost per TEU load from node j to node r
e_{0i}^{s}	Ship CO_2 emissions per TEU from the distant loading point to the entry point i (in t)
f_j^w	Leasing cost (during planning horizon) of a distribution centre of size w at node j (this cost includes all operational cost of the dedicated distribution centre and is equal to zero in the option of outsourcing).
c_j^{dc}	Deconsolidation/consolidation cost per TEU at a distribution centre at node j (only in the option of outsourcing).
S_j^w	Minimum cargo flow bound (in TEU) required for utilizing a dedicated distribution centre of size w at node j ($S_j^w = 0$ for the option of shared warehousing).
L^w	Capacity of a distribution centre of size w (L^w is considered infinite for the option of outsourcing)
N	Represents the minimum TEU volume for charging a block train
M	Represents a very large constant
S	Represents a very small constant
R_J	Replenishment orders of the DC from the distant Loading Point during the planning horizon
R_r	Replenishment order of the Regional Market from the DC during the planning horizon
C_{lt}	Full heavy duty truck load capacity expressed in TEUs
C_{st}	Full delivery truck load capacity expressed in TEUs
cap	CO_2 emissions cap (in t)

Eq(2) to Eq(4) guarantee the balance of inbound and outbound flows for each Entry Point, DC, and Regional Market. Eq(5) to Eq(8) guarantee that the amount of CO_2 emissions above the cap will be charged with a penalty plus a CO_2 emissions allowance cost and the amount below the cap will be sold and the earnings will be deducted from the freight rates charged in the routes from the distant loading point to the EPs. Eq(9) and Eq(10) guarantee that a block train will be deployed given a specific number of TEUs (N). Eq(11), guarantees that the activated dedicated DCs will handle at least the minimum TEU flow that justifies their dedicated use; thus, this equation is used only for options Tr-Sh/DC-Ded and Tr-Ded/DC-Ded. Eq(12) guarantees that when a distribution centre is activated, its capacity (size) will be adequate to handle the cargo flow that will pass through it, while Eq(13) allows only one DC in each node. Finally, Eq(14) to Eq(17) guarantee that either a heavy duty or a delivery truck or a combination of both will be employed for transporting the associated flows from the DCs to the RM's. The developed model is an extension of a two-level (entry points and DCs) capacitated location problem, with block train requirements. The model can be solved with most standard MILP solvers, e.g. Lingo® given the size of the problem.

4. Case Study/Managerial Insights

In this section, we demonstrate the implementation of the proposed model in a case study. Specifically, we consider a company's supply chain for transporting white goods in the South Eastern European market that includes Bulgaria, Romania and FYROM with a planning horizon of one year. The replenishment orders from the DCs are set on a monthly basis while from the retail stores on a daily basis (so Rj=12 and Rr=365). The Loading Point is the Port of Shanghai and the Entry Points may be the Ports of Thessaloniki (T), Varna (V), and Constanta (C). We consider 15 Regional Markets with retail delivery centre or store in each capital city satisfying the demand of the entire region. DCs are usually established close to major transportation nodes (e.g. ports) and major population centres. Taken into account the population data and the transportation nodes of the Market, we examine 16 potential DCs located on the 3 Entry Points (Ports of Thessaloniki, Varna, and Constant) and the 15 Regional Market's capitals (Note that Varna and Constanta are Entry Points and Regional market's capitals. To this end, currently the price of the cap is determined by the EU CO_2 emissions stock market and is equal to 4.13 €/t (March 2013).

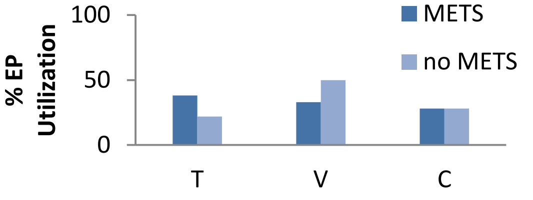

Figure 1: Entry point TEU % flows

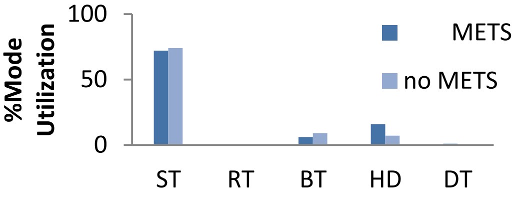

Figure 2: Transportation mode % utilization

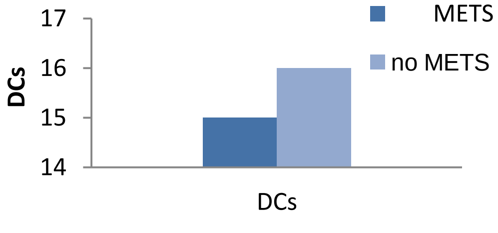

Figure 3: No of operating DCs

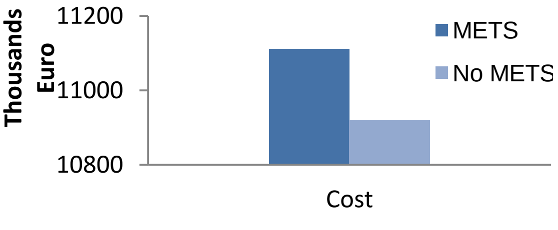

Figure 4: Total supply chain costs

We solved the model for two cases, with and without considering METS. The results indicated that cost minimization could be achieved, for both cases, through the supply chain network structure of option Tr-Ded/DC-Sh. Further on, and in order to demonstrate the effects of implementing METS in supply chain network design we developed the following four Figures for both cases of Option Tr-Ded/DC-Sh. Figure 1 presents the Entry Points (T- Thessaloniki, V - Varna, C - Constanta) included in the optimal network, and the percentage of total flow serviced by each of them. Figure 2 presents the percentage utilization of shipping transportation (ST) from the Loading Point to the Entry Points, of rail (RT), of block train (BT), and of heavy duty truck (HD) from the Entry Points to DCs and heavy duty as also delivery trucks (DT) from the

DCs to the retail stores in both cases. Figure 3 further illustrates the number of utilized DCs while Figure 4 the total logistics cost of option Tr-Ded/DC-Sh in both cases.

Figure 1 illustrates that the design of a supply chain network under METS would increase the number of TEU flows passing through the Entry Point of Thessaloniki. Moreover, as the Thessaloniki Entry Point has more cost effective road connections compared to the Varna and Constanta Entry Points, higher heavy duty truck utilization levels are observed (Figure 2). This in turn, has an effect on the number of operating DCs. In supply chain networks, as inbound flows are usually transported with a more cost effective transportation mode (such as rail or barge) compared to the heavy duty and delivery trucks in the outbound parts, the cost optimal supply chain structure includes more DCs in order to reduce the outbound transportation distances. Under METS, the higher utilization of Thessaloniki as an Entry Port results in higher usage of truck transportation and less rail in the inbound part. This in turn implies a lower difference between the inbound and outbound transportation costs, thus leading to a reduced number of DCs (Figure 3).

5. Conclusions

Supply chain stakeholders can realize significant changes in their supply chain network design decisions if CO_2 emissions cost parameters are incorporated in their decision-making process. We employed a case study to demonstrate the applicability of the proposed methodology. Our analysis indicates that a potential implementation of METS would lead to supply chain structures characterized by shorter shipping transportation routes. This in turn affects the hinterland transportation mode selection decisions and finally decisions on the number of operating DCs.

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