TACTICAL/OPERATIONAL DECISION MAKING FOR DESIGNING GREEN LOGISTICS NETWORKS

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Abstract

Cap and trade regulations along with an increasing consumer and company demand for green products and services constitute two major drivers for motivating corporations to adopt green practices. However, the adoption of such practices usually increases their operational costs. Therefore, the trade-off between "green" and cost-optimal policies is a common challenge for most organizations, at least in developed countries. The purpose of this paper is to assess alternative logistic network design options (applicable in most supply chains) taking into account both their cost and CO_2 emissions performance. The applicability of the proposed methodology is illustrated through the design of a major white good retailer's logistics network in the region of Greece. The results indicate that a company optimizes its cost performance by serving all its retail stores directly by truck through one central distribution center. On the other hand, a CO_2 emissions optimal performance includes additional distribution centers and the employment of rail instead of truck transportation. Moreover, longer review periods, despite the higher holding and backorder costs, result in lower transportation costs and CO_2 emissions.

Keywords: CO_2 emissions, environment, periodic review inventory control system.

1. Introduction

The effect of CO_2 emissions on climate change has been perceived by governments, international organizations and companies. As a result, emissions reduction policies such as emissions trading schemes, green taxes and environmental management systems have been proposed and gradually implemented. Additionally, corporate social responsibility issues have also arisen, designating the importance of a green image as a practice that could lead in higher sales and thus profitability. Thus, companies have started realizing the importance of ensuring a long term competitive advantage based on "green" policies. To this end, "Green Logistics Management" could be defined as the integration of ecological considerations in the design of logistics networks and operations.

In this paper, we propose a framework for examining the effect of both cost and CO_2 emissions minimization objectives on (i) strategic decisions related to the number of operating distribution centers and the type of transportation modes employed and (ii) operational decisions on the selection of entry ports, the determination of ordering, thus transportation, frequencies, along with the level of stocks at the nodes of the logistics network. Considering leased transportation and distribution centers through long term contracts, the above, typically long-term strategic decisions can be characterized as medium-term tactical ones.

Specifically, this paper compares alternative logistics network design options in a supply chain where the nodes employ independent inventory control policies. We focus on a periodic review base stock inventory control policy with the review period being a decision variable. For such a system a new model is employed for calculating the optimal review period and the optimal base stock quantity. Finally, for a specific case study we determine the logistics network design option that exhibits the best cost performance as well as the minimum CO_2 emissions, while providing managerial insights that can be applied in general cases.

The rest of the paper is organized as follows. In Section 2 we present a literature review, while focusing on inventory management techniques and models. Section 3 describes the logistics networks under study and the proposed methodological framework, while Section 4 analyzes the periodic review decision making model. Section 5 illustrates the applicability of the model through a specific case study, while section 6 sums up the findings of this research.

2. Literature Review

Green Logistics related research can be classified in three categories:

(i) strategic policies related to green network design (Li et al., 2008, Mallidis et al., 2012, Wang et al., 2011) as also reverse logistics network design (Fleishmann et al., 1997, Jayaraman et al., 2003, Alumur, et al., 2012) and green warehousing (Mckinnon et al., 2010).

(ii) tactical policies related to inventory management (Chung and Wee, 2011, Chen and Monahan, 2010, Ahiska and King, 2010, Wee et al., 2011, and Hsueh, 2011) and

(iii) operational policies related to vehicle routing (Bektas and Laporte, 2011) and equipment allocation (Beltran et al., 2009).

A detailed overview of related academic research efforts is presented in Dekker et al., (2012).

Specifically for environmental inventory management, Hsueh, (2011) considers product life cycle, inventory control and manufacturing/manufacturing issues simultaneously. To be more specific, he investigates the effect of product life cycle on inventory control in a manufacturing/remanufacturing system and determines the optimal production lot size, reorder point and safety stock during each phase of the product life cycle. Chung and Wee (2011), consider green product design and remanufacturing with the concept of re-usage. To be more specific, they develop a production inventory policy for a short life cycle product with a stationary demand, considering green product design with new technology and remanufacturing. Chen and Monahan (2010), employ a stochastic model with demand and environmental uncertainties. They derive the optimal policies of production planning and inventory control under both regulatory and voluntary pollution control approaches and investigate their operational and environmental impacts. Ahiska and King (2010), consider inventory optimization of a periodically reviewed single product stochastic manufacturing/remanufacturing system, with two stocking points, serviceable and recoverable inventories. The system is modeled using a Markov decision process and searches for the optimal policy that defines how many items to manufacture and remanufacture given the serviceable and recoverable inventory levels and manufacturing or remanufacturing work-in-process. Wee et al., (2011) considers Vendor Managed Inventory (VMI) strategies for the supply chain of a green electronics product. The proposed model determines the replenishment frequency and the order quantity for deteriorating items considering ordering cost, holding cost and deteriorating cost in forward and reverse supply chain. Finally, Bouchery et al., (2012) studies a two-echelon supply chain model where the demand is assumed to be a function of the products price and environmental quality. Then, and through the multi objective formulation of the EOQ model, they examine the impact of batch size on cost and carbon emissions.

The contribution of this manuscript is two-fold. Firstly, we provide a two objective optimization methodology that takes into account the cost and CO_2 emissions that constitute the major determinator of a logistics network environmental footprint. Secondly, we quantify the impact of CO_2 emissions minimization objectives on the design of three realistic logistics network options through extensive full-scale analyses using real data and present managerial insights.

3. Logistics Network Description

We consider a multinational company trading various products with similar characteristics (e.g. white goods or furniture) and its distribution network that serves a specific market. The distribution network is characterized by the number and hierarchy of distribution centers, the transportation modes chosen and the delivery frequency. For geographic and demand reasons, we assume that the market consists of a number of regions where each region is served by a number of retail stores (in this paper we examine two regions, but the proposed models can be extended to include more than two regions).

For the replenishment of the retail stores, we examine three logistic network design options which are defined in Table 1 and illustrated in Figure 1.

In the first option (base case) all the retail stores of both regions are served by one central distribution center on a one-to-one basis using trucks.

In the second option, the retail stores of each region are served by their own dedicated distribution center again with trucks. No collaboration between the distribution centers is allowed either in order placement to the manufacturer, or through laterals transshipments to reduce the stock out probability.

Table 1: Network Design Options

Option	Distribution Operations
DC	One Distribution Centre that serves two Regions
2DC	Two Distribution Centers, one for each Region
DC/SDC	One Central and one Satellite Distribution Center, one for each Region

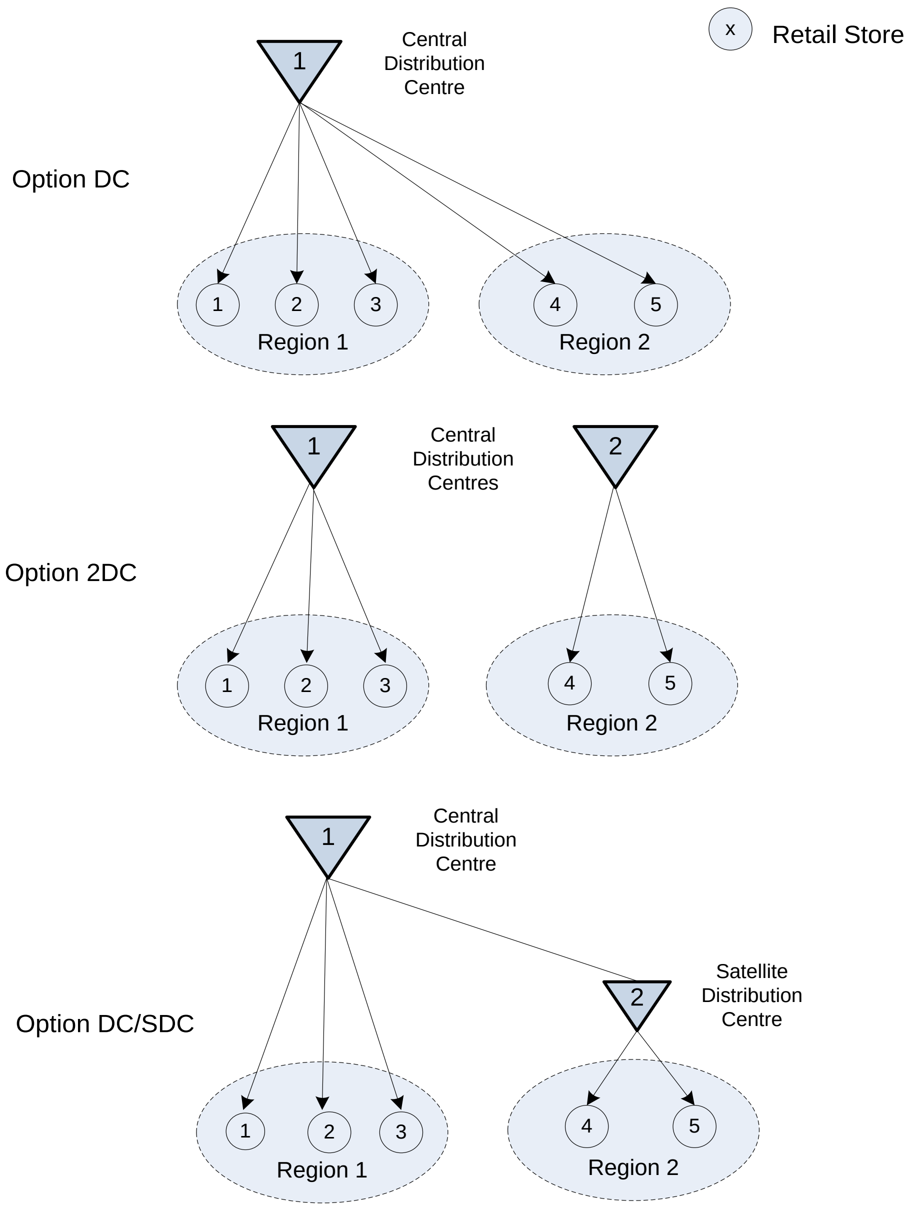

Figure 1: Logistics Network design options

The cost performance of this option depends on the trade-off between the operational cost of the second distribution center, the reduced outbound transportation cost (to the retail stores) and the different inbound transportation cost (to the distribution centers) which could be higher or lower depending on the efficiency of the employed transportation modes. Moreover, the network performance with respect to the emissions depends on the total transportation distances covered and the emission rates of the transportation modes employed.

Finally, the third option includes again two distribution centers with the difference that the second distribution center is replenished only through the first distribution center, thus operating as its satellite. This option is positioned between the first two options, provides similar reduced outbound transportation and less operational costs compared to the second option with an extra transportation for the replenishment of the satellite distribution center from the central distribution center.

Table 2: Performance of the network design options compared to the base case (0) *Option DC*

Performance / **Options**	**Inbound transp.**	**Outbound transp.**	**Inventories**	**DC costs**
DC	0	0	0	0
2 DC	0	-	++	++
1 DC/SDC	+	-	++	+

Remarks: the (-) symbol indicates reduction while the (+) increase.

In all options, we assume that the cargo is transported in containers, from a far away loading port (e.g. in South Eastern Asia) to an entry port, through deep sea shipping. These containers are then transported to central distribution centers, with intermodal connections (road connections for short distances and rail, short sea shipping, barges for longer distances), that serve for example the European or the US market. This assumption implies lengthy lead times from the loading port to the central distribution centers, and thus long replenished periods of a backorder at the central distribution centre. Considering that no customer would wait so long for the delivery of his/her order, we assume that the inventory levels of the central distribution centers must be large enough to satisfy practically all orders from the retail stores they serve. This implies the operation of a very large central distribution centre that exhibits a very low probability of a stock out occurrence.

On the other hand, the satellite distribution centre acts as an intermediate echelon that increases the complexity of the supply chain. However, the capacity of the satellite distribution should be smaller since any unsatisfied demand could be served though the back-up central distribution center.

Each retail store faces random demand. The analysis focuses on fast moving items/products for which the retail store employs a base stock periodic review ordering policy (R,S) for the replenishment of their stock from the distribution center (central or satellite depending on the option). The review periods of the retails stores are independent decision variables. The distribution centers (both central and satellite) also employ periodic review policies, but with predefined review periods, usually determined by the delivery frequency of the transportation mode employed for their replenishment. Specifically, the review period of the central distribution centers in all options is determined by the liner deep sea shipping schedule between the distant loading and the entry port, while the review period of the satellite distribution center of *Option DC/SDC* by the short sea shipping or the rail transportation schedule between the entry port and the nearby discharge terminal.

Finally, the distribution center facilities as well as the trucks are assumed to be leased through long term contracts and are therefore dedicated to serve the company. Thus, in case of trucks the company will be also accountable for the cost and the CO_2 emissions of their return trip.

4. Model Development

We examine whether splitting up a supply chain into two separate parts is worthwhile from a cost and an emission perspective. We assume that the splitting up into two regions is more or less predefined. Let $\mathbf{M_1}$, $\mathbf{M}_2$ denote the subset of retail stores serving regions 1 and 2 respectively. Each retail store m, $m \in \mathbf{M} = \mathbf{M_1} \cup \mathbf{M_2}$ faces stochastic demand per time unit for product p ($p \in \mathbf{P}$) with a probability density function $\varphi_m^p(\cdot)$ and a cumulative probability density function $\Phi_m^p(\cdot)$. In our analysis, we assume that the demand of product p per time unit at the retail store m follows a normal distribution with a mean μ_m^p and a standard deviation σ_m^p. We consider that demand is independently distributed in all time units. Each retail store employs a periodic review inventory control policy with a review period of R_m time units. At the review epochs, the order size is set as such in order to raise the inventory position of product p to S_m^p. The order arrives after a deterministic lead time L_m (common for all products of a specific retail store).

Following the standard analysis like in Silver, et al., (1998), the base stock quantity S_m^p can be written as the sum of the mean demand during the protection period $R_m + L_m$ and the safety stock, $z_m^p \cdot \sigma_m^p \sqrt{R_m + L_m}$ where z_m^p represents the safety stock factor for product p at the retail store m and determines its service level. .

$$S_m^p = \mu_m^p (R_m + L_m) + z_m^p \cdot \sigma_m^p \sqrt{R_m + L_m} \quad \forall m, p \tag{1}$$

. The typical expected cost formulas that appear in textbooks for a (R,S) model, charge backorder quantities once at the end of the review cycle. If we implement these formulas in our case, where the review period is a decision variable, the expected back orders of a specific retail store will be charged with different frequencies depending on the review period. Thus, for example, for a planning horizon of 100 time units and a review period of 10 time units, the backorder cost will be charged 10 times during the planning horizon. If we double the review period, the backorder cost will be charged only 5 times during the same planning horizon. Thus, it is not possible to compare the systems performance for different review periods. Therefore, in order to be able to compare policies with different review periods, we need a model that calculates on-hand and backorder levels continuously for every time unit. To this end, we develop a new modeling methodology, similar to that of Ray et al. (2010).

The general notation related to the proposed cost and emissions models as well as the methodology for the determination of (a) the expected on-hand and backorder quantities at the retail store and (b) the expected on hand quantities at the central distribution centre are presented in the following section for the first network option under study, while the additional notation and the necessary methodological modifications for the other options are discussed in their associated sections.

4.1 Option DC

Since the inventory control decisions of the retail stores are determined independently, we initially focus on a single retail store. To determine the expect total cost and total emissions of supplying any retail store, the steady state analysis concentrates on a typical replenishment cycle of length R_m time units, defined by the times of arrival of two consecutive orders. Specifically, if an order is placed at time 0 (review epoch), the next regular order will be placed at time R_m and it will arrive at time R_m+L_m. The replenishment cycle of interest is the time interval starting at the beginning of time unit L_m and ending at the end of time unit R_{m+} L_m.

A typical realization of inventory levels (net stock and inventory position) and orders is shown in Figure 2 for a system with $L_m < R_m$ and operating according to the rules described above.

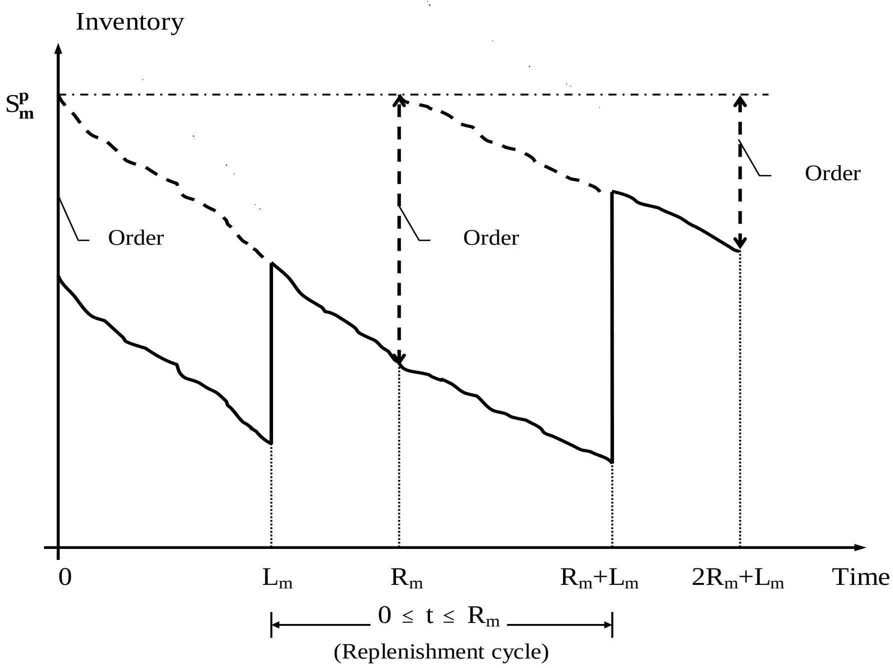

Figure 2: Evolution of net stock (solid line) and inventory position (dashed line) in a periodic review system using the base stock (order up to S) policy.

The expected on-hand and back order quantity of product p at any retail store m at time t is given by equations (2) and (3) respectively.

$$E\left[OH_m^p(t)\right] = \int_0^{S_m^p} \left(S_m^p - x\right) \varphi_{m\,L_m+t}^p(x)\,dx \qquad (2)$$

$$E\left[BO_m^p(t)\right] = \int_{S_m^p}^{\infty} \left(x - S_m^p\right) \varphi_{m\,L_m+t}^p(x)\,dx \qquad (3)$$

where $\varphi^{p}_{m\,(L_m+t)}(x)$ is the pdf of the demand of L_m+ t time units. Following the standard analysis for calculating expected on-hand quantities (Silver et al., 1998, pp. 721-724), equations (2) and (3) for normal demand can be easily transformed to:

$$E\left(OH^{p}_{m}(t)\right)=\sigma^{p}_{m}\sqrt{L_m+t}\left[\varphi^{p}_{m\,(L_m+t)}\left(k^{p}_{m}(t)\right)+k^{p}_{m}(t)\cdot\Phi^{p}_{m\,(L_m+t)}\left(k^{p}_{m}(t)\right)\right] \tag{4}$$

$$E\left(BO^{p}_{m}(t)\right)=\sigma^{p}_{m}\sqrt{L_m+t}\left[\varphi^{p}_{m\,(L_m+t)}\left(k^{p}_{m}(t)\right)-k^{p}_{m}(t)\left(1-\Phi^{p}_{m\,(L_m+t)}\left(k^{p}_{m}(t)\right)\right)\right] \tag{5}$$

where $k^{p}_{m}(t)$ represents the safety stock factor at time t, which is equal to z^{p}_{m} for t = R_m, i.e. $z^{p}_{m}=k^{p}_{m}(R_m)$. Moreover, S^{p}_{m} can also be calculated from equation (6):

$$S^{p}_{m}=\mu^{p}_{m}(L_m+t)+k^{p}_{m}(t)\cdot\sigma^{p}_{m}\sqrt{L_m+t},\quad 0\le t\le R_m \tag{6}$$

From eqs. (1), (6) we derive equation (7)

$$k^{p}_{m}(t)=\frac{\mu^{p}_{m}}{\sigma^{p}_{m}}\cdot\frac{R_m-t}{\sqrt{L_m+t}}+z^{p}_{m}\cdot\frac{\sqrt{L_m+R_m}}{\sqrt{L_m+t}}\quad 0\le t\le R_m \tag{7}$$

which can be used in eq. (4) and (5). The central distribution center (DC) faces the collective demand of the retail stores, which is normally distributed during its replenishment cycle R_{DC}. Its lead time, L_{DC}, is also considered deterministic. Consequently, the expected time-average on hand inventory level of product p at the DC, assuming that backorders are incurred only in very small quantities (Ray et al., 2010), can be estimated as:

$$E\left(OH^{p}_{DC}(R_{DC})\right)\approx z^{p}_{DC}\cdot\sqrt{\sum_{m\in M}(\sigma^{p}_{m})^{2}\cdot(R_{DC}+L_{DC})}+\frac{R_{DC}\cdot\sum_{m\in M}\mu^{p}_{m}}{2} \tag{8}$$

Where z^{p}_{DC} represents the safety stock factor for product p at the DC.

Finally, as larger DCs exhibit higher costs and emissions, we have to make an assessment of their capacities required in the examined options. Hence, we make an assumption that the capacity of the DC, K_{DC}, must be large enough to handle the peak demand of all products from its serving retail stores during a long planning horizon. Such capacity could consist of a quantity reserved for that safety stock that results in a negligible probability of a stock out occurrence (z^{p}_{DC} = 4, corresponding to a cycle service level of almost 1), denoted by $4\cdot\sqrt{\sum_{m\in M}(\sigma^{p}_{m})^{2}\cdot(R_{DC}+L_{DC})}$ and the peak net stock quantity (the net stock after order arrival), which can be approximated as $R_{DC}\cdot\sum_{m\in M}\mu^{p}_{m}$. We take the capacity somewhat on the conservative side in order to have some empty space. Please note that we are only concerned in making a comparison between options, in which we apply the same capacity assumption.

The proposed cost structure includes the holding cost per time unit of product p, denoted by h^p and charged on the expected on-hand inventory level of product p, at any retail store as well as the DC. The backorder cost per time unit of product p, denoted by b^p, charged on the expected backorder level of product p, at any retail store. The truck transportation cost per trip from the entry port to the DC is denoted by c_{DC}, while the truck transportation per roundtrip from the DC to the retail store m is denoted by c_m. Specifically for the transportation part between the entry port and the DC and assuming that one truck can transport one container, c_{DC} is charged on the total number of container trips required for serving the total shipment to the DC. The number of container trips needed to transport the total demand of the DC during its replenishment cycle R_{DC} can be calculated as the ceiling function $\left\lceil \left(R_{DC} \cdot \sum_{m \in M} \sum_{p \in P} \mu_m^p \right) / FCL \right\rceil$ where FCL represents the full container loading capacity. For the transportation part between the DC and the retail stores though, and since containers are deconsolidated at the DC, the products are transported loose in trucks. Thus, truck roundtrips are considered and therefore, c_m is charged on the total number of truck roundtrips required for serving the total demand of a retail store m during its review period. The number of truck roundtrips can be calculated again as the ceiling function $\left\lceil \left(R_m \cdot \sum_{p \in P} \mu_m^p \right) / FTL \right\rceil$, where FTL denotes the full truck load capacity. Finally, the operational cost of the DC per time unit is assumed as a non-linear function of its capacity K_{DC}, denoted by $G(K_{DC})$. Thus, the expected total cost $E(TC_{DC})$ of *Option DC* per time unit is given by:

$$\begin{aligned} E(TC_{DC}) = & \sum_{m \in M} \sum_{p \in P} \left[h^p \frac{1}{R_m} \cdot \int_0^{R_m} E(OH_m^p(t))\, dt + b^p \frac{1}{R_m} \cdot \int_0^{R_m} E(BO_m^p(t))\, dt \right] \\ & + \sum_{m \in M} c_m \cdot \frac{1}{R_m} \left\lceil \left(R_m \cdot \sum_{p \in P} \mu_m^p \right) / FTL \right\rceil + c_{DC} \cdot \frac{1}{R_{DC}} \left\lceil \left(R_{DC} \cdot \sum_{m \in M} \sum_{p \in P} \mu_m^p \right) / FCL \right\rceil \\ & + \sum_{p \in P} h^p E(OH_{DC}^p(R_{DC})) + G(K_{DC}) \end{aligned} \tag{9}$$

The emission-related parameters incorporate the transportation CO_2 emissions between the entry port and the DC, denoted by e_{DC} and between the DC to any retail store m, denoted by e_m. The emission parameter e_{DC} is charged on the total number of container trips required for serving the total demand of the DC during its replenishment period while e_m on the total number of truck roundtrips required for serving the total demand of the retail store m during its replenishment period from the DC.

Finally, the CO_2 emissions related to the operation of the DC per time unit is also assumed as a non-linear function of its capacity, denoted by $H(K_{DC})$. The expected total CO_2 emissions per time unit for the DC option are given by:

$$E(TE_{DC}) = \sum_{m\in M} e_m \cdot \frac{1}{R_m} \cdot \left\lceil \left(R_m \cdot \sum_{p\in P} \mu_m^p \right) / FTL \right\rceil + e_{DC} \cdot \frac{1}{R_{DC}} \left\lceil \left(R_{DC} \cdot \sum_{m\in M} \sum_{p\in P} \mu_m^p \right) / FCL \right\rceil + H \; K_{DC} \qquad (10)$$

Since the decision variables related to the DC (z_{DC}^p for each product p, and R_{DC}) are considered predefined the associated part of the objective functions (9) and (10) is constant. Thus, to obtain the optimal values of the decision variables related to any retail store, we have to optimize only the first two (out of the five) terms of (9) and only the first term of (10).

Proposition 1:

For given R_m, the optimal value of the $z_m^p = k_m^p(R_m)$ for product p at the retail store m is derived from:

$$\int_0^{R_m} \Phi_{m\,(L_m+t)}^p \; k_m^p(t)\; dt = \frac{b^p \cdot R_m}{h^p + b^p} \qquad (11)$$

Proof:

See Appendix

Employing proposition 1 and a grid search algorithm, we can easily determine the optimum value of R_m, which minimizes the expected total cost.

With respect to CO_2 emissions, the safety factor z_m^p does not appear in the total emissions objective function. Thus, the optimal R_m is obtained using again a grid search algorithm.

4.3 Option 2DC

In the logistics network design *Option 2DC*, the retail stores of subsets $\mathbf{M_1}$ and $\mathbf{M_2}$ are now served by two independent central distribution centers, DC_1 and DC_2 respectively. Thus, the optimal decisions variables that minimize total costs and CO_2 emissions are obtained by employing twice the methodology used for *Option 2DC*, once for each central distribution center.

Moreover, in order to make this option comparable to the other options (especially the third one), we assume that the replenishment order of DC_2 from the distant loading port, firstly arrives at the entry port that serves DC_1, and is then transshipped to DC_2 by rail/barge/feeder ship through the discharge terminal. Since retail stores $m \in M_2$ are now served by DC_2, their lead time will be lower compared to that of *Option DC*. However, the lead time of supplying DC_2, L_{DC_2}, is higher than the lead time of supplying DC_1 due to the additional transportation required. Moreover, additional parameters for the transportation cost and CO_2 emission are considered, and are related to the transportation from the entry port to the discharge terminal. This cost parameter is denoted by c_{DT}, while the emissions parameters by e_{DT}. These parameters are charged on the total number of container trips, $\left\lceil \left(R_{DC} \cdot \sum_{m\in M_2} \sum_{p\in P} \mu_m^p \right) / FCL \right\rceil$, required for transporting the entire demand of DC_2 during its replenishment cycle R_{DC} (common for the central distribution centers in all options). Additionally, the c_{DC} and e_{DC} parameters of *Option DC* are now charged on the total number of container trips required to transport the demand of the retail stores of M_1 and M_2, separately instead of the entire demand of all retail stores belonging to M as in *Option DC*. Finally, the cost and CO_2 emissions related to the operation of DC_1 and DC_2 per time unit are also assumed as non-linear functions of their capacity. Thus, the expected total cost and CO_2 emissions per time unit for *Option 2DC* are given by:

$$\begin{aligned}
E\ TC_{2DC} = & \sum_{m\in M}\sum_{p\in P}\left[h^p \frac{1}{R_m}\cdot\int_0^{R_m} E\ OH_m^p(t)\ dt + b^p \frac{1}{R_m}\cdot\int_0^{R_m} E\ BO_m^p(t)\ dt\right] \\
& + \sum_{m\in M} c_m\cdot\frac{1}{R_m}\left\lceil\left(R_m\cdot\sum_{p\in P}\mu_m^p\right)/FTL\right\rceil + c_{DC}\cdot\frac{1}{R_{DC}}\left\lceil\left(R_{DC}\cdot\sum_{m\in M_1}\sum_{p\in P}\mu_m^p\right)/FCL\right\rceil \\
& + \sum_{p\in P} h^p E\ OH_{DC_1}^p(R_{DC}) + G\ K_{DC_1} + c_{DT} + c_{DC}\cdot\frac{1}{R_{DC}}\left\lceil\left(R_{DC}\cdot\sum_{m\in M_2}\sum_{p\in P}\mu_m^p\right)/FCL\right\rceil \\
& + \sum_{p\in P} h^p E\left(OH_{DC_2}^p(R_{DC})\right) + G\left(K_{DC_2}\right)
\end{aligned} \tag{12}$$

$$\begin{aligned}
E\ TE_{2DC} = & \sum_{m\in M} e_m\cdot\frac{1}{R_m}\cdot\left\lceil\left(R_m\cdot\sum_{p\in P}\mu_m^p\right)/FTL\right\rceil + e_{DC}\cdot\frac{1}{R_{DC}}\left\lceil\left(R_{DC}\cdot\sum_{m\in M_1}\sum_{p\in P}\mu_m^p\right)/FCL\right\rceil + H\ K_{DC_1} \\
& + e_{DT} + e_{DC}\cdot\frac{1}{R_{DC}}\left\lceil\left(R_{DC}\cdot\sum_{m\in M_2}\sum_{p\in P}\mu_m^p\right)/FCL\right\rceil + H\ K_{DC_2}
\end{aligned} \tag{13}$$

The optimization methodology is the same as the one employed for *Option DC*.

4.4 Option DC/SDC

In the third logistics network option, instead of the second independent distribution center of *Option 2DC*, a satellite distribution centre (SDC) is established in the same location (that continues serving the retail stores belonging to the subset $\mathbf{M_2}$).

SDC also employs a periodic review inventory control policy, with a predefined review period R_{SDC} and a lead-time L_{SDC} and its orders are fulfilled by the DC (that now faces the collective demand of all retail stores as in *Option DC*). L_{SDC} will now be lower than L_{DC_2} of *Option 2DC*, since SDC is supplied by the central DC in contrast to DC_2 which is supplied by distant loading port.

Additionally, the drayage costs and emissions c_{DC} and e_{DC} parameters of *Options DC* and *2DC* are now charged three times instead of two as in *Option 2DC*. The first time, on the number of container trips required for transporting the total demand of the DC during R_{DC}, from the entry port to the DC while the second and third times, on the number of container trips required for transporting the total demand of the SDC, during R_{SDC}, from the DC to the entry port and from the discharge terminal to the SDC respectively.

Finally, the c_{DT} and e_{DT} parameters of *Option 2DC* are now charged on the total number of container trips required for transporting the total demand of the SDC during R_{SDC} instead of the total demand of DC_2 during R_{DC}.

Moreover, the backup replenishment of the SDC from the DC allows for lower service levels at the SDC (compared to the very high service levels of central distribution centers) and thus, the backorder cost may be significant and it should be included in the expected total cost. The backorder cost parameter, denoted by b^p_{SDC}, is charged on the expected number of backorders of product p at the end of the replenishment cycle R_{SDC}, which can be determined by:

$$E\left[BO^p_{SDC}(R_{SDC})\right] = \int_{S^p_{SDC}}^{\infty} \left(x - S^p_{SDC}\right) \varphi^p_{SDC\ R_{SDC}+L_{SDC}}(x)\,dx \qquad (14).$$

The above equation can be easily transformed based on Silver et al., (1998)

to: $$E\left[BO^p_{SDC}(R_{SDC})\right] = \sigma^p_{SDC}\sqrt{R_{SDC}+L_{SDC}}\left[\varphi^p_{SDC\ R_{SDC}+L_{SDC}}\left(z^p_{SDC}\right) - z^p_{SDC}\cdot\left(1-\Phi^p_{SDC\ R_{SDC}+L_{SDC}}\left(z^p_{SDC}\right)\right)\right]$$

(15)

where $\varphi^p_{SDC\ R_{SDC}+L_{SDC}}\left(z^p_{SDC}\right)$ represents the pdf of the normally distributed demand for product p at the SDC during $R_{SDC}+L_{SDC}$ time units and z^p_{SDC} the safety stock factor of product p at the SDC.

Moreover, the holding cost per time unit of product p at the SDC is charged on the expected on hand inventory level of product p at the SDC, $E\left[OH^p_{SDC}(R_{SDC})\right]$, estimated similarly to (8). Finally the operational costs and CO_2 emissions of the SDC are expressed as a non linear function of its capacity K_{SDC} estimated again similarly to that of the DC. Thus, the expected total cost and CO_2 emissions per time unit of *Option DC/SDC* can be estimated as:

$$\begin{aligned}
E\left[TC_{DC/SDC}\right] = &\sum_{m\in M}\sum_{p\in P}\left[h^p\frac{1}{R_m}\cdot\int_0^{R_m} E\left[OH^p_m(t)\right]dt + b^p\frac{1}{R_m}\cdot\int_0^{R_m}E\left[BO^p_m(t)\right]dt\right] \\
&+\sum_{m\in M} c_m\cdot\frac{1}{R_m}\left\lceil\left(R_m\cdot\sum_{p\in P}\mu^p_m\right)/FTL\right\rceil + c_{DC}\cdot\frac{1}{R_{DC}}\left\lceil\left(R_{DC}\cdot\sum_{m\in M}\sum_{p\in P}\mu^p_m\right)/FCL\right\rceil \\
&+\sum_{p\in P}h^p E\left[OH^p_{DC}(R_{DC})\right] + G\left(K_{DC}\right) + \left(c_{DT}+2\cdot c_{DC}\right)\cdot\frac{1}{R_{SDC}}\left\lceil\left(R_{SDC}\cdot\sum_{m\in M_2}\sum_{p\in P}\mu^p_m\right)/FCL\right\rceil \\
&+\sum_{p\in P}h^p E\left(OH^p_{SDC}(R_{SDC})\right) + \sum_{p\in P}b^p_{SDC}\frac{1}{R_{SDC}}E\left(BO^p_{SDC}(R_{SDC})\right) + G\left(K_{SDC}\right)
\end{aligned} \qquad (16)$$

$$\begin{aligned}
E\left[TE_{DC/SDC}\right] = &\sum_{m\in M} e_m\cdot\frac{1}{R_m}\cdot\left\lceil\left(R_m\cdot\sum_{p\in P}\mu^p_m\right)/FTL\right\rceil + e_{DC}\cdot\frac{1}{R_{DC}}\left\lceil\left(R_{DC}\cdot\sum_{m\in M}\sum_{p\in P}\mu^p_m\right)/FCL\right\rceil + H\left(K_{DC}\right) \\
&+\left(e_{DT}+2\cdot e_{DC}\right)\cdot\frac{1}{R_{SDC}}\left\lceil\left(R_{SDC}\cdot\sum_{m\in M_2}\sum_{p\in P}\mu^p_m\right)/FCL\right\rceil + H\left(K_{SDC}\right)
\end{aligned} \qquad (17)$$

The cost and emissions optimization methodologies for the retail stores of Region 1 and the emissions optimization methodologies for the retail stores of Region 2 and the SDC are the same as those employed for *Options DC and 2DC*. For the cost optimization of the retail stores of Region 2 and the SDC though, the optimization methodologies are different. For the retail stores of Region 2, a stock out at the SDC would increase the time required for the fulfillment of a customer order, by the additional time needed to place this order to and receive it from the DC. Thus, the end customer perceives various lead times depending on the availability of their order at the SDC. To address this issue we employ the effective (expected value) lead time, denoted by $L_m^{p'}$, for the product p at the retail store m estimated by:

$$L_m^{p'} = \Phi_{SDC\ R_{SDC}+L_{SDC}}^{p}\left(z_{SDC}^{p}\right) \cdot L_m + \left(1-\Phi_{SDC\ R_{SDC}+L_{SDC}}^{p}\left(z_{SDC}^{p}\right)\right) \cdot \left(L_m + L_{SDC} + \frac{R_{SDC}}{2}\right) \qquad (18),$$

where $\Phi_{SDC\ R_{SDC}+L_{SDC}}^{p}\left(z_{SDC}^{p}\right)$, represents the cdf of the normally distributed demand for product p at the SDC during $R_{SDC}+L_{SDC}$ time units (or the service level α) and $1-\Phi(z_{SDC}^{p})$ the probability of a stock out occurrence of product p at the SDC**.** Finally**,** $\frac{R_{SDC}}{2}$ represents the mean delay due to the periodicity of shipments from the DC. If we substitute the L_m parameter of equations (4) and (5), with the effective lead time $L_m^{p'}$ and given the first two terms of equation (16) we observe that the decision variables at the retail stores of Region 2 depend on the z_{SDC}^{p} decision variables at the SDC. Thus, and since the z_{SDC}^{p} decision variables for the products p at the SDC are not predefined we have to jointly determine the optimal values of the decision variables at the retail stores of Region 2 and the SDC. This condition makes the analysis complex and thus an analytical solution is mathematically intractable. Therefore, the optimum values of the R_m, z_m^p decision variables at the retail stores of Region 2 and the z_{SDC}^{p} decision variables at the SDC can be only determined by exhaustive grid search.

5. Case Study

We consider the logistics network of a white goods retailer, which distributes its products in the Greek market. We examine the supply of three fast moving products (refrigerators, washing machines, and ovens) that result in approximately 80% of the total sales. Since products under study are volume intensive the volume (in m^3) is employed as a measurement unit for the examined items. We assume that the products demand per day at the retail stores is normally distributed with a coefficient of variation (cv=0.3). Moreover, we assume that the associated products are transported in 40ft containers.

The first logistics network consists of one entry port (**P_o**) that of Piraeus, one DC, located in Aspropirgos (**DC_1**), the central logistics area of Athens, and two regions. The first region includes three privately owned retail stores in wider Athens (Marousi-**RM_1**, Argiroupoli-**RM_2**, Peristeri-**RM_3**), and the second one includes two retail stores, one in Larissa-**RM_4** and one in Thessaloniki-**RM_5**. The **DC_2** or **SDC** of

Options 2DC and *1DC/SDC* respectively is located in Kalochori and served by rail, through the rail terminal of Thessaloniki (RT) located nearby it. Since the loading and transportation times from Piraeus rail terminal to Thessaloniki rail terminal is approximately one day, the lead time of $\mathbf{DC_2}$ is one day longer than the lead time of $\mathbf{DC_1}$**,** while the lead time of SDC is one day plus the transportation time between the entry port and $\mathbf{DC_1}$ as discussed earlier. In all options, product flows to the retail stores of the first region are transported in delivery trucks with a carrying capacity of 35 m^3, while to the retail stores of the second region in heavy duty trucks with a carrying capacity of 66 m^3.

The review periods of the DCs and the SDC are 32 and 8 days respectively, while the allowable values for the review periods of the retail stores (decision variables) are assumed to be powers of two.

5.1 Calculation of the transportation and distribution center cost and CO2 emissions parameters

In the following paragraphs we describe the methodology employed for calculating the transportation costs and CO_2 emissions as also distribution centers operational costs and CO_2 emissions for the logistics network design options under study.

Truck costs

We had access to heavy-duty and delivery truck transportation costs from a transportation company per trip in the routes of the logistics network design options under study. These costs incorporate the truck leasing costs, assuming that the truck is utilized for 90% of the day, the truck driver's expenses, its maintenance and repair costs, its fuel costs and the toll costs per trip. In order to derive the transportation cost per roundtrip we also charge the return trip which is assumed to be 20% less. This reduction reflects the reduction in the amount of fuel consumed by the empty running truck in the return trip.

Truck CO_2 emissions

Boer et al. (2011) provide fixed CO_2 emissions amounts per km produced by the fully loaded heavy duty and delivery trucks employed in our analysis. Moreover and since trucks are assumed to be leased, the company will be also accountable for the CO_2 emissions amounts produced by the empty truck on the return trip. In this case and in order to incorporate the impact of lower loading factors we assume that the emissions per km for the empty trucks will be approximately 31% less (Coyle 2007).

Rail Cost

The rail costs considered in the analysis, have been retrieved by the Greek Railway Organization and incorporate a block train freight rate of 386€ per 40 ft cntr trip.

Rail CO_2 emissions

The rail transportation emissions are calculated based on an average fixed amount of 27.91g/t-km of CO_2 emissions (Ebert, 2005). The distance considered between the entry port of Piraeus and the rail station of Thessaloniki is estimated to be approximately 516 km. Thus and assuming that the 40 ft cntr has an average weight of 8 tons we have estimated an average value of 0.115 tons of CO_2 emissions per 40 ft container trip.

Table 3 summarizes the transportation costs and CO_2 emissions along with the distances and the lead times of the routes in the network under study. (D) Represents the delivery truck, (HD) the heavy duty truck and (R) the rail transportation. Moreover (RT), represents a roundtrip, while (T), the 40ft cntr trip.

Table 3: Transportation costs, CO_2 emissions, lead times and distances in the options under study

Route	Options	Tr. type	Cost (€)	CO_2 (tons)	Lead time (days)	Dist. (kms)
DC_1-RM_1-DC_1	All	D	252/RT	0.017/RT	0.05	24.3
DC_1-RM_2-DC_1	All	D	288/RT	0.020/RT	0.06	28.5
DC_1-RM_3-DC_1	All	D	218/RT	0.020/RT	0.06	28.5
DC_1-RM_4-DC_1	DC	HD	720/RT	0.49/RT	0.40	359.0
DC_1-RM_5-DC_1	DC	HD	1000/RT	0.71/RT	0.60	526.0
DC_2-RM_5-DC_2	2DC, 1DC/SDC	HD	270/RT	0.011/RT	0.03	8.0
DC_2-RM_4-DC_2	2DC, 1DC/SDC	HD	365/ RT	0.20/ RT	0.15	147.0
EP-DC/DC_1	All	HD	150/T	0.021/T	0.03	8.0
RT-DC_2/SDC	All	HD	150/T	0.021/T	0.03	8.0
EP-DT	2DC, 1DC/SDC	R	386/T	0.110/T	1.00	516

DCs operational costs and CO_2 emissions

We have retrieved data from various companies on the dimensions, operating costs and electricity consumption of various sized distribution centers established in Greece. The costs considered incorporate, leasing or depreciation costs, salary and forklift costs and other operational expenses, such as electricity and telecommunication costs, etc. Regarding the electricity consumption data (in KWh) and in order to convert them into CO_2 emissions we consider a value of 761 g/KWh (Greek Energy efficiency report, 2011). Table 4 summarizes the capacity (in m^3) and the daily operating costs and CO_2 emissions of the examined distribution centers, assuming an 80% utilization of their height and space.

Table 4: Capacity and cost parameters for various sized DCs

Capacity (m^3)	Operating costs €/day	CO_2 emissions tons/day

100,000	2,740	0.36
39,580	2,192	0.26
32,400	1,579	0.28
14,112	667	0.14
8,400	700	0.08
2,000	217	0.05
1,000	150	0.04

Given the above data we developed two logarithmic regression equations. The first one is employed for estimating the distribution centers operating costs c per day for a given capacity k while the second one for the distribution centre CO_2 emissions e per day for a given capacity k.

Distribution centre operational cost per day: $c = 564.6\ln(k) - 4{,}112.5$ (€)

Distribution centre CO_2 emissions per day: $e = 0.0721\ln(k) - 0.5034$ (tons CO_2),

For $1{,}000\ m^3 < k < 100{,}000\ m^3$

5.2 Model development and results

We solved 6 instances of the model by combining the three logistics network design options of table 1 with the two optimization criteria, cost and CO_2 emissions. Table 5 depicts the mean daily demands for these products at the examined retail stores while table 6 the holding and backorder costs of the product under study. Moreover, Tables 7 and 8 depict the optimum values of the R_m, z_m^p , z_{SDC}^p , decision variables under the cost and CO_2 emissions optimization criteria respectively. Since products under study are similar, the holding and backorder costs are expressed in the same proportion to their unit price. Therefore, the optimal service levels for these products in each retail store depend only on their review period. Finally, and for the CO_2 emissions optimization criterion, the optimum z_m^p decision variable values for the products p of retail store m are estimated by substituting the optimum R_m, in terms of CO_2 emissions, into equation (11).

Table 5: Mean daily demand for the products of the retail stores under study

Products / Retail Stores	Refrigerators	Washing Machines	Ovens
RM_1	30	30	40
RM_2	20	25	20

RM_3	25	15	20
RM_4	40	35	25
RM_5	50	40	30

Table 6: Holding and backorder costs per item/day.

Products / Retail Stores	Refrigerators		Washing Machines		Ovens	
	Hold.C.	**Back.C.**	**Hold.C.**	**Back.C.**	**Hold.C.**	**Back.C.**
RM_1	0.7	35	0.5	25	0.4	20
RM_2	0.7	35	0.5	25	0.4	20
RM_3	0.7	35	0.5	25	0.4	20
RM_4	0.7	35	0.5	25	0.4	20
RM_5	0.7	35	0.5	25	0.4	20

Table 7: Decision variable values under the cost minimization objective

Options / Retail Stores	DC		2DC		1DC/SDC		
	$z_m^{1,2,3}$	R_m **(days)**	$z_m^{1,2,3}$	R_m **(days)**	$z_m^{1,2,3}$	R_m **(days)**	$z_{SDC}^{1,2,3}$
RM_1	2.06	1	2.06	1	2.06	1	-
RM_2	2.06	1	2.06	1	2.06	1	-
RM_3	1.42	4	1.42	4	1.42	4	-
RM_4	1.42	4	2.06	1	2.06	1	-
RM_5	2.06	1	2.06	1	2.06	1	-
SDC	-	-	-	-	-		1.3

Table 8: Decision variable values under the CO_2 emissions minimization objective

Options / Retail Stores	DC		2DC		1DC/SDC		
	$z_m^{1,2,3}$	R_m **(days)**	$z_m^{1,2,3}$	R_m **(days)**	$z_m^{1,2,3}$	R_m **(days)**	$z_{SDC}^{1,2,3}$
RM_1	1.05	8	1.05	8	1.05	8	-
RM_2	1.05	8	1.05	8	1.05	8	-
RM_3	0.32	32	0.32	32	0.32	32	-
RM_4	0.32	32	0.32	32	1.05	8	-
RM_5	0.32	32	0.32	32	1.05	8	-
SDC	-	-	-	-	-	-	1.3

We observe that the CO_2 emissions optimal solutions exhibit higher review periods compared to their respective cost optimal solutions. As higher review periods reduce transportation frequencies, transportation CO_2 emissions are also reduced. For the cost optimal solutions though, higher review periods reduce on one hand transportation costs, but on the other hand increase holding and backorder costs. Thus, in this case the review periods tend to be lower. The above statement can be clearly identified in the following tables 9 and 10. Moreover the behavior of these cost and CO_2 emissions parameters for higher review periods is explained in more detail by the following Figure 2.

Table 9: holding and backorder cost break down (€/day) of the options under study

Options	Opt. Crit.	Holding Cost					Backorder Cost				
		RMs	DC	DC_1	DC_2	SDC	RMs	DC	DC_1	DC_2	SDC
DC	Cost	293	4,642	-	-	-	40	-	-	-	-
2DC	Cost	261	-	2,396	2,557	-	29	-	-	-	-
1DC/SDC	Cost	202	4,642	-	-	592	32	-	-	-	22.4
DC	CO_2	2,702	4,642	-	-	-	184	-	-	-	-
2DC	CO_2	2,595	-	2,396	2,557	-	185	-	-	-	-
1DC/SDC	CO_2	1,277	4,642	-	-	576	112	-	-	-	34.0

Remark: we exclude the ocean transportation costs and emissions which are the same in all options.

Table 10: Transportation and DC operating cost breakdown (€/day)

Options	Optim. Crit.	Transportation Costs					DC Operational Costs			
		RMs	DC	DC_1	DC_2	SDC	DC	DC_1	DC_2	SDC
DC	Cost	4,974	1,013	-	-	-	1,329	-	-	-
2DC	Cost	2,984	-	558	1,943	-	-	955	953	-
1DC/SDC	Cost	2,984	1,013	-	-	2,487	1,329	-	-	204
DC	CO_2	4,585	1,013	-	-	-	1,329	-	-	-
2DC	CO_2	2,696	-	558	1,943	-	-	955	953	-
1DC/SDC	CO_2	2,739	1,013	-	-	2,487	1,329	-	-	204

Table 11: CO_2 emissions break down of the logistics network design option under study

Options	Optimization Criterion	Transportation Emissions (tons/t)	DC Oper. emissions (tons/day)
1DC	**Cost**	2.55	0.191
2DC	**Cost**	1.10	0.289
1DC/SDC	**Cost**	1.239	0.239
1DC	**CO_2**	2.32	0.191
2DC	**CO_2**	0.99	0.289
1DC/SDC	**CO_2**	1.159	0.239

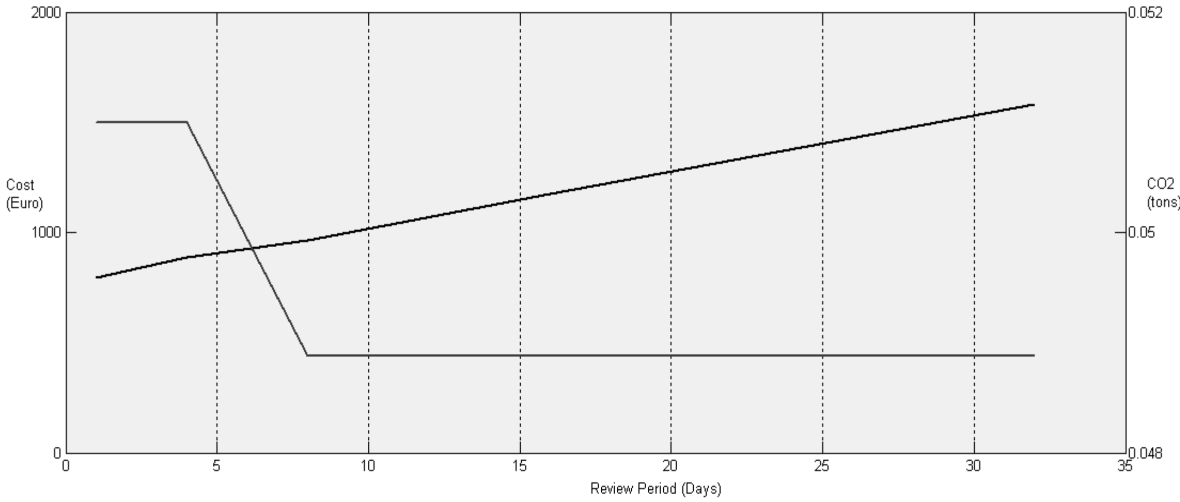

Figure 2: Effect of higher review periods on the RM_1 cost and CO_2 emissions

The black line refers to total logistics costs while the grey line to the transportation CO_2 emissions (transportation costs exhibit the same behavior).Under the cost optimization criterion, and even though transportation costs are reduced (until the specific review period point of 8 days), the total logistics costs constantly increase. This indicates that the holding and backorder cost increases are higher than the transportation cost reductions achieved as the review periods increase. Under the CO_2 emissions optimization criterion we observe a drop until the review period point of 8 days and then a constant behavior. This indicates that after this review period point, trucks exhibit the same utilization levels. Thus the number of truck roundtrips per time unit for a review period of 8 days will be equal to that of 16 days.

Another interesting finding is that the first option with one DC is the best in terms of cost while the second with two DCs in terms of CO_2 emissions. To be more specific and if the company goes from *Option 1DC to 2DC* it will incur a 2.8 % increase in its total logistics costs and a 49% reduction of its CO_2 emissions. Moreover and if the company goes from *Option 1DC* to *Option 1DC/SDC*, its expected total logistics costs will increase by 9.9% while its CO_2 emissions will decrease by 44.2%. The cost increase is mainly due to the relatively high holding and distribution centre operating cost increases while

the CO_2 emissions reduction due to the environmentally friendlier rail transportation compared to truck transportation.
Finally, an interesting finding involves the relatively high cost increase in case a company adopts the policy that minimizes CO_2 emissions compared to the outcome of cost minimization. To be more specific and if you change the optimization criterion from cost to a CO_2 then the cost increases are 17.6%, 17.4% and 6.7% for the three option under study respectively.

Table 12: Cost, and CO_2 emissions for the optimal solutions of 6 problem instances.

Instance	Optimization Criterion	Option	Cost (€)	CO_2 (tons)
1	Cost	*1DC*	12,289	2.73
2	Cost	*2DC*	12,635	1.38
3	Cost	*1DC/SDC*	13,507	1.48
4	CO_2	*1DC*	14,454	2.51
5	CO_2	*2DC*	14,838	1.28
6	CO_2	*1DC/SDC*	14,412	1.40

6. Discussion

The results of the paper indicate that tactical network design as also operational inventory control decisions could be significantly affected when environmental objectives are considered in the optimizations process. On a tactical level the optimum networks structure with respect to costs leads to more centralized logistics networks compared to the CO_2 emissions optimum. Moreover, on a operational level, the inclusion of CO_2 emissions minimization objectives results in higher review periods compared to the outcome of cost minimization.
We used the Market of Greece as a background for presenting the methodology proposed in this study. Transport emissions can be reduced by opening more DCs, either as a satellite or as a separate DC. This however, increases inventory costs. Hence a logistic optimization should indicate for which costs increase we can get a CO_2 reduction. In the case shown in this paper, a 2.8% costs increase could reduce emissions by almost 50%, which is a really large decrease.

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APPENDIX

Proof of Proposition I:

By differentiating the expected holding and backorder cost per time unit for each product p

at the retail store m, $h^p \frac{1}{R_m} \int_0^{R_m} \sigma_m^p \sqrt{L_m+t} \left[\varphi^p_{m\, L_m+t} \;\; k_m^p \;\; t \;\; + k_m^p \;\; t \cdot \Phi^p_{m\, L_m+t} \;\; k_m^p \;\; t \;\; \right] dt$

$+ b^p \frac{1}{R_m} \int_0^{R_m} \sigma_m^p \sqrt{L_m+t} \left[\varphi^p_{m\, L_m+t} \;\; k_m^p \;\; t \;\; - k_m^p \;\; t \cdot 1\text{-}\Phi^p_{m\, L_m+t} \;\; k_m^p \;\; t \;\; \right] dt$, with respect to z_m^p and using

$(k_m^p \;\; t \;\; = \left(\frac{\mu_m^p}{\sigma_m^p} \cdot \frac{R_m - t}{\sqrt{L_m+t}} + z_m^p \cdot \frac{\sqrt{L_m+R_m}}{\sqrt{L_m+t}} \quad 0 \le t \le R_m \right)$ we obtain:

$$h^p \frac{1}{R_m} \int_0^{R_m} \sigma_m^p \sqrt{L_m+t} \left(\frac{\partial \varphi^p_{m\,(L_m+t)}(k_m^p(t))}{\partial k_m^p(t)} \cdot \frac{\partial k_m^p(t)}{\partial z_m^p} + \frac{\partial k_m^p(t)}{\partial z_m^p} \cdot \Phi^p_{m\,(L_m+t)}(k_m^p(t)) + k_m^p(t) \cdot \frac{\partial \Phi^p_{m\,(L_m+t)}(k_m^p(t))}{\partial k_m^p(t)} \cdot \frac{\partial k_m^p(t)}{\partial z_m^p} \right) dt +$$

$$b^p \frac{1}{R_m} \int_0^{R_m} \sigma_m^p \sqrt{L_m+t} \left(\frac{\partial \varphi^p_{m\,(L_m+t)}(k_m^p(t))}{\partial k_m^p(t)} \cdot \frac{\partial k_m^p(t)}{\partial z_m^p} - \frac{\partial k_m^p(t)}{\partial z_m^p} + \frac{\partial k_m^p(t)}{\partial z_m^p} \cdot \Phi^p_{m\,(L_m+t)}(k_m^p(t)) + k_m^p(t) \cdot \frac{\partial \Phi^p_{m\,(L_m+t)}(k_m^p(t))}{\partial k_m^p(t)} \cdot \frac{\partial k_m^p(t)}{\partial z_m^p}) \right) dt =$$

For normal demand and since $\frac{\partial \varphi^{p}_{m(L_m+t)}(k^{p}_{m}(t))}{\partial k^{p}_{m}(t)} \cdot \frac{\partial k^{p}_{m}(t)}{\partial_{\alpha} z^{p}_{m}} + k^{p}_{m}(t) \cdot \frac{\partial \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))}{\partial k^{p}_{m}(t)} \cdot \frac{\partial k^{p}_{m}(t)}{\partial_{\alpha} z^{p}_{m}} = 0$

the above equations can be simplified to:

$$h^{p}\frac{1}{R_m}\int_0^{R_m} \sigma^{p}_{m}\sqrt{L_m+t}\left(\frac{\partial k^{p}_{m}(t)}{\partial z^{p}_{m}} \cdot \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\right)dt + b^{p}\frac{1}{R_m}\int_0^{R_m} \sigma^{p}_{m}\sqrt{L_m+t}\left(-\frac{\partial k^{p}_{m}(t)}{\partial z^{p}_{m}} + \frac{\partial k^{p}_{m}(t)}{\partial z^{p}_{m}} \cdot \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\right)dt =$$

$$h^{p}\frac{1}{R_m}\int_0^{R_m} \sigma^{p}_{m}\sqrt{L_m+t}\left(\frac{\sqrt{L_m+R_m}}{\sqrt{L_m+t}} \cdot \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\right)dt + b^{p}\frac{1}{R_m}\int_0^{R_m} \sigma^{p}_{m}\sqrt{L_m+t}\left(-\frac{\sqrt{L_m+R_m}}{\sqrt{L_m+t}} + \frac{\sqrt{L_m+R_m}}{\sqrt{L_m+t}} \cdot \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\right)dt =$$

$$h^{p}\frac{1}{R_m}\int_0^{R_m} \sigma^{p}_{m}\cdot\sqrt{L_m+R_m}\cdot\Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\, dt + b^{p}\frac{1}{R_m}\int_0^{R_m} -\sigma^{p}_{m}\cdot\sqrt{L_m+R_m} + \sigma^{p}_{m}\cdot\sqrt{L_m+R_m}\cdot\Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\, dt =$$

$$h^{p}\frac{1}{R_m}\int_0^{R_m} \sigma^{p}_{m}\cdot\sqrt{L_m+R_m}\cdot\ \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\, dt + b^{p}\frac{1}{R_m}\int_0^{R_m} \sigma^{p}_{m}\cdot\sqrt{L_m+R_m}\cdot\ \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t)) - 1\ \ dt =$$

$$h^{p}\frac{1}{R_m}\sigma^{p}_{m}\cdot\sqrt{L_m+R_m}\cdot\int_0^{R_m}\ \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\, dt + b^{p}\frac{1}{R_m}\sigma^{p}_{m}\cdot\sqrt{L_m+R_m}\cdot\int_0^{R_m}\ \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t)) - 1\ \ dt =$$

Applying the first order condition we get:

$$\frac{1}{R_m}\sigma^{p}_{m}\sqrt{L_m+R_m}\cdot\ h^{p}\cdot\int_0^{R_m}\Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))dt + b^{p}\cdot\int_0^{R_m}\ \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\text{-}1\ dt = 0 \Leftrightarrow$$

$$h^{p}\int_0^{Rm}\Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))dt + b^{p}\int_0^{Rm}\Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t)) - b^{p}\int_0^{Rm}1dt = 0 \Leftrightarrow$$

$$(h^{p}+b^{p})\cdot\int_0^{R_m}\Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))dt - b^{p}\cdot R_m = 0\ .\ \ (1)$$

Moreover and since the second grade derivative with respect to z^{p}_{m} of (1): $h^{p}+b^{p}\ \cdot\int_0^{R_m}\frac{\partial \Phi^{p}_{m(L_m+t)}(k^{p}_{m}(t))}{\partial k^{p}_{m}(t)}\cdot\frac{\partial k^{p}_{m}(t)}{\partial_{\alpha} z^{p}_{m}}dt =\ h^{p}+b^{p}\ \cdot\int_0^{R_m}\varphi^{p}_{m(L_m+t)}(k^{p}_{m}(t))\cdot\frac{\partial k^{p}_{m}(t)}{\partial z^{p}_{m}} > 0$ an optimal z^{p}_{m} value exists that satisfies the first order condition for a specified value of R_m.