Eco-efficient supply chain networks: development of a design framework and application to a real case study

Claudia Colicchia

University of Hull, Hull University Business School, Logistics Institute

Cottingham Road, Hull, UK, HU6 7RX

e-mail: c.colicchia@hull.ac.uk; Tel. +44 (0)1482 347550

Alessandro Creazza (corresponding author)

University of Hull, Hull University Business School, Logistics Institute

Cottingham Road, Hull, UK, HU6 7RX

e-mail: a.creazza@hull.ac.uk; Tel. +44 (0)1482 347586

Fabrizio Dallari

Logistics Research Centre, LIUC University, Castellanza, Italy

Corso Matteotti 22, 21053, Castellanza, Italy

e-mail: f.dallari@liuc.it; Tel. +39 0331 572268

Marco Melacini

Politecnico di Milano, Department of Management, Economics and Industrial Engineering

Via Lambruschini 4/b, 20156, Milano, Italy

e-mail: marco.melacini@polimi.it ; Tel. +39 02 23994059

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Abstract

This paper presents a supply chain network design framework that is based on multi-objective mathematical programming and that can identify ‘eco-efficient’ configuration alternatives that are both efficient and ecologically sound. This work is original in that it encompasses the environmental impact of both transportation and warehousing activities. We apply the proposed framework to a real-life case study (i.e. Lindt & Sprüngli) for the distribution of chocolate products. The results show that cost-driven network optimisation may lead to beneficial effects for the environment and that a minor increase in distribution costs can be offset by a major improvement in environmental performance. This paper contributes to the body of knowledge on eco-efficient supply chain design and closes the missing link between model-based methods and empirical applied research. It also generates insights into the growing debate on the trade-off between the economic and environmental performance of supply chains, supporting organisations in the eco-efficient configuration of their supply chains.

Keywords: supply chain network design, eco-efficiency, green supply chain management, supply chain optimisation, food supply chain

1. Introduction

The environmental sustainability of supply chains has rapidly become a priority for companies of all sizes and industries across the globe (Seuring 2013, Shaw et al. 2013, Büyüközkan and Cifci 2012). This is a result of the increasing pressures, both external (e.g. legislative requirements, consumer pressure, competitive forces) and internal (e.g. need for a more efficient use of resources), to implement 'green' supply chains. To respond to this necessity, authors have developed and discussed the concept of green supply chain management (GSCM). Hassini, Surti and Searcy (2012) defined GSCM as 'the management of supply chain operations, resources, information and funds in order to maximize the supply chain profitability while at the same time minimizing the environmental impacts'. Within the GSCM framework developed by Srivastava (2007), the design of supply chain networks for 'eco-efficiency' emerges as a critical area for research and practice. The objective is to identify supply chain network configurations that can embrace the environmental and economic dimensions of sustainability (Chaabane, Ramudhin and Paquet 2011). Approaches to supply chain network design for eco-efficiency include diverse quantitative models, but research on the subject appears to be in a stage of intense development and consequently calls for additional studies. In particular, Brandenburg et al. (2014) stress the lack of investigations on the environmental sustainability of distribution processes along with the related warehousing activities. Moreover, a substantial dearth of practical applications that rely on real empirical data is highlighted in the current body of knowledge, which predominantly provides readers with illustrative examples (Brandenburg et al. 2014, Seuring 2013). The existing literature also contains a considerable debate on the trade-off between the environmental sustainability and the economic performance of supply chain networks. In fact, although many companies view environmental sustainability initiatives as driving additional costs (Abbasi and Nilsson 2012), it is also recognised that environmental sustainability in supply chains can simultaneously lead to cost reductions (Rossi et al., 2013; Quariguasi Frota-Neto et al., 2008). However, the relationship between these two major objectives is still a source of great conflict in the academic debate.

Given this background and the emerging gaps, the objective of this paper is threefold:

- First, to contribute to the existing body of knowledge on the eco-efficient design of supply chain networks, focusing on distribution and embracing both the environmental impact of transportation and the impact of the storage in warehouses.
- Second, to close the critical missing link between model-based methods and empirical research by taking into account real-life issues and complexity.
- Third, to delve deeper into the trade-off between the economic and environmental objectives and the related implications for the configuration of supply chain networks.

To achieve the abovementioned objectives, in this paper we develop a supply chain network design framework for eco-efficiency. We then apply the developed design framework to a real-life case study, i.e. the Lindt & Sprüngli Company, for their distribution of chocolate products in Italy. The chosen context of application is particularly relevant to the study of eco-efficient supply chain network design given that chocolate products are perishable in nature. The perishable food products industry is recognised to be critical from an energy consumption and greenhouse gas emissions viewpoint (Harris, Mumford and Naim 2014, Zailani, Amran and Jumadi 2011, Lin and Ho 2008). The distribution of this category of products is similarly critical given the refrigeration requirements for their preservation along the supply chain and the relevance of the generated logistics flows (Akkerman, Farahani and Grunow 2010).

Through the development and application of the proposed design framework, we gain significant theoretical contributions and practical insights from real field data. The application to the case company also demonstrates the practical relevance of the design framework and contributes to the development of tools to support organisations in the eco-efficient configuration of their supply chain networks. Developing the framework and applying it to the real case study gave us the opportunity to collect significant field data and evidence to contribute to the debate on the trade-off between the environmental sustainability and the economic performance of supply chains from both managerial and industrial perspectives.

The remainder of this paper is organised as follows. After the theoretical background presented in Section 2, Section 3 describes the adopted methodology for conducting the research. In Section 4, the proposed design framework is introduced. In Section 5, we apply the framework to the Lindt & Sprüngli case study and discuss the obtained results, and in Section 6, we conclude the paper and provide future research directions.

2. Theoretical background

In order to provide an overview of the theoretical background of the present study, we conducted a review of the literature focused on the design of eco-efficient supply chain networks. Given that we applied our eco-efficient supply chain network design framework to the perishable food industry, we performed an additional specific investigation on the supply chain network design with reference to this particular sector.

2.1 Supply chain network design for 'eco-efficiency'

A vast body of knowledge is available on the different facets of green supply chain management. According to the framework proposed by Srivastava (2007), two main approaches for 'greening' the supply chain can be adopted: green design (product and process) and green operations (waste management, reverse logistics and network design, green manufacturing and remanufacturing). With respect to this framework, the focus of our research is on network design in supply chains. Traditionally, the focus of the optimal configuration of supply chain/logistics networks mainly referred to costs, responsiveness and the related trade-offs (Simchi-Levi D., Kaminsky and Simchi-Levi E. 2008; Beamon 1999). Creazza, Dallari and Rossi (2012), Melo, Nickel and Saldanha-da-Gama (2009) and Meixell and Gargeya (2005) present exhaustive reviews of the traditional approaches for the design and configuration of supply chain networks. Traditional design approaches aimed at improving the performance of supply chains by optimising trade-offs that traditionally included cost and responsiveness. In recent years, the literature has been extending the focus of the design of supply chain networks by also embracing their environmental impact (e.g. Jaegler and Burlat 2012, Büyüközkan and Berkol 2011, Langella and Zanoni 2011, Chaabane, Ramudhin and Paquet 2011, Eksioglu et al. 2009). Previous literature has addressed the topic of supply chain network design for eco-efficiency through different approaches. Extensive reviews on this topic (Brandenburg et al. 2014, Seuring 2013, Nikolopoulou and Ierapetritou 2012) offer an outline of the available models for the design of eco-efficient supply chain networks. In particular, these contributions show the presence of various problem formulation approaches such as mathematical programming models (e.g. linear deterministic models, complex non-linear stochastic models), simulation methods, heuristic methods and analytical models. The available reviews highlight that the environmental concerns in the problem formulation are principally addressed through multi-criteria decision making and multi-objective programming methodologies. Among these, multi-objective optimisation models have been judged as particularly suitable for addressing the widely debated trade-offs between the conflicting key performance indicators (i.e. economic versus environmental objectives) that are typically included in eco-efficient supply chain network design (Chaabane, Ramudhin and Paquet 2011). Within this remit, multiple non-dominated solutions exist. A common and widely adopted approach to generate these solutions is to aggregate different objective functions through numerical scalar weights that might be varied to represent the relative importance of any of the key performance indicators that are to be optimised (Langella and Zanoni 2011; Wang, Lai and Shi 2011).

Even though it is recognised that sustainable practices can lead to performance improvements and cost reduction simultaneously (Subramanian, Talbot and Gupta 2010; Porter and Van der Linde 1995), companies that seek to design eco-efficient supply chain networks are often hampered by their ability to discern sound choices from both environmental and economic points of view (Colicchia et al. 2013).

Furthermore, other interesting outcomes result from the analysis of previous literature reviews and other scientific contributions. It emerges that researchers have extensively focused on the early stages of the product and process design (Ahmetovici, Martin and Grossmann 2010, Cano-Ruiz and McRae 1998), green production network configuration and capacity planning (You et al. 2011, Zamboni, Bezzo and Shah 2009, Hugo and Pistikopoulos 2005), remanufacturing and disassembly processes (Grossmann and Guillen-Gosalbez 2010, Beamon and Fernandes 2004) and reverse and closed-loop supply chains (Abdallah, Diabat and Simchi-Levi 2012, Corsano, Vecchietti and Montagna 2011). The forward logistics and distribution processes, along with the related warehousing activities, appear to be almost neglected by the currently available contributions on supply chain network design for eco-efficiency (Brandenburg et al. 2014, Nikolopoulou and Ierapetritou 2012).

Other relevant insights are provided by Nikolopoulou and Ierapetritou (2012) and Sheu and Talley (2011). These authors discuss the misalignment between industry and academia of the priorities of eco-efficient supply chain network design: while industry is more focused on sustainability aspects related to processes, academia concentrates on sustainability as a bigger picture, and methods and tools for eco-efficient supply chain network design are largely overlooked from an industrial perspective. Similarly, Seuring (2013) states that the link to empirical data is missing for most of the related research. In fact, the reviewed modelling papers offer theoretical examples of numerical ‘made-up’ illustrations of the presented models or use industrial sector data for illustrative purposes only. Very few contributions actually build on empirical research.

2.2 Supply chain network design for eco-efficiency in the perishable food industry

The design of food supply chain networks is particularly focused on three important food-industry-specific challenges: food safety, food quality and sustainability. This is particularly relevant for those products whose qualitative and safety features are more critical to preserve along the supply chain, i.e. perishable food. The quality and safety of perishable food are generally preserved through refrigeration and temperature control. In fact, temperature control affects product quality by influencing the level of quality degradation, and it affects product safety by limiting the growth of potentially harmful bacteria (Akkerman, Farahani and Grunow 2010). In turn, the refrigeration processes for preserving food quality and safety deeply affect the sustainability dimension of the food supply chain in that they entail additional energy consumption, especially in storage and distribution (Zanoni and Zavanella 2012).

Researchers have begun to address eco-efficient supply chain network design in the perishable food industry. The literature indicates that researchers have especially focused on case-based perspectives (Ala-Harja and Helo 2014) rather than on modelling approaches (Brandenburg et al. 2014). Among the developed modelling approaches, it is possible to mention mixed integer linear programming, simulation, heuristics and meta-heuristics and analytical models/scenario analysis. Extensive reviews by Akkerman, Farahani and Grunow (2010) and Ahumada and Villalobos (2009) examine quantitative modelling approaches for the design and planning of food supply chain networks. Among the various approaches presented in the literature, mathematical programming is the most adopted methodology for the optimisation of food supply chain networks; binary decision variables are used to decide whether potential logistics facilities can be activated to connect the supply chain network (Akkerman, Farahani and Grunow 2010).

An interesting insight from our analysis emerges from a paper by Akkerman, Farahani and Grunow (2010). The authors stress that despite the relevance of properly designed food product supply chain networks, only a limited number of scientific contributions exist on this topic. Furthermore, notwithstanding the importance of the sustainability concern in the current industry situation, the authors emphasise that the extant body of knowledge is particularly lacking in explicit consideration of eco-efficiency in the development of modelling approaches. When eco-efficiency is taken into account, the environmental impact is reduced by minimising the travelling distance, without taking into account the prominent contributions of warehousing and storage.

3. Methodology

Given our focus and objectives, and taking into account the methodological approaches adopted by the authors in the reviewed literature, we decided to rely on quantitative modelling.

To achieve the first objective (i.e. to contribute to the existing body of knowledge on the eco-efficient design of supply chain networks), we developed a quantitative supply chain network design framework to identify eco-efficient supply chain network configuration options. We relied on multi-objective (binary) mathematical programming, as suggested by the taxonomy on quantitative models for GSCM proposed by Brandenburg et al. (2014). In doing this, and similar to other approaches in the literature, we developed three optimisation models (Langella and Zanoni 2011; Wang, Lai and Shi 2011):

- the 'cost-effective model', aimed at minimising the overall distribution costs;
- the 'carbon-effective model', aimed at minimising the CO_2 emissions related to overall distribution;
- the 'eco-efficient model', which combines the abovementioned models to optimise both distribution cost and CO_2 emissions using a multi-objective optimisation approach.

Specifically, we first defined the generic structure of the supply chain network to be addressed and also the decision variables. Then, for each of the optimisation models, we identified the objective function, constraints and model parameters.

We built upon the mathematical programming-based design model proposed by Creazza, Dallari and Rossi (2012), the objective of which is to find the optimal configuration of a supply chain network through the minimisation of the overall logistics cost (i.e. the sum of the costs related to primary transportation and secondary distribution and warehousing). The rationale for this choice is that the model developed by those authors also embraces design issues related to distribution, including both transportation and warehousing. Furthermore, this model was specifically developed to resolve a supply chain configuration problem that was characterised by a complexity level that was typical of real-life logistics networks, and the model was applied to an industrial case study.

An additional justification for our approach is that multi-objective (binary) mathematical programming has been applied numerous times to solve supply chain optimisation problems (Schoen 2002), including supply chain network design for sustainability (Akkerman, Farahani and Grunow 2010). Our approach allows for decision support tools to be easily developed, enabling realistic and precise solutions for network configuration problems in conjunction with available and reliable software packages.

To achieve the second objective (i.e. to close the critical missing link between model-based methods and empirical research), we applied the developed design framework to a real-life case study, i.e. the company Lindt & Sprüngli. To gather the necessary field information, we designed a data collection protocol. We first conducted extensive interviews with the key informants within the organisation, i.e. the supply chain and operations director and the logistics and distribution manager. This allowed us to map the company's supply chain features, requirements, processes and current network configuration. Second, in order to operationalise the design framework, we collected the company's numerical data related to its transportation and warehousing activities. This was necessary in order to allocate a value to the models' parameters. We also relied on secondary data (e.g. literature and published reports by public bodies) to support the operationalisation of the framework. See Section 5.1 for additional details. In order to solve the optimisation models, we adopted Lindo What's Best!™ MS Excel add-in.

To achieve the third objective (i.e. to delve deeper into the trade-off between the economic and environmental objectives and its implications), we discussed the obtained numerical results, including a sensitivity analysis. See Section 5.2 and Section 5.3 for details.

4. The supply chain network design framework for eco-efficiency

The supply chain network that we address in the present paper (Figure 1) is common in distribution activities, and it is also suitable also for the distribution of perishable food products (Chopra and Meindl 2013). It is structured according to the following topological variables:

- One given un-capacitated central warehouse (CW) that represents the point of origin of the distribution flows.
- A series of potential transit points (TPi) with a limited amount of product inventory.
- A series of given delivery points (DPq) that represent the destination points of the distribution flows, each characterised by a specific demand profile.

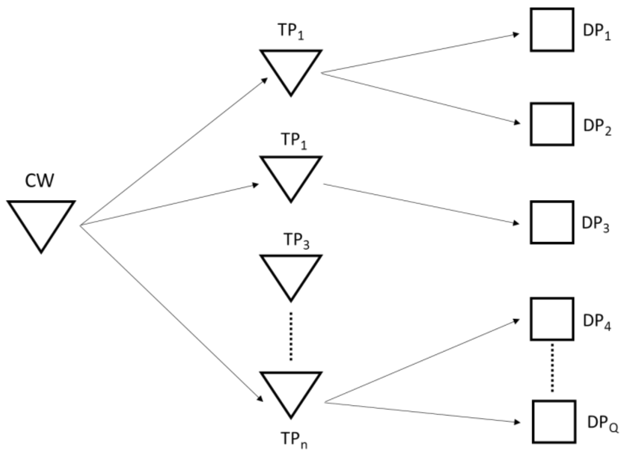

Figure 1. The structure of the considered supply chain network

We assume that the replenishment flows from the CW to each TP_i are organised through full truck load (FTL) shipments and that the last mile delivery from each TP_i to each DP_q is performed by means of less than truckload (LTL) shipments. Delivery points are served according to a single sourcing policy, which is also suitable for distributing perishable food products (Ahuja et al. 2007).

Since a real-life supply chain network for distributing products to end customers could easily have over 20,000 accounts, there is a need to aggregate the delivery points into macro-groups or clusters (Simchi-Levi D., Kaminsky and Simchi-Levi E. 2008). As suggested by Creazza, Dallari and Rossi (2012), it is suitable to aggregate these delivery points by defining a set of aggregated delivery points (ADP_j), which should be based on the Eurostat NUTS codification (Nomenclature des Unite's Territoriales Statistiques [Nomenclature of Territorial Units for Statistics]) and which represent the centre of gravity of the demand of the delivery points included in each geographical cluster. This aggregation is intended to reduce the complexity of the geographical system under consideration without impairing the internal and practical validity of the model (Simchi-Levi D., Kaminsky and Simchi-Levi E. 2008).

4.1 Decision Variables

We aim to optimise our supply chain network by making the following decisions, which can be expressed by defining the binary decision variables:

- Which and how many TPis must be activated out of a set of potential locations;
- Which TPi, if activated, must serve a given ADPj.

As far as the nodes of the supply chain network are regarded, only the activation of the TP_is is a decision variable because the CW and the set of ADP_js are considered given. Taking into account the linkages between the nodes, only those that connect TP_is and ADP_js are decision variables, whereas the linkages between CW and TP_is are determined based on the resulting overall distribution cost. The amount of products shipped from a TP_i to an ADP_j is not a decision variable, owing to the single sourcing policy. These variables will apply to each model, and the optimisation will be carried out under the annual ADP_j's demand constraints.

4.2 Objective function, constraints and model parameters

For each model for our supply chain network design framework, we present in this section the specific objective function along with the related constraints and parameters.

4.2.1 The cost-effective model

The objective function of the cost-effective model is to minimise distribution costs (Equation 1) (see Table 1 for the adopted notation). Specifically, it is composed of two parts, the primary transportation cost (first term) and the secondary distribution cost, which includes warehousing (second term).

$$\min(\mathrm{OF}\ 1) = \min\ \left[\left(\sum_{j=1}^{m}\sum_{i=1}^{n}\frac{D_j}{PD_j}\cdot b_{i,j}\cdot cp_i\right) + \left(\sum_{j=1}^{m}\sum_{i=1}^{n} D_j\cdot b_{i,j}\cdot cs_{i,j}\right)\right] \quad (1)$$

Table 1. Notation adopted for the cost-effective model

Indices	
I	index for transit points
j	index for aggregated delivery points
n	number of transit points
m	number of aggregated delivery points
s	index for the transit points with domain {1;n-i}
Variables	
b_{ij}	binary decision variable, which allows for defining whether ADP_j is served by TP_i ($b_{ij} = 1$) or not ($b_{ij} = 0$)
Parameters	
D_j	overall annual demand of ADP_j [kg]
PD_j	average product density for the products requested by each ADP_j [kg/m^3]
cp_i	primary transportation unit cost to ship one unit of product from CW to TP_i [€/m^3]
cs_{ij}	secondary distribution cost to ship one unit of product from TP_is to ADP_js. [€/kg]. This also includes the cost to store and handle products at TP_i.
$d_{i,i+s}$	Road distance between transit point i and transit point i+s with s {1;n-i} [km]
Z	minimum distance between two activated TP_is [km]
a_i	average duration of stay of products at TP_is [days]
DY	numbers of working days in the considered time window
w_i	maximum storage capacity of each TP_i [m^3]

The constraints are as follows:

$$\sum_{i=1}^{n} b_{i,j} = 1 \quad \forall j \tag{2}$$

Equation (2) represents the constraint to the single sourcing policy: each ADP_j can only be served by a single TP_i, which completely fulfils the demand of that ADP_j. Therefore, only one link can be activated between a certain ADP_j and all of the potential TP_is.

$$d_{i,i+s} \cdot B_i \cdot B_{i+s} \geq Z \quad \forall i, s \tag{3}$$

with $B_i = 1 \; if \; \sum_{j=1}^{m} b_{i,j} \geq 1 \quad \forall i,$ = 0 else (4)
and $B_{i+s} = 1 \; if \; \sum_{j=1}^{m} b_{i+s,j} \geq 1 \quad \forall i,$ = 0 else (5)

Equation (3) represents the constraint to the minimum distance between two generic activated TP_is (i.e. TP_i and TP_{i+s}). This constraint is necessary because activating two TP_is with a very small distance between them might lead to crossing the replenishment flows from the two considered transit points. This could generate evident organisational complications that could lead to decreased efficiency in the distribution process. The threshold value Z must be set taking into account the typical operating context of transit points for the local distribution of products.

$$\sum_{j=1}^{m} \frac{D_j}{PD_j} \cdot a_i \cdot b_{i,j} \cdot \frac{1}{DY} \leq w_i \quad \forall i \tag{6}$$

Equation (6) depicts the constraint to the maximum storage capacity of each TP_i.

With respect to cp_i, it is necessary to derive the cost function that relates cp_i to the relevant independent variable, i.e. the travelled distance from the CW to the generic TP_i (Creazza, Dallari and Rossi 2012). Moving from the transportation accounting reports of the focal company, it is possible to gather the information associated with the travelled distances from the CW to each TP_i and the related primary transportation costs (usually expressed in €/m^3). A correlation analysis of the dependent (cp_i) and independent (travelled distance) variables allows us to derive the best-fitting interpolation function. With the distance from the CW to each potential new TP_i, it is then possible to obtain the value of cp_i for each potential TP_i.

To define cs_{ij}, it is necessary to perform a correlation analysis to understand what variables affect the variation of the secondary distribution unit cost. Because the correlation analysis must reflect the actual features of each specific context, it is necessary to investigate the goodness of fit of different functions related to potential independent variables.

This is advisable because the *to-be* configuration of the network could result in new linkages between TP_is and ADP_js compared with the *as-is* configuration, and consequently, it is necessary to accommodate the calculation of costs in the new configuration.

4.2.2 The Carbon-Effective Model

The carbon-effective model differs from the cost-effective model in terms of objective function and additional parameters (see Table 2 for the adopted notation), although the decision variables and the constraints remain unchanged.

Table 2. Notation adopted for the carbon effective model

Indices	
i	index for transit points
j	index for aggregated delivery points
n	number of transit points
m	number of aggregated delivery points
Variables	
b_{ij}	binary decision variable that allows for defining whether ADP_j is served by TP_i ($b_{ij} = 1$) or not ($b_{ij} = 0$)
B_i	binary variable that depicts whether TP_i is activated (B_i = 1 if $\sum_{j=1}^{m} b_{i,j} \geq 1 \quad \forall i$) or not ($B_i = 0$)
Parameters	
D_j	overall annual demand of ADP_j [kg]
PD_j	average product density for the products requested by each ADP_j [kg/m^3]
EP_i	CO_2 emissions generated per km in the primary transportation activity from the CW to the TP_is [kg CO_2/km]
d_i	road distance between the CW and the TP_is [km]
d_{ij}	road distance between the TP_is and the ADP_js [km]

ES_{ij}	CO_2 emissions generated per km in the secondary distribution activity from the CW to the TP_is [kg CO_2/km]
K_i	energy required for storing goods in the TP_is [kWh]*
C	CO_2 emissions per kWh consumed in storing products in the TP_is [kg CO_2/kWh]
V_a	average available loading capacity for the fleet of heavy good vehicles that connect the CW and the TP_is [m^3/vehicle]
V_f	average available loading capacity for the fleet of light vehicles that connect the TP_is and the ADP_js [m^3/vehicle]
Sp_i	average utilisation rate for the vehicles that connect the CW and the TP_is [%]
Ss_i	average utilisation rate for the vehicles that connect the TP_is and the ADP_js [%]

The objective function is to minimise the CO_2 emissions from the overall distribution activity in the supply chain network (Equation 7). Specifically, the objective function is composed of three parts that represent the CO_2 emissions from the primary transportation activity (first term), the CO_2 emissions from the secondary distribution activity (second term) and the CO_2 emissions from the product storage (third term).

$$\min(\text{OF } 2) =$$

$$= \min\left[\left(\sum_{j=1}^{m}\sum_{i=1}^{n} EP_i \cdot \frac{D_j}{PD_j} \cdot \frac{1}{Va \cdot SP_i} \cdot d_i \cdot b_{i,j}\right) + \left(\sum_{j=1}^{m}\sum_{i=1}^{n} Es_{ij} \cdot \frac{D_j}{PD_j} \cdot \frac{1}{Vf_i \cdot Ss_i} \cdot d_{ij} \cdot b_{i,j}\right) + \left(\sum_{i=1}^{n} K_i \cdot C \cdot B_i\right)\right] \qquad (7)$$

Consistent with the extant body of literature on GSCM (McKinnon, Browne and Whiteing 2012), the CO_2 emissions generated by the primary transportation and the secondary distribution are related to the gases from the trucks' engines, and the CO_2 emissions generated by the storage activity are connected to the energy consumed at the TP_is.

Based on the estimation of the CO_2 emissions generated by vehicles in the transportation activity, it is possible to rely on the data released by Defra (2013), i.e. the department of the United Kingdom government that is responsible for protecting the environment, manufacturing, agriculture, fisheries and rural communities. Data from Defra (2013) provide an estimate of the kilograms of CO_2 per travelled kilometre, distinguishing among different types of vehicles and based on their utilisation rate. When refrigerated transportation is requested, additional sources of information, such as the European Commission, provide the correction factors that are needed in order to account for the additional fuel consumption of the refrigerated units; specifically, it is estimated that refrigerated vehicles use 19% more energy than that consumed by heavy goods vehicles (HGV) and 16% more than that consumed by light trucks (European Commission 2011). It is possible to perform an interpolation and derive a function (for each kind of vehicle, both HGVs and light trucks) to describe the variation in the CO_2 emissions depending on the vehicle utilisation rate (i.e. Sp_i and Ss_i).

With respect to the CO_2 emissions generated from storing products in warehouses (i.e. parameter K_i), Marchant and Baker (2012) provide guidelines to assess the related consumption of energy. Three main sources need to be taken into account: power for equipment, temperature regulation (cooling or heating), and lighting (internal and external). For refrigerated transportation, Prakash and Singh (2008), Evans (2007) and Werner et al. (2006) offer more specific data related to the energy consumption of refrigerated cells. These authors highlight that economies of scale exist when the storage capacity (m^3) of refrigerated cells is considered. Specifically, *ceteris paribus* the unit energy consumption decreases as the size of the refrigerated cell increases, according to different mathematical expressions. The data presented by the authors in particular show that the energy consumption varies in different countries, mainly owing to the effects of local weather conditions, the technical standards that are commonly adopted and warehouse operating conditions. Based on country-specific energy consumption data and given an average volume utilisation rate for refrigerated cells, the average stock level (m^3) to be stored gives the necessary storage capacity that should be accounted for the calculation of the related energy consumption.

Finally, to convert the consumption expressed in kWh into CO_2 emissions (i.e. parameter C), we can rely on data from Mac Kay (2009), who distinguishes between different conversion factors depending on the energy sourcing mixes, which are specific to different countries.

4.2.3 The Eco-Efficient Model

The last step of the proposed supply chain network design framework is to develop an eco-efficient model, that is, one that can concurrently take into account both economic and environmental performance. This can be done following the multi-objective optimisation approach that has been proposed in the literature (i.e. Langella and Zanoni 2011; Wang, Lai and Shi 2011): an aggregate objective function is generated by combining the objective functions that were previously presented. To do this, we adopt an approach that entails the conversion of the CO_2 emissions to a monetary value that can be added to the distribution costs. In fact, the monetary value of the emitted quantity of CO_2 appears to be appropriate from the business perspective and effective for managerial decision making (Colicchia, Dallari and Melacini 2011). Following the multi-objective optimisation approach, we propose a new objective function that is equal to the weighted sum of the objective functions of the cost-effective (OF 1) and carbon-effective (OF 2) models after the appropriate conversion into monetary values (performed through the parameter CC) (Equation 8). The weights (α_1 for economic performance and α_2 for environmental performance) represent the relative importance of the cost-effective and carbon-effective optimisations.

$$\min(\alpha_1 \cdot \mathrm{OF}\ 1 + \alpha_2 \cdot \mathrm{CC} \cdot \mathrm{OF}\ 2) \tag{8}$$

Where $0 \leq \alpha_1 , \alpha_2 \leq 1$ and $\alpha_1 + \alpha_2 = 1$

The greatest challenge in this case is determining the weights and the value of parameter CC. With reference to the weights, in the literature there is no unanimity on the value to be assigned to the different performance indicators. Indeed, it is the role of managers and decision makers to determine the values of the weights in order to represent the business orientation (Langella and Zanoni, 2011). With parameter CC, literature and other sources of information are necessary to provide data about the considered conversion process (e.g. Johnson and Hope 2012).

5. An application of the supply chain network design framework: the Lindt & Sprüngli case study

Lindt & Sprüngli (hereafter referred to as Lindt) is a multinational chocolate manufacturer that was founded in 1845 in Zurich (Switzerland). It is one of the world's leading companies in producing premium solid chocolate, which requires refrigerated transportation and storage in order to preserve the quality and safety of the products. Although the product density varies markedly among different product families, the served customers within the same market area require a mix of products characterised by a similar average product density. The company delivers its products to a very large number of small and capillary distributed delivery points; in the present paper, we focus on the Italian market. All of the numerical data presented in the paper were disguised for strict confidentiality reasons.

Lindt's current supply chain network in Italy is composed of one CW where the company's entire product range is stored. Downstream, a network of 22 TP_is is used at present; in these locations, a certain amount of inventory is stored for short periods, which is necessary for ensuring high responsiveness to customer demand (the location of the current TP_is cannot be disclosed for confidentiality reasons). From the TP_is 28,000 customers are served in the Italian territory (DP_q) using a single sourcing policy. Deliveries are organised with full truck load shipments from the CW to the transit points by means of HGVs and with less than truck load shipments from the TP_is to customers by means of light trucks. Whereas the activities within the CW are managed in-house by Lindt, the TP_is are run by third-party logistics providers, and the transportation activities are outsourced to haulage companies.

5.1 Implementation

TP_is must be selected from among the 22 current locations and 16 other potential sources. The choice of the potential locations has been driven by the geographical distribution of Lindt's customer demand concurrently with the analysis of the availability of refrigerated warehouses and transit points in the current Italian contract logistics market.

Lindt's distribution processes present a series of critical issues, such as the strongly seasonal activity profile of the chocolate industry, the geographical features of the Italian territory and the high number of delivery points. To reflect these criticalities, the time bucket considered in the model was aligned with the peak season (mid-August/mid-February). The two main islands (i.e. Sardinia and Sicily) were excluded from the analysis because at the time of this research no potential facilities were available other than the ones already in use. Finally, we aggregated the demand, and we obtained 81 ADP_js from 25,972 delivery points replenished from 18 TP_is (main islands excluded).

The following model parameters were set for the Lindt case:

- cp_i: through a correlation analysis of the cost and distance data related to the 18 TP_is we considered, we derived the cost function reported in Figure 2.

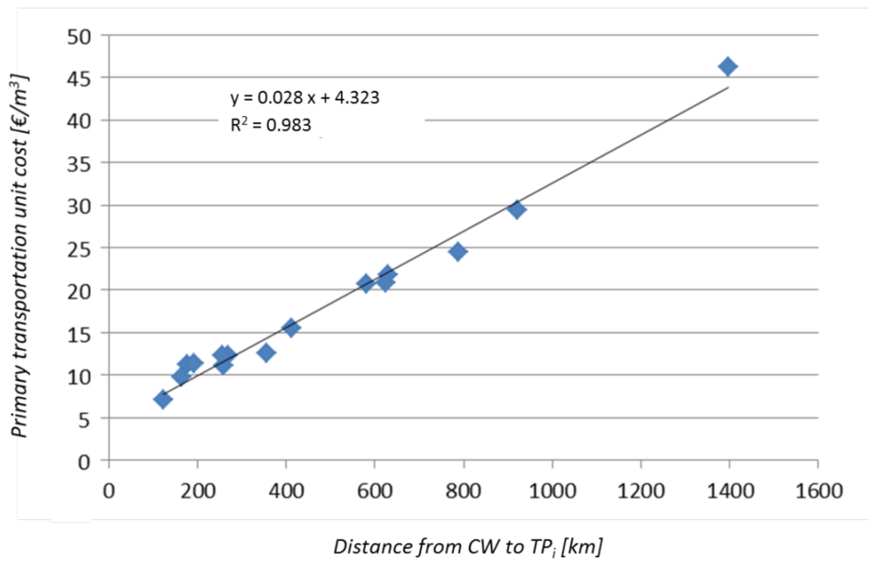

Figure 2. The cost function for the primary transportation

- cs_{ij}: we performed a correlation analysis among different potential independent variables. We found that the average drop size of deliveries from the TP_is and the average distance from the TP_is to ADP_j are strongly related to the secondary distribution unit cost. Hence a bi-variate correlation analysis was necessary, which produced the cost function reported in Figure 3.

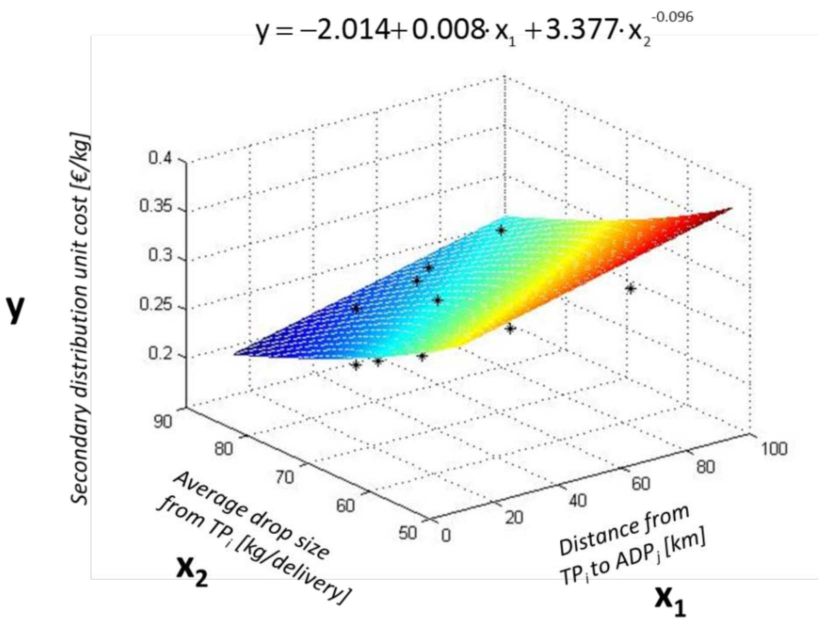

Figure 3. The cost function for the secondary distribution

- Z = 120 km (taking into account the Italian geographical morphology and the typical geographical distribution of delivery points in the territory).
- DY = 90 days.
- V_a = 45 m^3 (based on data provided by the company - fleet of HGVs).
- V_f = 10 m^3 (based on data provided by the company - fleet of light trucks).
- Sp_i = 85% for each TPi.
- Ss_i = 90% for each TPi.
- K_i: the company provided energy consumption data related to their 18 TP_is that currently store the chocolate products. We also interviewed logistics service providers in the cold/chilled food supply chain in Italy in order to obtain the warehouse energy consumption data for the 16 other potential TP_is that were included in the model (which are supposed to

operate under the same conditions as the current ones). Taking into account the volume of products stored [m^3] and the related energy consumed [kWh], we were able to derive the following energy consumption relationship (Equation 9).

$$K_i = 95{,}056 \cdot \left(\frac{D_j}{PD_j} \cdot \frac{1}{DY} \cdot a_i\right) \cdot \frac{1}{U} + 54{,}872.04 \tag{9}$$

where U is the volume utilisation rate for the refrigerated cells, equal in the considered case to 0.85 according to the company's data.

- C = 667 g CO_2/kWh (Mac Kay [2009] with reference to Italy).
- $Ep_i = 0.512 \cdot Sp_i + 1.052$ [kg CO_2/km] (Defra, 2013)
- $Es_i = 0.262 \cdot Ss_i + 0.928$ [kg CO_2/km] (Defra, 2013)
- $\alpha_1 = \alpha_2 = 0.5$ (equal weights in this study were adopted so as not to include any preference in allocating priority to the two objectives).
- CC = 199 €/kg CO_2 (Johnson and Hope 2012; see Table 3), according to the indications received from the company. Given the criticality of this choice along with the wide range of different available values, a sensitivity analysis was conducted on parameter CC (see Section 5.3).

Table 3. Values of parameter CC according to Johnson and Hope (2012)

		CC ($)	**CC (€)***
Discount rate	*1,0%*	266	199
	1,5%	122	91
	2,0%	62	46
	2,5%	35	26
	3,0%	21	16
	5,0%	5	4
UK Green Book		55	41
Weitzman		175	131

** exchange rate at June 2013*

5.2 Results and discussions

We first tested the accuracy of the model and of the input data by running the cost-effective model to derive the distribution cost of the current configuration of Lindt's supply chain network. The model provided an overall distribution cost that is very similar to the company's actual figures in the considered time bucket of year 2012, with a difference of only -1.2%.

We then solved the optimisation problem by means of Lindo What's Best!™ MS Excel add-in. Table 4 synthesises the results obtained for the configuration problem for each model and compares them with the as-is configuration of Lindt's supply chain network (the base case).

Table 4. Results of the optimisation for the Lindt case

	Base Case	**Cost-effective model**	**Carbon-effective model**	**Eco-efficient model**
Number of activated TPis	18	17	8	16
Primary transportation cost (%)	25.40	24.80	25.80	24.60
Secondary distribution and warehousing cost (%)	74.60	72.10	77.70	72.40
Overall distribution cost (%)	**100.00**	**96.90**	**103.50**	**97.00**
CO_2 emissions - primary transportation (%)	36.55	34.94	34.70	34.80
CO_2 emissions - secondary distribution (%)	12.12	15.18	19.88	15.34
CO_2 emissions - warehousing (%)	51.32	49.15	30.37	47.06
CO_2 emissions - overall (%)	**100.00**	**99.27**	**84.95**	**97.20**

Note: To maintain the confidentiality of the numerical data, the overall distribution cost and the CO_2 emissions of the base case are expressed as an index number of 100, with costs and emissions deriving from the three models based on this value.

From the obtained results, it is first interesting to note how the cost and environmental performance of the supply chain affect the physical configuration of Lindt's supply chain network. In detail, when the economic optimisation is run, 17 TP_is are activated (instead of the 18 TP_is in the base case) with a concurrent decrease in the overall distribution cost (-3.1%) and in the CO_2 emissions (-0.73%). When the focus of the optimisation is on reducing CO_2 emissions, a major change in the physical configuration occurs with only 8 TPis activated. This configuration allows for a 15.1% decrease in CO_2 emissions compared with the base case, which occurs because of the economies of scale that derive from the energy consumption function related to the refrigerated storage activity. However, with fewer activated TP_is, the overall distribution cost increases (+3.5%)

because of the increased intensity of the secondary distribution. A concurrent optimisation of the economic and environmental performance through the application of the eco-efficient model (with $\alpha_1 = \alpha_2 = 0.5$) leads to more balanced overall savings from both the distribution cost (-3%) and the CO_2 emissions (-2.8%) perspectives with 16 activated TP_is.

Notably, for all three models, the number of activated TP_is is smaller than the current configuration. This suggests that the company is running a supply chain network characterised by a certain degree of redundancy, which is possibly attributable to the need for flexibility in serving customers. It is important to underline that in addition to changing the number of activated TP_is, the three models propose different configurations of the supply chain network in terms of the locations of the distribution facilities and the linkages among the nodes of the network.

The graphical representation of the results offers additional insights (Figure 4).

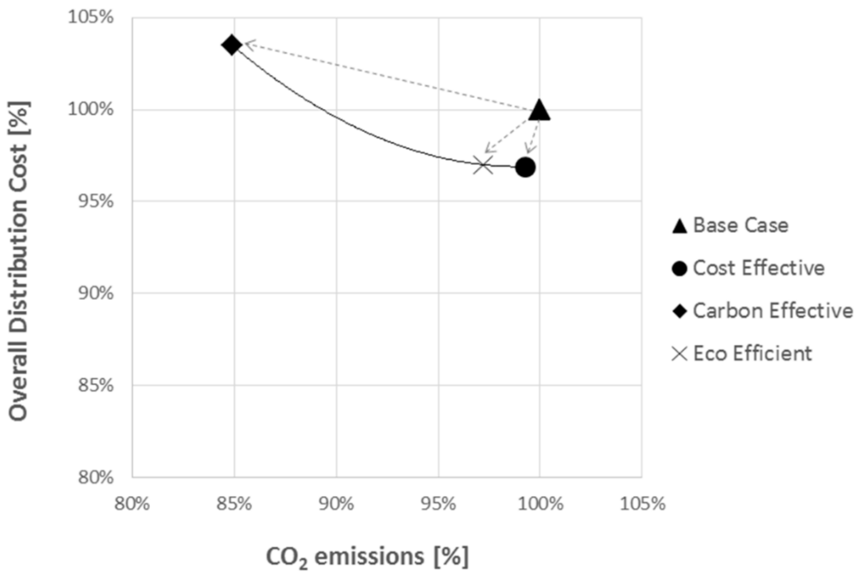

Figure 4. The trade-off between the economic and environmental performance (Base Case = 100%)

It appears that CO_2 emissions can be reduced regardless of the specific objective function of the applied optimisation model. The results indicate that by optimising the configuration of the supply chain network based only on cost, a beneficial effect for the environment may be obtained as well.

Our data show that the range of variation in the overall distribution cost is more limited compared with the range of variation in the CO_2 emissions. In particular, either with the same level of economic performance or allowing for a slight increase in distribution costs, environmental performance can be significantly improved (in terms of reduced CO_2 emissions).

The results presented in this paper appear to confirm the existence of the Pareto-optimal frontier (see the illustrative trend-line in Figure 4). This frontier indicates that different trade-off combinations exist between the economic and environmental objectives depending on the relative weight of the considered objectives (Quariguasi Frota-Neto et al. 2008). Our eco-efficient model for the described case represents one of the possible combinations. On the boundary of the Pareto-optimal frontier, each company should strive to find the most suitable combination of the values of the weights of the objectives. This needs to be done consistently with the corporate strategy, so as to maximise the value for the stakeholders (i.e. the right cost for the right environmental impact).

5.3 Sensitivity analysis

As mentioned in Section 5.1, we conducted a sensitivity analysis on the value of the parameter CC, which we used to convert CO_2 emissions into monetary value. This appears to be the most critical parameter to be studied in that its value has not yet been defined specifically in the literature and its variations span a very wide range. Johnson and Hope (2012) propose a set of values ranging from 4 €/kg CO_2 to 199 €/kg CO_2 (Table 3). In Table 5, we report the results of the sensitivity analysis that we performed with respect to this parameter.

Table 5. Results of the sensitivity analysis

	CC - values in €/kg_CO_2							
	199	**131**	**91**	**46**	**41**	**26**	**16**	**4**
Number of Activated TPis	16	16	16	17	17	17	17	17
Primary transportation cost (%)	24.60	24.60	24.60	24.70	24.70	24.70	24.70	24.70
Secondary distribution and warehousing cost (%)	72.40	72.40	72.40	72.20	72.20	72.20	72.20	72.20
Overall distribution cost (%)	**97.00**	**97.00**	**97.00**	**96.90**	**96.90**	**96.90**	**96.90**	**96.90**
CO_2 emissions - primary transportation (%)	34.80	34.80	34.80	34.94	34.94	34.94	34.94	34.94
CO_2 emissions - secondary distribution (%)	15.34	15.37	15.37	15.16	15.16	15.18	15.18	15.18
CO_2 emissions - warehousing (%)	47.06	47.06	47.06	49.15	49.15	49.15	49.15	49.15
CO_2 emissions - overall (%)	**97.20**	**97.23**	**97.23**	**99.25**	**99.25**	**99.27**	**99.27**	**99.27**

Note: The results of the sensitivity analysis refer to the overall distribution cost and the CO_2 emissions of base case expressed as an index number of 100 (see Table 4).

From Table 5, it appears that for CC values greater than 46 €/kg_CO_2, environmental performance is sufficiently relevant to affect the configuration of the supply chain network. In contrast, for values equal to or less than 46 €/kg_CO_2, even with minor adjustments, the configuration and the cost related to the supply chain network nearly overlap with the optimal configuration that is derived from the cost-effective model.

6. Conclusions

The present paper addressed the topic of supply chain network design for eco-efficiency. We achieved the first objective (i.e. to contribute to the existing body of knowledge on the eco-efficient design of supply chain networks) by developing a supply chain network design framework based on multi-objective (binary) mathematical programming. This framework encompasses both environmental and economic objectives, and it is composed of three optimisation models, i.e. cost-effective, carbon-effective and eco-efficient models. From a theoretical viewpoint, we contribute to filling the gap in the extant body of knowledge on quantitative models that address eco-efficient supply chain network design, especially on distribution processes and the related warehousing activities. In terms of the practical and managerial implications, the proposed framework is a tool that can be used by supply chain managers to derive an optimal configuration of supply chain networks based on the priority objectives of a given company's top management (i.e. by changing the weights of the aggregate objective function). Furthermore, the framework can be used to analyse the variations in network performance with reference to changes in key parameters of the model(s).

With reference to the second objective (i.e. to close the critical missing link between model-based methods and empirical research), we applied the developed design framework to a real-life case study, gathering meaningful insights from the field. The application of the framework to the Lindt case study allowed us to engage with real-life data and complexity, which closes the critical link to empirical research that is so often advocated by previous researchers. The achievement of this objective makes a further contribution to the body of knowledge on eco-efficient supply chain network design by producing a number of insights at a managerial rather than merely illustrative level.

To achieve the third objective (i.e. to delve deeper into the trade-off between economic and environmental objectives and its implications for the configuration of supply chain networks), we discussed the obtained numerical results, and we performed a sensitivity analysis on them. From a theoretical viewpoint, our research sheds light on and contributes to the growing debate on the trade-offs between the economic and environmental performance of supply chains. Specifically, this study supports the existence of trade-offs, but also it offers insights into the optimal management of these trade-offs. Our data show that both economic and environmental objectives can be simultaneously pursued in the goal of maximising the overall value of the objective function for network configurations that need to be eco-efficiently optimised. Once a steady state condition has been reached on the Pareto-efficient frontier, the trade-off between the considered objectives emerges. Even though the improvement of the environmental performance is traditionally perceived as requiring considerable additional costs, our results show that such improvement can be achieved with only a slight increase in distribution costs. The complexity of managing the investigated trade-off in the real-life industrial contexts calls for the development of tools that can support decision making, such as the design framework we propose in this paper.

A limitation of this paper is that it applies its framework to a single logistics network context, although the investigated case is well representative of the typical organisation of distribution activities. One direction for future research is to apply our proposed model to other industrial case studies in the same or other sectors. This could be beneficial to further close the observed missing link between theory and practice. It would be also valuable to increase the amount of field evidence related to the trade-off between economic and environmental performance, which itself requires additional investigations to support decision making in supply chain management. Applications to industrial cases in the same sector could be useful for comparing and contrasting the evidence and results discussed in this paper and for generating supplementary insights. Applications to other sectors could be beneficial to collect a wider, more diverse range of field evidence to inform managerial practices. By sharing discussions on how to manage the trade-off between environmental and economic objectives across industries, it will be possible to identify and better understand the critical factors that affect the mechanisms that underpin the abovementioned trade-off. Potential areas of application could be sectors such as the pharmaceutical industry, which is particularly critical from an energy consumption and greenhouse gas emissions viewpoint along with its high distribution costs.

Additional research that focuses on the combination of the environmental and the economic performance could also be undertaken in order to identify an appropriate value for the parameter for converting CO_2 into monetary values, which is critical for both optimisation and robust outcomes. In fact, the value of this conversion parameter is affected by a certain variability over time, due to social and economic trends exogenous to companies' decisions. Thus, additional studies that focus on quantifying the monetary value of CO_2 emissions are necessary in order to better support companies in the multi-faceted decision making regarding environmental decisions related to supply chains.

References

Abbasi, M., and F. Nilsson. 2012. "Themes and challenges in making supply chains environmentally sustainable." *Supply Chain Management: An International Journal* 17 (5): 517 – 530.

Abdallah, T, A. Diabat, and D. Simchi-Levi. 2012. "Sustainable supply chain design: a closed-loop formulation and sensitivity analysis." *Production Planning & Control: The Management of Operations* 23 (2-3): 120-133.

Ahmetovici, E., M. Martin, and I. E. Grossmann. 2010. "Optimization of energy and water consumption in corn-based ethanol plants." *Industrial & Engineering Chemistry Research* 49 (17): 7972–7982.

Ahuja, R. K., W. Huang, H. E. Romeijn, and D. R. Morales. 2007. "A Heuristic Approach to the Multi-Period Single-Sourcing Problem with Production and Inventory Capacities and Perishability Constraints." *INFORMS Journal on Computing* 19 (1): 14-26.

Ahumada, O., and J. R. Villalobos. 2009. "Application of planning models in the agri-food supply chain: A review." *European Journal of Operational Research* 196 (1): 1-20.

Akkerman, R., P. Farahani, and M. Grunow. 2010. "Quality, safety and sustainability in food distribution: a review of quantitative operations management approaches and challenges." *OR Spectrum* 32 (4): 863–904.

Ala-Harja, H., and P. Helo. 2014. "Green supply chain decisions – case-based performance analysis from the food industry." *Transportation Research Part E: Logistics and Transport Review* 69 (1): 97-107.

Beamon, B. M. 1999. "Measuring supply chain performances." *International Journal of Operations and Production Management* 19 (3): 275–292.

Beamon, B. M., and C. Fernandes. 2004. "Supply-chain network configuration for product recovery." *Production Planning & Control: The Management of Operations* 15 (3): 270-281.

Brandenburg, M., K. Govindan, J. Sarkis, and S. Seuring. 2014. "Quantitative models for sustainable supply chain management: Developments and directions." *European Journal of Operational Research* 233 (2): 299-312.

Büyüközkan, G., and C. Berkol. 2011. "Designing a sustainable supply chain using an integrated analytic network process and goal programming approach in quality function deployment." *Expert Systems with Applications* 38 (11): 13731–13748.

Büyüközkan, G., and G. Cifci. 2012. "Evaluation of the green supply chain management practices: a fuzzy ANP approach." *Production Planning & Control: The Management of Operations* 23 (6): 405-418.

Cano-Ruiz, J., G. McRae. 1998. "Environmentally conscious chemical process design." *Annual Review of Energy and the Environment* 23: 499-536.

Chaabane, A., A. Ramudhin, and M. Paquet. 2011. "Designing supply chains with sustainability considerations." *Production Planning & Control: The Management of Operations* 22 (8): 727-741.

Chopra, S., and P. Meindl. 2013. *Supply chain management: Strategy, planning and operations*. Upper Saddle River: Prentice-Hall.

Colicchia, C., F. Dallari, and M. Melacini. 2011. "A simulation-based framework to evaluate strategies for managing global inbound supply risk." *International Journal of Logistics Research and Applications* 14 (6): 371-384.

Colicchia, C., G. Marchet, M. Melacini, and S. Perotti. 2013. "Building environmental sustainability: empirical evidence from Logistics Service Providers." *Journal of Cleaner Production* 59 (15): 197–209.

Corsano, G., A. R., Vecchietti, and J. M. Montagna. 2011. "Optimal design for sustainable bioethanol supply chain considering detailed plant performance model." *Computers & Chemical Engineering*, 35 (8): 1384–1398.

Creazza, A., F. Dallari, and T. Rossi. 2012. "An integrated model for designing and optimising an international logistics network." *International Journal of Production Research* 50 (11): 2925-2939.

Department for Environment Food & Rural Affairs (DEFRA). 2013. "2013 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors". Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224437/pb13988-emission-factor-methodology-130719.pdf

Ekşioğlu, S. D., A. Acharya, L. E. Leightley, and S. Arora. 2009. "Analyzing the design and management of biomass-to-biorefinery supply chain." *Computers & Industrial Engineering* 57 (4): 1342–1352.

European Commission. 2011. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Final Report to the European Commission - DG Climate Action. Available at: http://ec.europa.eu/clima/policies/transport/vehicles/docs/ec_hdv_ghg_strategy_en.pdf

Evans, J. 2007. “Cold storage of food: Review of available information on energy consumption and energy saving options.” *Technical report, Food Refrigeration and Process Engineering Research Centre (FRPERC)*, University of Bristol, UK.

Grossmann, I. E., and G. Guillén-Gosálbez. 2010. “Scope for the application of mathematical programming techniques in the synthesis and planning of sustainable processes.” *Computers & Chemical Engineering* 34 (9): 1365–1376.

Harris, I., C. L. Mumford, and M. M. Naim. 2014. “A hybrid multi-objective approach to capacitated facility location with flexible store allocation for green logistics modelling.” *Transportation Research Part E: Logistics and Transport Review* 66 (1): 1-22.

Hassini, E., C. Surti, and C. Searcy. 2012. “A literature review and a case study of sustainable supply chains with a focus on metrics.” *International Journal of Production Economics* 140 (1): 69-82.

Hugo, A., and E.N. Pistikopoulos. 2005. “Environmentally conscious long-range planning and design of supply chain networks.” *Journal of Cleaner Production* 13 (15): 1471–1491.

Jaegler, A. and P. Burlat. 2012. “Carbon friendly supply chains: a simulation study of different scenarios.” *Production Planning & Control: The Management of Operations* 23 (4): 269-278.

Johnson, L. T., and C. Hope. 2012. “The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique.” *Journal of Environmental Studies and Sciences* 2 (3): 205-221.

Langella, I. M., and S. Zanoni. 2011. “Eco-efficiency in logistics: a case study on distribution network design.” *International Journal of Sustainable Engineering* 4 (2): 115-126.

Lin, C. Y., and Y. H. Ho. 2008. “An empirical study on logistics service providers’ intention to adopt green innovations.” *Journal of Technology Management & Innovation* 3 (1): 17-26.

MacKay, D. J. C. 2009. *Sustainable Energy - Without the Hot Air*. Cambridge: UTI Cambridge.

Marchant, C., and P. Baker. 2012. “Reducing the environmental impact of warehousing.” In *Green Logistics: improving the environmental sustainability of logistics*, edited by A. McKinnon, M. Browne, and A. Whiteing. London: Kogan Page.

McKinnon, A., M. Browne, and A. Whiteing. 2012. *Green Logistics: improving the environmental sustainability of logistics.* London: Kogan Page.

Meixell, M. J., and V. B. Gargeya. 2005. “Global supply chain design: A literature review and critique.” *Transportation Research Part E: Logistics and Transport Review* 41 (6): 531-550.

Melo, M. T., S. Nickel, and F. Saldanha-da-Gama. 2009. “Facility location and supply chain management – A review.” *European Journal of Operational Research* 196 (2): 401–412.

Nikolopoulou, A., and M. G. Ierapetritou. 2012. “Optimal design of sustainable chemical processes and supply chains: A review.” *Computers & Chemical Engineering* 44 (14): 94–103.

Porter, M., and C. van der Linde. 1995. “Green and competitive: ending the stalemate.” *Harvard Business Review* Sept-Oct: 120-134.

Prakash, B., and R. P. Singh. 2008. “Energy Benchmarking of Warehouses for Frozen Foods.” *Public Interest Energy Research (PIER) Program Contract and Research Project Reports*. California Energy Commission, PIER Program.

Quariguasi Frota Neto, J., J. M. Bloemhof-Ruwaard, J. A. E. E. van Nunen, and E. van Heck. 2008. “Designing and evaluating sustainable logistics networks.” *International Journal of Production Economics* 111 (2): 195-208.

Rossi, S., C. Colicchia, A. Cozzolino, and M. Christopher. 2013. “The logistics service providers in eco-efficiency innovation: an empirical study.” *Supply Chain Management: an International Journal* 18 (6): 583-603.

Schoen, F. 2002. “Two-phase methods for global optimization”. In *Handbook of global optimization – Volume 2*, edited by P.M. Pardalos and H.E. Romejin. Dordrecht: Kluwer Academic Publishers.

Seuring, S. 2013. “A review of modeling approaches for sustainable supply chain management.” *Decision Support Systems* 54 (4): 1513–1520.

Shaw, K., R. Shankar, S.S. Yadav, and L.S. Thakur. 2013. “Modeling a lowcarbon garment supply chain.” *Production Planning & Control: The Management of Operations*, 24 (8-9): 851-865.

Sheu, J., and W. K. Talley. 2011. “Green Supply Chain Management: Trends, Challenges, and Solutions.” *Transportation Research Part E: Logistics and Transport Review* 47 (6): 791–792.

Simchi-Levi, D., S. Kaminsky, and E. Simchi-Levi. 2008. *Designing & Managing The Supply Chain - Concepts, Strategies and Cases*, 3rd edition, New York: McGraw-Hill.

Srivastava, S. K. 2007. “Green supply-chain management: A state-of-the-art literature review.” *International Journal of Management Reviews* 9 (1): 53-80.

Subramanian, R., B. Talbot, and S. Gupta. 2010. “An Approach to Integrating Environmental Considerations within Managerial Decision-Making.” *Journal of Industrial Ecology* 14 (3): 378–398.

Wang, F., X. Lai, and N. Shi. 2011. “A multi-objective optimization for green supply chain network design.” *Decision Support Systems* 51(2): 262-269.

Werner, S. R. L., F. Vaino, I. Merts, and D. J. Clelenad. 2006. “Energy use in the New Zealand cold storage industry.” Paper presented at the IIR-IRHACE Conference, The University of Auckland.

You, F., L. Tao, D. J. Graziano, and S. W. Snyder. 2012. “Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input–output analysis.” *AIChE Journal* 58 (4): 1157-1180.

Zailani, S., A. Amran, and H. Jumadi. 2011. “Green innovation adoption among logistic service providers in Malaysia: an exploratory study on the managers’ perceptions.” *International Business Management* 5 (3): 104-113.

Zamboni, A., F. Bezzo, and N. Shah. 2009. “Spatially explicit static model for the strategic design of future bioethanol production systems. 2 Multi-objective environmental optimization.” *Energy & Fuels* 23 (10): 5134– 5143.

Zanoni, S., and L. Zavanella. 2012. “Chilled or frozen? Decision strategies for sustainable food supply chains.” *International Journal of Production Economics* 140 (2): 731-736.