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Efficiency & sustainability model to design and manage two-stage logistic networks

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Abstract

The distribution and storage efficiency together with the environmental sustainability are mandatory targets to consider when designing and managing modern supply chain (SC) networks. The current literature continuously looks for quantitative multi-perspective strategies and models, including and best balancing such issues that often diverge.
This paper presents and applies a bi-objective optimization model to best design and manage two-stage logistic networks looking for the best trade-off between the SC stock level and the building and distribution environmental impact. The existence of good balance confirms the possibility to reduce the average SC stock level without a relevant increase of the emissions due to frequent replenishments.

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Keywords: Logistic Network Design; Lean Management; Inventory Control; Sustainability; Multi-objective Optimization; Supply Chain Management.

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1. Introduction

Lean Management (LM) is an industrial philosophy aiming to increase productivity and to reduce costs and no-value added activities in the form of overproduction, transporting, inventory and defects. The main goal of LM is waste elimination. Green Management (GM) integrates the environmental thinking in Supply Chain Management (SCM), including sustainable product design, low-carbon material sourcing and selection, green manufacturing processes, end-of-life management and reverse logistics of the products at the end of their lifespan [1]. LM and GM share the common goal of waste elimination even if their focus is on different types of waste. A large number of researchers investigates the benefits of implementing such two practices separately. Few contributions exist in the literature examining the integration between LM and GM in the field of SCM, especially from a quantitative, i.e. modelling, point of view. The combination of LM and GM can lead to great results, higher than the sum of the performance from their separate application.

Starting from this framework, this paper shortly revises the literature about recent studies on the topic before presenting and applying a bi-objective optimization model to design and manage modern logistic networks investigating possible balance between the storage efficiency, the building and distribution sustainability. In the analysis, LM is modeled in terms of storage efficiency while GM in terms of building and distribution emissions.

According to these goals, the reminder of this paper is organized as follows: the next Section 2 presents a short literature review of the topic. Section 3 introduces the bi-objective model for logistic networks design, while Section 4 applies the model to a case study about a mid-scale Italian network located in the Emilia-Romagna region. Finally, Section 5 concludes this paper with some remarks and future research opportunities.

2. Literature review

Few contributions exist in the literature examining the relationship between LM and GM in the field of SCM, especially from a quantitative, i.e. modelling, point of view. First considered as “parallel universes”, increasing authors recognize more than just a simply co-existence [2]. In particular, studies and research works carried out in this field find that the concurrent implementation of LM and GM produces synergic effects and great results [3-5]. Despite such synergic win-win effects, the replenishment frequency rises as the main point of collision. In product manufacturing and distribution processes, LM calls for a replenishment frequency of small product batches, according to the Just-in-Time (JIT) principle, to decrease the warehouse stock level [6-7]. Conversely, GM calls for a sparse shipments of larger batches to reduce the environmental impact of trucks and the other carrier vehicles. Furthermore, the distance between the logistic actors plays a critical role. LM calls for distances to be as short as possible. This means that a short lean supply chain (SC), e.g. regional networks, is also green, but as distances increase lean and green are in conflict. In the age of global trade, few SC are local with short transportation links. In addition, the low cost of labor in the developing countries is an important factor in choosing where to locate production sites [6].

Kainuma and Tawara [8] face these questions from a quantitative approach. In their study, using the multi-attribute utility theory, they evaluate the performances of the SC not only from a managerial perspective but also from an environmental performance viewpoint. Through computational experiments, the authors quantify the benefit of information sharing to decrease the average stock level in the SC and the out-of-stock ratio at the retailer level. Bergmiller and McCright [9] propose a statistical analysis concluding that including elements of Green Operations Systems to Lean firms leads to stronger Lean results. Their analysis compares measure of elements of Green Management System and Green Waste Reduction Technique with scores of Lean results. Evidences show that GM drives Lean results and improves the cost performance. Similarly, King and Lenox [10] analytically prove that the adoption of ISO 9001 quality management standard increases the probability that managers adopt the ISO 14001 environmental management standard. Finally, Miller et al., by using discrete event simulation modeling, state that LM and GM can have a more significant, positive impact on multiple aspects when implemented concurrently rather than separately [11].

Table 1 shows a preliminarily classification of the relevant literature from 2006 to 2016.

Table 1. Relevant literature contributions classification.

Id.	Year	Optimization KPI			Investigation strategy			Case study/Application		Reference
		Stock	*Emission*	*Cost*	*Statistical*	*Optimization*	*Rule-of-thumb*	*Qualitative example*	*Numerical example*	
1	2006	✓				✓			✓	[8]
2	2010		✓			✓			✓	[12]
3	2013		✓	✓			✓		✓	[13]
4	2013		✓	✓			✓		✓	[14]
5	2013	✓	✓	✓			✓		✓	[15]
6	2014		✓	✓			✓		✓	[16]
7	2014	✓		✓			✓	✓		[17]
8	2015	✓	✓	✓			✓	✓		[18]
9	2016		✓	✓	✓				✓	[19]

The review shows that emissions and costs are the most considered KPIs, since they cross both LM and GM. Furthermore, the most of the analysis are through practical rules-of-thumb and examples from the field rather than through optimization or modelling methods [3]. This paper tries to contribute to this research stream introducing a mathematical bi-objective model to investigate the best balance between LM and GM in the field of SCM.

3. Bi-objective model for the logistic networks design

3.1. Problem description, assumptions and notations

This study considers a three levels and two stages logistic network as in Fig. 1. The problem goal is the determination of the best shipment and storage plan of commodities from r factories to s customers passing through n distribution centers (DCs). The customers are not necessarily the final consumers. DCs represent a further intermediate level helping to reduce transportation time and the global number of shipments.

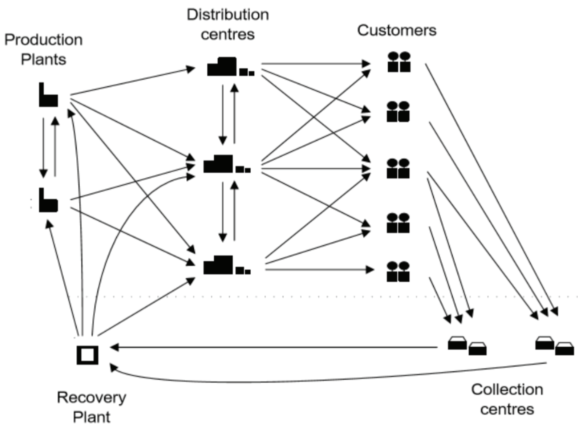

Fig. 1. Structure of the logistic network, adapted from [20].

After production, the factories make stock at the DCs. Here, products are stored, according to the available capacity and the inventory level and, then, final deliveries connect to the customers. A LM strategy is assumed. This implies that inventory level is as low as possible. To achieve this goal, factories try to distribute commodities in daily deliveries, through small batch production, despite this implies high $CO_{2\text{-eq}}$ emissions. The proposed approach attempts to determine the optimal volume to be transported from each source to each destination to simultaneously minimize the stock level at DC warehouses (LM goal) and the $CO_{2\text{-eq}}$ emissions generated by shipments and by the use and maintenance of the DC buildings e.g. illumination, heating, (GM goal).

The proposed bi-objective optimization model adopts the following assumptions according to the standard literature within supply chain modelling [20]:

- Single-product model;
- *Drive-through* distribution strategy;
- Stock at DCs;
- Shipping fleet sized on the model planned flows of materials.

These assumptions are still realistic and representative of common networks. Furthermore, the model is flexible and can be adapted to match different assumptions (e.g. multi-product model, stock at different levels, input limitations on the shipping capacity fleet).

The following notations are used.

- Indices

i DCs $i = 1, \dots, N$
j customers $j = 1, \dots, S$
m shipping modes $m = 1, \dots, L$
p factories $p = 1, \dots, R$
t time periods $t = 1, \dots, T$

- Parameters

A_i dimension of DC i $[m^2]$
C_{pt} production capacity of factory p in period t $[tons]$
D_{jt} demand of customer j in period t $[tons]$
d_{pi} distance between producers p and DC i $[km]$
d_{ij} distance between DC i and customer j $[km/trip]$
e_e $CO_{2\text{-eq}}$ emissions of 1 electric kWh $\left[tonCO_{2-eq}/kWh\right]$
e_{mco2eq} $CO_{2\text{-eq}}$ emissions of vehicle m $\left[tonCO_{2-eq}/km\right]$
f_c climate factor $[kWh/m^2]$
ff energy consumption of mobile material handling equipment $[kW]$
f_i illumination factor $[kWh/m^2]$
$G_{start,i}$ stock level of DC i in period 1 $[tons]$
v_f average speed of mobile material handling equipment $[km/h]$
W_f capacity of mobile material handling equipment $[tons/trip]$
W_m capacity of vehicle m $[tons]$
X_i average distance travelled by mobile material handling equipment $[km/trip]$

- Decisional variables

G_{it} stock level of DC i in period t $[tons]$
G_{max} max stock value $[tons]$
K_{ijt} 1 if DC i supplies customer j in period t, 0 otherwise $[binary]$
X_{mpit} tons of products transported from factory p to DC i with vehicle m in period t $[tons]$
X_{mijt} tons of products transported from DC i to customer j with vehicle m in period t $[tons]$

Z_{mpit} trips from factory p to DC i through vehicle m in period t
Z_{mijt} trips from DC i to customer j through vehicle m in period t

- Objective functions

$\square_1$ Maximum stock level at the DCs per period $[tons/period]$
$\square_2$ $CO_{2\text{-eq}}$ emissions $[tons]$

The analytic formulation of the bi-objective model is in the following.

$$\square_1 = G_{max} \tag{1}$$

$$\square_2 = \sum_{m=1}^{l}\sum_{p=1}^{r}\sum_{i=1}^{n}\sum_{t=1}^{T} Z_{mpit} * d_{pi} * e_{mco2eq} + ee * \sum_{i=1}^{n}\sum_{t=1}^{T}\left[\left(A_i * (f_i + f_c) + \sum_{m=1}^{l}\sum_{j=1}^{s}\left(X_{mijt} * \frac{x_i}{w_f} * \frac{ff}{v_f}\right)\right)\right] + \sum_{m=i}^{l}\sum_{i=1}^{n}\sum_{j=1}^{s}\sum_{t=1}^{T} Z_{mijt} * d_{ij} * e_{mco2eq} \tag{2}$$

(1) minimizes the stock level at DC warehouses, while (2) represents the green objective function that minimizes the environmental footprint generated by the distribution of goods (outbound logistic) and the use and maintenance of the DC buildings (inbound logistic).

$$\sum_{i=1}^{n} K_{ijt} = 1 \qquad \mathrm{j, t} \tag{3}$$

$$\sum_{m=1}^{l} X_{mijt} \leq K_{ijt} * D_{jt} \qquad \mathrm{i, j, t} \tag{4}$$

$$\sum_{i=1}^{n}\sum_{m=1}^{l} X_{mpit} = C_{pt} \qquad \mathrm{p, t} \tag{5}$$

$$\frac{X_{mpit}}{W_m} \leq Z_{mpit} \leq \frac{X_{mpit}}{W_m} + 1 - \mathcal{E} \qquad \mathrm{m, p, i, t} \tag{6}$$

$$\frac{X_{mijt}}{W_m} \leq Z_{mijt} \leq \frac{X_{mijt}}{W_m} + 1 - \mathcal{E} \qquad \mathrm{m, i, j, t} \tag{7}$$

$$G_{it} = G_{i,t-1} + \sum_{m=1}^{l}\sum_{p=1}^{r} X_{mpit} - \sum_{m=1}^{l}\sum_{j=1}^{s} X_{mijt} \qquad \mathrm{i, t}\backslash\{1\} \tag{8}$$

$$G_{i1} = G_{start,i} + \sum_{m=1}^{l}\sum_{p=1}^{r} X_{mpi1} - \sum_{m=1}^{l}\sum_{j=1}^{s} X_{mij1} \qquad \mathrm{i} \tag{9}$$

$$G_{max} \geq G_{it} \qquad \mathrm{i, t} \tag{10}$$

$$K_{ijt} \in \{0,1\} \quad i,j,t \quad (11)$$

$$Z_{mpit}, Z_{mijt} \geq 0, integer \quad m,p,i,j,t \quad (12)$$

$$G_{max}, G_{it}, X_{mpit}, X_{mijt} \geq 0 \quad m,p,i,j,t \quad (13)$$

(3) forces each customer to be supplied by one DC. (4) ensures that the customer demand is met, while (5) is the production capacity limit of each factory. (6) and (7) fix the integer number of trips to deliver all products. (8) defines the stock level for each DC and time period except for the first one that is in (9). (10) sets G_{max} consistently, while (11)-(13) give consistence to the decisional variables.

The model parameters are available and potentially easy to acquire within operative environments with the support of the standard literature. As example, the company target plan and DBMS (e.g. SAP) store updated trends of the product market demand, the production capacity constraints and the stock quantities. Target values of the environmental emissions and the climate and illumination factors are widely discussed by national and sectorial regulations. Finally, distances and the entity geo-referencing data are commonly available from maps and geographical databases.

The model complexity is expressed by $N(R+S+4)+2L+RT+S(T+1)$ input parameters and $NT\big(S+1+2L(R+S)\big)+1$ decisional variables.

4. Model application

4.1. Case study description

A case study applies the proposed model. It is representative of a mid-scale logistic Italian network for companies operating in the Emilia-Romagna region. The SC includes 3 factories, 10 DCs and 20 customers. Each factory delivers commodities choosing among 3 different modes of transport. The considered planning horizon is of about 15 days. Fig. 2 presents the case study geography where the yellow spots are factories, the blue spots are the DCs and the red spots are the customers. The set of input data, i.e. parameters, used to feed the bi-objective model are available upon request to the Authors and leads to 626 parameters and 23,851 decisional variables supporting the realism of the proposed case study.

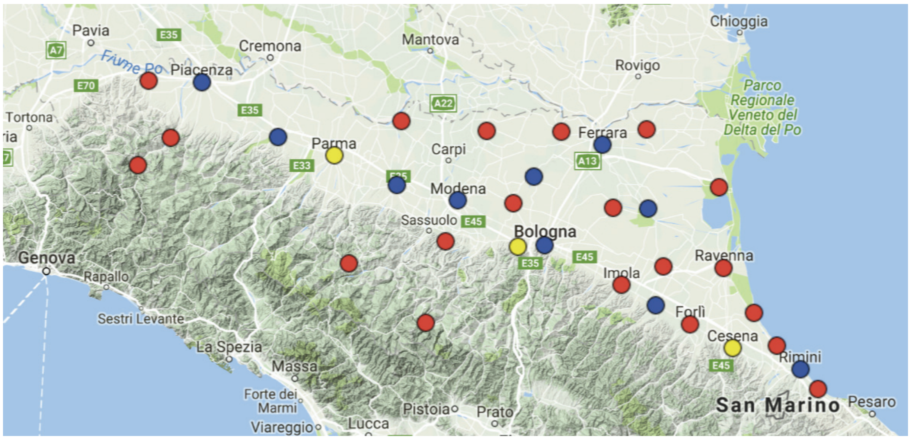

Fig. 2. Case study geography.

The model is coded in AMPL language and processed adopting Gurobi Optimizer© v.5.5 solver. An Intel® Core™ i7-3770 CPU @ 3.40GHz and 16.0GB RAM workstation is used. The global solving time is approximately of six hours to build the whole Pareto frontier as presented in the next Section 4.2.

4.2. Results and discussion

Fig. 3 presents the so-called Pareto frontier obtained through the application of the Normalized Normal Constraint Method (NNCM) on a set of 20 intervals [20]. The anchor points, i.e. the best lean and green solutions, lead to a maximum stock value of 45 tons/period (emitted $CO_{2\text{-eq}}$ of 2262.8 tons) and to an emitted $CO_{2\text{-eq}}$ of 1843.8 ton$CO_{2\text{-eq}}$ (with maximum stock of 363 tons/period), respectively.

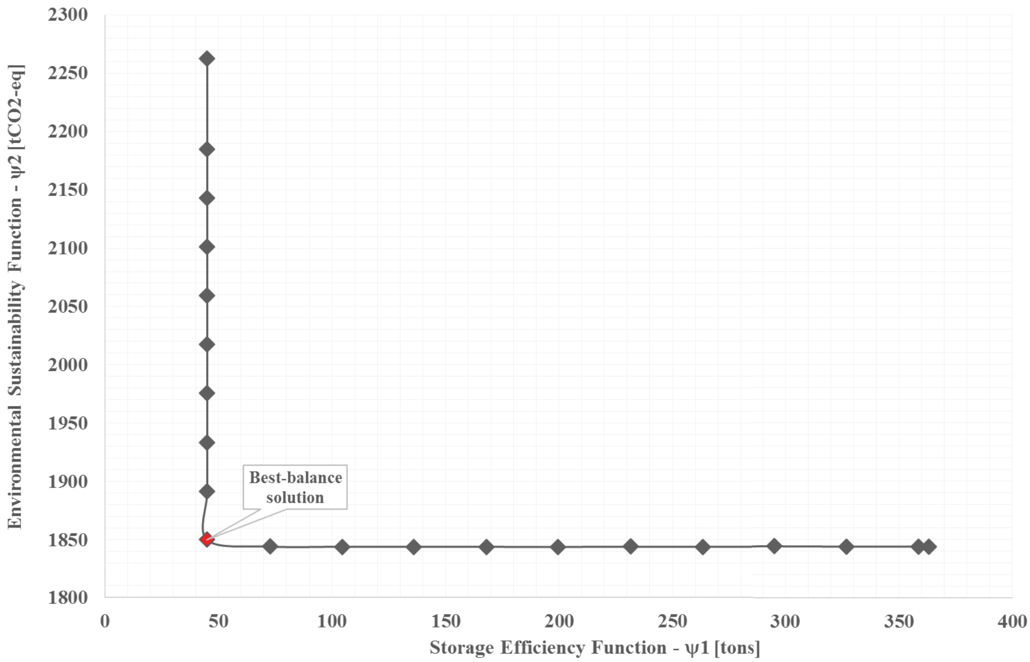

Fig. 3. Case study, Pareto frontier

The Pareto frontier skewness shows the existence of a good balance solution between storage efficiency and environmental sustainability. The chosen best-balance solution presents a maximum stock of 45.06 tons/period and 1849.8 tons of emitted $CO_{2\text{-eq.}}$ and it allows concluding that it is possible to decrease one objective function with low increase of the other one.

This study proves that the concurrent implementation of storage efficiency and environmental sustainability strategies is a great opportunity for companies to reduce the negative impacts on the environment and to increase the overall productivity, finding a network configuration best balancing such two, often divergent, issues.

5. Conclusions and future research

Nowadays Lean Management (LM) and Green Management (GM) play a pivotal role in modern supply chains (SC) suggesting the need of an integrated approach in SC design and management. The joint implementation of LM and GM is a new challenge explored by few researchers and practitioners, especially from a quantitative perspective. This paper presents a bi-objective model simultaneously optimizing LM, in terms of storage efficiency through the SC, and GM, in terms of building and distribution environmental emissions.

A case study, representative of a mid-scale Italian network, applies the proposed model. Results show the possibility to best balance storage efficiency and environmental sustainability confirming the possibility to reduce the SC average stock level without increasing excessively the environmental emissions.

Future research focuses on two directions of development, the former deals with the application and verification of the proposed model against an organic set of regional, national and international industrial contexts, the latter deals with the inclusion of the cost dimension within the objective function panel. The literature analysis and the common practice confirm that cost is of dramatic interest for companies so that it is of value to outline a three-objective analysis to explore the feasible solution space optimizing storage efficiency, environmental sustainability and the policy cost of the network.

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