Journal of Cleaner Production 105 (2015) 14–27

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Towards supply chain sustainability: economic, environmental and social design and planning

Bruna Mota [a,*], Maria Isabel Gomes [b], Ana Carvalho [a], Ana Paula Barbosa-Povoa [a]

[a] Centro de Estudos de Gestao, IST, Universidade de Lisboa, Av. Rovisco Pais, 1049-101 Lisboa, Portugal
[b] Centro de Matematica e Aplicacoes, FCT, Universidade Nova de Lisboa, Monte de Caparica, 2829-516 Caparica, Portugal

ARTICLE INFO

Article history:
Received 28 February 2014
Received in revised form
21 July 2014
Accepted 21 July 2014
Available online 1 August 2014

Keywords:
Closed-loop supply chain
Environmental impact
Social benefit
Multi-objective
Location model

ABSTRACT

Costumers and governments are pressuring companies to become more sustainable. However, the lack of research on how to incorporate these issues makes this a challenging task. To fill this gap a generic multi-objective mathematical programming model for the design and planning of supply chains, integrating the three dimensions of sustainability is presented. The economic pillar of sustainability is addressed in this work considering the costs of the supply chain. Then ReCiPe, an environmental assessment methodology, indicated in the literature and by the European Commission as the most developed one currently available, is for the first time applied to supply chain design optimization. Finally, a social indicator appropriate to assess strategic decisions is proposed. This social indicator considers the impact of social and political concerns on company's performance. The relevance of this model as a decision support system is highlighted with its application to a real case study of a Portuguese battery producer and distributor. A set of strategies to select the best solution among the obtained optimal ones is presented. Results show that the model allows improvements in all the three dimensions of sustainability and offers important managerial insights.

1. Introduction

The global context of modern economy forces companies to achieve excellence in terms of efficiency in their logistics operations, in particular, when customer satisfaction is directly affected (Stock et al., 2010). Customers are becoming more and more demanding not only in terms of product quality but also on a fast, flexible and consistent delivery service (Christopher, 2012). With customers being the centre of the business, companies want to develop a service level that meets customers' expectations, but at the same time they want it at the lowest possible cost. Additionally, most companies have a large number of customers geographically disperse and deal with a large number of products and transportation modes. With such a complex supply chain, it is important to assure that conscious decisions are made at the design and planning levels.

Adding to the problem, in the last decades the social and political consciousness woke up for the negative environmental and social impacts of industry (Hutchins and Sutherland, 2008). Climate change, resource depletion, and human health problems are leading to a point of no return (Carvalho et al., 2013). Sustainable development, defined in 1987 as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987), is now more important than ever. Yet, if in the past this concept was more environmentally oriented, in current literature sustainability is considered to be supported by three main pillars: economic, environmental and also social sustainability (Elkington, 2004).

The European Commission has stated its concern and commitment to these matters, declaring that "*Sustainable development remains a fundamental objective of the European Union under the Lisbon Treaty*". A sustainable development strategy was developed as well as a broad range of policies which continue to be updated, as the European Commission clearly states: "*unsustainable trends persist and the EU still needs to intensify its efforts*" (Commission, 2009).

Putting all these aspects into perspective, companies are pressured to look at their entire supply chain in order to become more sustainable while maintaining their competitiveness. Sustainable supply chain management (SSCM) was defined by Seuring and Müller (2008) as *"the management of material, information and*

* Corresponding author. Tel.: +351 927 562 423.
E-mail addresses: bruna.mota@tecnico.ulisboa.pt (B. Mota), mirg@fct.unl.pt (M.I. Gomes), anacarvalho@tecnico.ulisboa.pt (A. Carvalho), apovoa@tecnico.ulisboa.pt (A.P. Barbosa-Povoa).

http://dx.doi.org/10.1016/j.jclepro.2014.07.052
0959-6526/

capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements". It is the balance between these three pillars that offers a challenge, from the strategic to the operational level. The social pillar in particular has been left unaccounted for and we are still far from achieving the so called sustainable supply chain (Seuring, 2013).

This work aims to address this challenge from the strategic point of view, aiming to give a step forward into answering the following research question:

How can sustainability be integrated into supply chains' design and planning decisions?

A generic multi-objective mathematical programming model for the design and planning of closed loop supply chains that simultaneously considers economic, environmental and social performances is proposed in this work. A social indicator has been created to assess social impact at a strategic level. An environmental assessment methodology, ReCiPe, extensively used in the literature but not on supply chain optimization models, is implemented. The model is applied to a case study developed with the collaboration of a Portuguese lead battery producer and distributor.

The paper is organized as follows. In the next section, the background literature is presented, focusing on closed loop supply chain research, as well as environmental and social impact assessment. In Section 3 the developed model is characterized. In Section 4, the case study is described, being the results presented and discussed in Section 5. Lastly, in Section 6, final conclusions are drawn and future work directions discussed.

2. Background

2.1. Closed-loop supply chains

As defined by Fleischmann et al. (1997), reverse logistics concerns "the logistics activities all the way from used products no longer required by the user to products again usable in a market". Environmental legislation that obliges firms to assume responsibility for the entire life cycle of the product is now common to several countries. However, factors other than legislation compliance instil companies to pursue this option. One of them is the "green" image perceived by the costumers who now more than ever ponder such issues in their purchasing decisions (Fleischmann et al., 1997). Moreover, it has been proven that effective management of reverse logistics operations can in fact increase profitability (Ilgin and Gupta, 2010). Fleischmann et al. (1997) further state that even though adding complexity to the problem, both forward and reverse flows must be considered simultaneously to provide adequate planning. Indeed closed-loop supply chain (CLSC) research has evolved significantly and many papers have been published as stated in several reviews. Fleischmann et al. (2001) first introduce the impact of product recovery on facility location decisions. Guide and Van Wassenhove (2002) claim that the supply chain should be seen as a closed loop system where reverse logistics activities should be included, such as the collection, transportation and reprocessing of collected products. Salema et al. (2010) further include the tactical planning of the CLSC operation in a generic modelling framework, from where our contribution is derived. Guide and Van Wassenhove (2009) review the area over the last 15 years, focusing on profitable value recovery. Ilgin and Gupta (2010) offer a description of the main type of modelling techniques and topics addressed in CLSC research. Stindt and Sahamie (2014) analyse CLSC research in different sectors of the process industry. Dekker et al. (2012) state that most papers focused on CLSC do not explicitly deal with the supply chain environmental impacts, and draw attention to the need for new models to support environment related decision making. Tang and Zhou (2012) claim that models to assess the people/society impact of supply chains are lacking and identify this issue as a future challenging research stream. More recently, Cardoso et al. (2013) presented a model for the design and planning of closed-loop supply chains where activities such as supply, production, assembling or disassembling are detailed while considering the supply chain dynamics. Our contribution arises from these identified research gaps, by providing a model that integrates environmental impact assessment and societal impact in CLSC design and planning.

2.2. Environmental impact

Literature on green supply chains is diverse. Several methods and frameworks have been proposed to assess environmental impact. However, Life-Cycle Assessment (LCA) has been described as the most scientifically reliable method currently available for studying and evaluating the environmental impacts of a certain product or process, allowing both retrospective and prospective assessment (Ness et al., 2007). This is reinforced when the European Commission states that LCA currently provides the best framework for assessing the potential environmental impacts of products and has included in its Sustainable Development Strategy the goal of developing and standardizing LCA methodologies (Commission, 2003).

LCA is an environmental impact assessment method that quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services. It takes into account the entire life cycle of the good or service, from the extraction of resources, through production, use, recycling and disposal (Commission, 2010). A typical LCA method follows the generic structure presented in Fig. 1. It begins with the collection of the life-cycle inventory of a given good or service (step 1), followed by the characterization step where the environmental impact of each emitted substance or resource consumed is determined and categorized in either a midpoint and/or endpoint environmental impact category (step 2). Midpoint categories correspond to the environmental mechanism itself while endpoint categories correspond to the subsequent damage. Then follows a normalization step (step 3) and weighting step (step 4) to then arrive at a single score (step 5).

Several different LCA methods are available and continue being developed. These may use different models in the characterization step, different normalization assumptions and/or different weighting factors (Carvalho et al., 2014). Several authors compare different LCA methodologies. Renou et al. (2008) addressed the influence of impact assessment methods in wastewater treatment LCA. Pizzol et al. compared eight different methodologies in the eco-toxicological impact of metals on the aquatic and terrestrial ecosystem (Pizzol et al., 2011a), and compared nine methodologies on the impact of metals on human health (Pizzol et al., 2011b). The European Commission also released a method recommendation report for Life Cycle Impact Assessment in the European context (Commission, 2011).

Some literature exists where authors apply LCA methodologies to supply chain design (Seuring, 2013). Frota Neto et al. (2008) developed a framework for the design and evaluation of sustainable logistic networks, using the European pulp and paper industry as example. The environment index is used to assess ecological impact. Guillén-Gosálbez and Grossmann (2009) addressed the design of sustainable chemical supply chains in the presence of

Fig. 1. Typical structure of LCA methods.

uncertainty in the life cycle inventory associated with the network operation. Eco-indicator 99 was the selected methodology. Bojarski et al. (2009) also address the optimization of supply chain planning and design considering economic and environmental issues. The environmental impact is this time assessed through IMPACT 2002+. Duque et al. (2010) developed a mixed-integer linear programming model which is able to suggest optimal processing and transportation routes. The environmental impact is again measured through Eco-indicator 99. Pinto-Varela et al. (2011) addressed the planning and design of supply chain structures for annual profit maximization, while considering environmental aspects, accounted through Eco-indicator 99. Mele et al. (2011) developed a mixed-integer linear program to optimize the economic and environmental performance of supply chains for the combined production of sugar and ethanol. Again Eco-indicator 99 is used as well as Global Warming Potential. Santibañez-Aguilar et al. (2011) presented a multiobjective model for the optimal planning of a biorefinery, being the environmental impact measured with Eco-indicator 99. In fact, Eco-indicator 99 is one of the most used methodologies in optimization models.

As seen, there are several methods available which have been applied to different sectors and areas. So it is difficult to conclude on which of the methods is better. ReCiPe is a follow up of Eco-indicator 99 combined with CML 2002 and it follows the typical LCA structure described in Fig. 1. The methods behind this methodology are thoroughly described in Goedkoop et al. (2009). This methodology is, according to the European Commission report (Commission, 2011), the most developed one currently available. For these reasons it has been the selected methodology to assess the environmental impact in this work. Some authors have already started using this methodology. Borrion et al. (2012), for example, studied the environmental performance of bioethanol production from wheat straw.

2.3. Social performance

The Global Reporting Initiative (GRI) describes the social dimension of sustainability as the one that "*concerns the impacts the organization has on the social systems within which it operates*" (GRI, 2013). The importance of this pillar of sustainability is clear. Still there is a strong deficit in the amount of published literature on social impact assessment (Brandenburg et al., 2014; Seuring and Müller, 2008), mostly due to the difficulty in measuring such impacts (Zhao et al., 2012).

The Sustainability Reporting Guidelines (GRI, 2013) aim at helping organizations to measure their performance within the three dimensions of sustainability. Due to its ease of use and comprehensiveness it is now commonly used by companies to report and monitor their evolution on sustainable issues (Roca and Searcy, 2012). In these guidelines the social pillar is divided into four categories: Labour Practices and Decent Work, Human Rights, Society, and Product Responsibility. Within these categories, several reporting criteria are depicted (16, 12, 11 and 9 criteria, respectively). For example, the employment aspect is included in the category of Labour Practices and Decent Work, supplier human rights assessment is included in the category of Human Rights, the local communities' aspect is included in the Society category, and customer health and safety is included in the category of Product Responsibility.

Several authors have used such criteria in the development of social assessment indicators, as reviewed by Jørgensen et al. (2008). Hutchins and Sutherland (2008) also review metrics, indicators and frameworks of social impacts, and their ability to evaluate the supply chains social sustainability. However, most metrics are referred to as subjective and qualitative. Hutchins and Sutherland (2008) specifically propose quantifiable indicators (labour equity, healthcare, safety, and philanthropy) that, even though they do not cover all dimensions of social sustainability, can be used in decision-making related to supply chains.

However, the majority of the indicators in literature are based on passed occurrences or are designed to evaluate the social performance of the company at the operational level of supply chain decision-making (e.g. (Chee Tahir and Darton, 2010; Labuschagne and Brent, 2008; Labuschagne et al., 2005)). To our knowledge, the very few works that do exist at a strategic level are focused only on employment, as is the case of You et al. (2012) that determine the social benefit of a cellulosic biofuel supply chain, measured through full-time equivalent yearly jobs created. Hassini et al. (2012) corroborate this conclusion claiming that none of the measures described in their review have been designed to be used in a supply chain context. There is then the need to introduce the concept of social sustainability at the strategic level, and here literature is practically inexistent (Seuring, 2013).

3. Model characterization

3.1. Problem definition

The problem described in this paper aims to determine the supply chain network as well as the planning decisions that minimize costs, minimize environmental impact and maximize social benefit, in a solution of compromise. In this generic modelling framework the decisions at the design level are taken for a given time horizon (e.g. 1 year). This time horizon is composed by time periods in which demand and return values must be satisfied (e.g. months). The model allows for detailed planning on attaining this satisfaction.

The problem is modelled through Mixed Integer Linear Programming (MILP) and can then be described in a summarized form as follows:

Given

- a possible superstructure for the location of the supply chain entities,
- the investment costs,
- products' bills of materials,
- the relation between forward and reverse products,
- travel time between each pair of interacting network agents,
- the minimum disposal fraction,
- the minimum usage time for each return product,
- forward product return fractions,
- the maximum and minimum flow capacities,

- the maximum and minimum acquisition and production capacities,
- the maximum storage capacities,
- the initial stock levels,
- the costs with salaries,
- the environmental impact factor of each facility for each impact category,
- the environmental impact factor per unit of transportation for each impact category,
- the environmental impact factor per product unit for each impact category,
- the regional factor associated to each facility, and for each time period and product,
- customer's demand volume,
- the unit transportation cost between each pair of interacting network agents,
- the factory acquisition and production unit costs,
- each facility unit storage cost, and
- the unit disposal cost.

Determine

- the network structure,
- the production and storage levels, and
- the flow amounts,

So as to

- minimize the global supply chain cost,
- minimize the environmental impact, and
- maximize social benefit, in a solution of compromise.

The developed model is described in detail in the next section.

3.2. Model formulation

The considered supply chain involves a four-echelon structure: factories and warehouses; warehouses and customers; customers and warehouses; warehouses and factories, as described in Fig. 2. I_f represents the factories, I_a the warehouses, I_c the clients, and I_r the recovery centers. f_1 and r_2 represent primary distribution, while f_2 and r_1 represent secondary distribution.

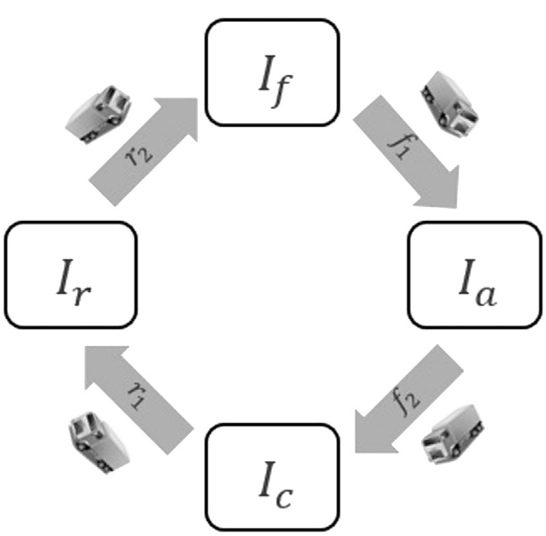


Fig. 2. Schematic representation of the network.

The definition of sets, variables and parameters of the model are given in Appendix. The description of the constraints, objective functions and the multi-objective approach are made below. Three types of objectives as mentioned above are considered: cost; environmental and social assessment. On the constraints these are grouped into five main types: material flow constraints, demand and return constraints, capacity constraints (of both vehicles and facilities) and operational constraints such as maximum distance travelled per time period.

3.2.1. Model constraints

The model constraints describe the problem characteristics that need to be guaranteed and are detailed below:

Material flow constraints

$$S_{mi(t-1)} + \sum_{\overline{m}j:(\overline{m},j,i)\in F} rp_{m\overline{m}} X_{\overline{m}jit} = \sum_{\overline{m}j:(\overline{m},j,i)\in F|F_s} rp_{m\overline{m}} X_{\overline{m}ijt} + S_{mit}, (m,i)\in V_{nos} \wedge t\in T \quad (1)$$

Equation (1) concerns the material balance constraint set for each entity. This constraint assures that at any time period, for any entity and for each product, the inbound flow must equal the outbound flow plus the difference between the existing and the new retained stocks taking into account the relation between different products (rp_{mn}).

Demand and return constraints

$$\sum_{j:(m,i,j)\in F} X_{mjit} = pd_{mit}, (m,i)\in \check{V}_c \wedge t\in T \quad (2)$$

$$\sum_{j:(m,i,j)\in F} \sum_{t\in T} X_{mijt} \le \sum_{\overline{m}j:(\overline{m},j,i)\in F} \sum_{t\in T} rp_{m\overline{m}} X_{\overline{m}jit}, (m,i)\in \widehat{V}_c \wedge t\in T \quad (3)$$

Equation (2) sets a constraint regarding the demand, where each customer has a demand value defined for each period (pd_{mit}) which needs to be entirely satisfied within that same period. Constraint (3) models customer returns. The total volume of returns available at each customer depends on the supplied amount.

Capacity constraints

$$\sum_{m:(m,i)\in V_{nos}|\widehat{V}_c} S_{mit} \le msc_i Y_i, i\in I \wedge t\in T \quad (4)$$

$$\sum_{m:(m,i)\in \check{V}_f} S_{mit} \ge mst_i Y_i, i\in I_f \wedge t\in T \quad (5)$$

$$\sum_{m:(m,i,j)\in F} X_{mijt} \le cv_{ij} Z_{ijt}, (i,j)\in A \wedge t\in T \quad (6)$$

$$Z_{ijt} \le \sum_{m:(m,i,j)\in F_{out}} \frac{X_{mijt}}{cv_{ij}} + 1, (i,j)\in A_{out} \wedge t\in T \quad (7)$$

Constraint (4) sets maximum limits on total storage capacities (msc_i) and constraint (5) sets minimum stock level (mst_i) in the factory. Constraint (6) limits the amount of products to be transported, according to vehicle capacity (cv_{ij}). Constraint (7) determines the necessary number of trips between each pair of entities according to vehicle capacity. This constraint acts as a valid inequality, improving the computational time of the model.

Operational constraints

$$Z_{ijt} \leq Z_{jit}, (i,j) \in (A_{r1} \cup A_{r2}) \wedge t \in T \quad (8)$$

$$\sum_j Z_{ijt} d_{ij} \leq mk, (i,j) \in A_{f2} \wedge t \in T \quad (9)$$

Equation (8) constrains the number of trips between each pair of entities. Constraint (9) limits the number of kilometres covered by vehicles.

Flow constraints

$$Z_{ijt} \leq BigM.Y_i, (i,j) \in \left(A_{f2} \cup A_{r2}\right) \wedge t \in T \quad (10)$$

$$Z_{ijt} \leq BigM.Y_j, (i,j) \in \left(A_{r1} \cup A_{f1}\right) \wedge t \in T \quad (11)$$

Constraints (10) and (11) limit the occurrence of flows between only opened facilities.

$$X_{mijt}, S_{mit} \in \mathbb{R}_0^+; Y_i \in \{0,1\}; Z_{ijt} \in \mathbb{N} \quad (12)$$

Finally, constraint (12) presents the variables definitions.

3.2.2. Cost assessment

The objective function that takes into account the economic performance of the company is shown in equation (13). The first term concerns the fixed costs of each entity (cf_i) controlled by the binary variable Y_i which equals 1 when entity i is opened. The second term accounts for raw materials costs acquired from suppliers where cs_{mit} represents the unit cost of product m acquired in entity i for period t, and X_{mijt} is a continuous variable for the amount of product m served by entity i to entity j at time t. The third term relates to the costs of transportation which is performed by the company's own fleet, and depends on parameters such as vehicle consumption, fuel price and vehicle maintenance. The fourth term is related to outsourced transportation, which varies with contracted costs (per kg.km), the amount of units transported and the kilometres travelled. The fifth term represents the costs of product recovery (cp_{mi}) from the clients. The sixth and final term concerns the costs with human resources (chr_i) that result from opening a given entity.

$$\begin{aligned} \min \text{Cost} = & \sum_{i \in I_a} cf_i Y_i + \sum_{mij:(m,i,j) \in F_S} \sum_{t \in T} cs_{mit} X_{mijt} + \sum_{ij:(i,j) \in A_{own}} \\ & \times \sum_{t \in T} ct_{ij} d_{ij} Z_{ijt} + \sum_{mij:(m,i,j) \in F_{out}} \sum_{t \in T} ct_{ij} d_{ij} X_{mijt} \\ & + \sum_{mi:(m,i) \in \widehat{V}_c} cp_{mi} \left(\sum_{j \in I_a} \sum_{t \in T} X_{mijt} \right) + \sum_{i \in I_a} chr_i Y_i \end{aligned} \quad (13)$$

3.2.3. Environmental impact assessment

The environmental impact is determined using ReCiPe 2008 (Goedkoop et al., 2009). The supply chain as a system is used as a functional unit, since it is this system that we wish to compare. This means that a Life Cycle Analysis is performed on the products, transportation mode and entities (warehouses and factories) existent within the defined boundaries of the supply chain being studied.

The Life Cycle Inventory (LCI) of each product, transportation mode and entity is retrieved from the Ecoinvent database (assessed through the software SimaPro 7.3.2). From this results an inventory list l (e.g. pollutants, resources depleted) and the corresponding quantities (q_l), which are used to determine the environmental impact (I_{ac}) of each activity a (production, transport and installation of entities) on impact category c, according to Equation (14). The characterization factors (C_{acl}) are the ones from the ReCiPe 2008 methodology.

$$I_{ac} = \sum_l C_{acl} q_l \quad (14)$$

The resulting environmental impacts are used as input data (parameters) to the mathematical model. Referring back to Fig. 1, for better understanding, we are now at the end of step 2. The following steps (3, 4 and 5) are performed within the developed function as is described next.

An overall environmental impact of production (P_c), transport (T_c) and installation of entities (E_c) is performed for each impact category, according to Equations (15)–(17), respectively.

$$P_c = \sum_{t \in T} \sum_{mij:(m,i,j) \in F} I_{mc} X_{mijt} \quad (15)$$

$$T_c = \sum_{k \in K} \sum_{t \in T} \sum_{ij:(i,j) \in I} I_{kc} Z_{kijt} d_{ij} \quad (16)$$

$$E_c = \sum_{i \in I} I_{ic} A_i Y_i \quad (17)$$

Then these values are aggregated into a single score (NI) using the normalization and/or weighting factors (η_c) of the ReCiPe 2008 methodology, as shown in Equation (18). This single score acts as the model's objective function that is to be minimized.

$$\min NI = \sum_c (P_c + T_c + E_c) \eta_c \quad (18)$$

3.2.4. Social assessment

Given the inexistence of social indicators suitable for supply chain design optimization, the social dimension of sustainability is introduced in the model through the creation of a new indicator. Following two social subcategories of GRI, *Labour Practices and Decent Work*, where criteria regarding employment are described, and Society, where the negative impacts of not having employment on society are accounted for, the idea behind this new social benefit indicator arose. Furthermore, the European Commission has made it clear, through its agenda for the 2014-2020 funding period, that their main focus is on fostering economic growth and regional development, and promoting job creation. Hence, economic incentives for projects that contribute to job creation and regional development are available and their possibility should be considered when deciding on facility location. This led to the definition of a Social Benefit indicator (SB), which prefers job creation in the less developed regions. This is given by Equation (19).

$$SB = \sum_{i \in I} w_i \mu_i Y_i \quad (19)$$

where w_i is the number of jobs created at region i and μ_i represents a regional factor, which can assume different values according to the intended purpose of the study. Unemployment rate, population density and income distribution are examples of possible regional factors. For instance, if unemployment is a major concern in a given country or state, a regional factor is created so that the possible locations for the entities of the supply chain are scored and ordered according to the respective unemployment rates. The Social Benefit indicator can then be introduced in the model so as to be maximized or minimized, according to the way the regional factor was defined. Following the example of the unemployment rate, the goal would be to introduce the Social Benefit indicator in a way that would prefer the location of entities in regions with higher unemployment rates. It should be noted that this indicator aims overall social benefit, which might not mean increased social benefit within the company in particular.

Through the developed social indicator, this model offers a tool for company decision makers to analyse what level of economic incentives would provide a competitive advantage in their facility location decisions.

3.2.5. Multi-objective approach

Since the goal is to provide a solution of compromise between economic, environmental and social impacts, this work also comprehends a multi-objective approach. Among the available methods, the ε-constraint method was chosen given the simplicity and applicability of its implementation.

Here we wish to minimize costs, minimize environmental impact and maximize social benefit, as described in Equation (20).

$$\min \ (f_1(\boldsymbol{x}), f_2(\boldsymbol{x})) \wedge \max f_3(\boldsymbol{x}) \ st \ \boldsymbol{x} \in S, \tag{20}$$

where $\boldsymbol{x}$ is the vector of decision variables, $f_1(\boldsymbol{x})$, $f_2(\boldsymbol{x})$ and $f_3(\boldsymbol{x})$ are the objective functions (cost, environmental impact and social benefit, respectively) and S is the feasible region.

The ε-constraint method allows us to optimize one of the objective functions using the others as constraints. By varying the constraint bounds, we obtain points that are Pareto efficient defining a discretized Pareto front. Therefore, using this method, we might have:

$$\begin{aligned} &\min \quad f_1(\boldsymbol{x}) \\ &s.t. \quad f_2(\boldsymbol{x}) \le f_2^{\min}(\boldsymbol{x}) + k\Delta\varepsilon_2, \\ &f_3(\boldsymbol{x}) \ge f_3^{\min}(\boldsymbol{x}) + k\Delta\varepsilon_3, \\ &\boldsymbol{x} \in S, \end{aligned} \tag{21}$$

with $k = 0,\ldots,n$ and. $\Delta\varepsilon_i = \frac{f_i^{\max} - f_i^{\min}}{n}, i = 2, 3.$

For the calculation of the range of the objective functions over the efficient set, a lexicographic optimization is performed, as described in Mavrotas (2009). In addition, to guarantee the efficiency of the obtained solutions, the method proposed by the same author was applied. This method consists of transforming the objective function constraints to equalities by explicitly incorporating the appropriate slack or surplus variables (s_2 and s_3) and by penalizing these new variables at the objective function. Model (21) becomes:

$$\begin{aligned} &\min \quad (f_1(\boldsymbol{x}) + eps \times (s_2 + s_3)) \\ &s.t. \quad f_2(\boldsymbol{x}) + s_2 = f_{2_{min}}(\boldsymbol{x}) + k\Delta\varepsilon_2, \\ &f_3(\boldsymbol{x}) - s_3 = f_{3_{min}}(\boldsymbol{x}) + k\Delta\varepsilon_3, \\ &\boldsymbol{x} \in S \text{ and } s_i \in R^+, \end{aligned} \tag{22}$$

where eps is an adequately small number (usually between 10^{-3} and 10^{-6}, so that it does not affect the objective function).

4. Case study

The LBP company is one of the major companies in Portugal dedicated to the production and selling of batteries. Due to confidentially reasons the company name, as well as data, are altered. Nonetheless the relation among values is maintained. One of the main objectives of this company is to provide the best quality service in terms of customer deliveries. Therefore, as a strategic decision, it was decided that together with production, selling should be one of the company's core businesses. At the present they are following a self-sales strategy where a 24-hour delivery police must be guaranteed. In order to achieve such goal the company has decided to internalize the distribution to the final customers. Warehouses have stocks that, in addition to the transportation flexibility, allow the delivery of products within the predefined delivery time. Given the positive customers feed-back, this sales strategy is perceived as a competitive advantage over their direct competitors. Thus an optimization of the current logistics network has been defined as a supply chain strategic decision where not only logistics costs should be considered but also environmental and social impacts should be analysed, being this company pursuing a sustainable image. This is in consonance with the recycling strategy implemented by the company where the aim is to recycle as much as possible end-usage batteries, which is justified by an economical factor – lead as raw material is quite expensive – as well as by environmental concerns.

In order to address these issues, the multi-period model previously presented is solved. It considers simultaneously production, storage, collection and recycling activities. Moreover, the different transportation modes integrated within the formulation reflect the company's customer satisfaction policy. The time modelling allows not only the strategic definition of the network structure but also a more detailed analysis concerning planning decisions. The study is performed for a one year timeframe.

4.1. Company characterization

4.1.1. Network and customers

The current distribution network is formed by 12 rented warehouses spread over the country (Fig. 3) which are supplied by a

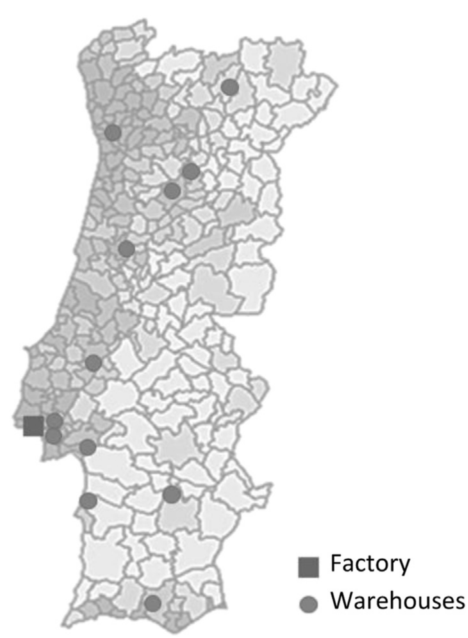


Fig. 3. Location of all network facilities.

single factory. This factory is located at the centre of continental Portugal and is responsible for all the production. The 12 warehouses differ in terms of function and dimension. In addition to distribution, all warehouses act as direct sales points and serve more than two thousand customers.

This network is a consequence of successive adjustments over the years, based on the existing customer location and cost-benefit analysis of each new location. Therefore, no integrated analysis was ever done and the management board does not know if this effective network is also efficient in terms of costs.

The company has about 2300 customers spread over several Portuguese municipalities. Given the strategic nature of this work, customers are clustered according to their municipality, which results in 237 groups of customers. Given the 278 existing municipalities, the company covers about 85% of Portuguese mainland municipalities. All customers' demand has to be fully satisfied. Therefore it is assumed that all supplying orders are economically viable whatever the amounts involved. As an immediate consequence, no minimum limits are imposed on flows between warehouses and customers.

Due to the costumer clustering, demand is also aggregated by municipality and month, since this is the smallest time unit assumed in this study.

The network super-structure is composed by all possible locations for the existing network entities: customers, warehouses and the factory. As mentioned the network is composed of 237 customers at the municipality level. These locations act also as possible warehouse locations. The super-structure is completed with the location of the single factory that is not to be changed. Each warehouse location is characterized by a maximum storage capacity and a fixed cost. To the maximum storage capacity, both new and collected products are accounted. The factory is characterized by minimum and maximum storage/production capacities. These capacities account for raw-materials and finished products. In order to model the direct sales to customer performed from the factory, a fictitious warehouse is defined with the same location as the factory.

4.1.2. Transportation

The company owns a large vehicle fleet. As a consequence and given the distribution of the company's facilities, the costs related with customer distribution are high and the company aims at reducing them.

For the inbound distribution (and collection) the vehicles are sub-contracted. This concerns all direct and reverse flows that connect the factory to the warehouses and licenced customers. The outbound distribution (and collection), which is related to the direct and reverse flows that connect warehouses to customers, is exclusively performed by the company's vehicles. After delivering the products, they have always to return to the departing warehouse.

Being this a strategic to tactical problem, two different vehicles are considered depending on the route to be performed: (i) the inbound transportation and (ii) the outbound transportation. Statistical analysis of existing data allowed to determine the most frequently used vehicles and to estimate average vehicles capacity.

Given the mix of batteries that are transported, an “average” battery is also assumed which allows the definition of maximum limits for vehicles and storage capacities. It is also assumed that there is only one vehicle available per warehouse for the outbound transportation – company practice.

4.1.3. Products

The company produces several different types of products that will simply be named as batteries. These can differ in size, volume, weight and type of usage. Within the seven classes of products the two most representatives are the vehicle batteries and the industrial ones. However, these products have similar production costs and customers' orders are usually a mix of products.

As mentioned, along with the traditional product supplying, this company also deals with the return of end-of-life (EOL) products. Therefore, the reverse logistics flow exists and involves product collection and its transportation back to the warehouses. After a delivery, the vehicle brings EOL products back to the warehouse. Concerning the return volume available at customers, the existing data allow us to estimate that the maximum return rate is at 15% of customers demand. Afterwards, all used products are sent back to the factory where they are traded with suppliers by raw-materials. This reverse flow has been a business opportunity for more than 50 years and is still considered as very important for this company.

To differentiate new from used batteries two products are modelled. Once used batteries arrive at the factory, they are traded with the suppliers for new raw-materials. From four EOL batteries, the company recovers the amount of raw-material needed in the production of a new battery. Then we have integrated used batteries in the production of a new one in the relation of four to one.

4.2. Cost assessment

For the economical objective, the following costs are considered:

- Since all existing warehouses are rented spaces, the rent cost is assumed as a fixed cost. No holding stock costs are considered since, as long as there is capacity, one stored battery or the warehouse at full capacity costs the same.
- For the transportation costs two different calculation methods are used, one for own vehicles and another for sub-contracted transportation. In the former case, we assume that the cost varies with vehicle consumption, fuel price and vehicle maintenance costs per kilometre. For the latter the cost varies per kilogram transported and per kilometre. Values defined for these parameters were validated using fitting curves obtained with historical data from the company. Regarding the transportation cost of the reverse network from the customer to the warehouse, since all the vehicles that supply customers have to return to the warehouse, there is always a return cost even if the vehicle returns empty (this value is equal to the forward transportation cost).
- The modelled raw-materials refer to the metals that compose batteries. The price paid to the suppliers is indexed to the London Metal Exchange prices to which a cost per tonne is added. Although the acquisition cost of raw-materials changes overtime, the selling price of used batteries varies accordingly. Therefore, the indexed term was neglected and the selling of used batteries was indirectly considered in the model. Since each used battery is valued as 25% of a new one, the profit of selling used batteries is modelled as the integration of recycling materials in the production of new products.
- The company pays costumers an amount for each collected battery, this collection cost acts as an incentive to attract customer to return products. No other activity (such as cleaning, sorting, processing, among others) is performed by the company.
- A cost with human resources is also considered. This cost is assessed for each warehouse according to the maximum battery capacity. It is considered that for each 100 batteries in the warehouse one employee is necessary. Another employee is considered at each warehouse for the transportation between

the warehouse and the clients. This data is based on company practices.

4.3. Environmental assessment

When applying this model to the case-study, three activities were considered as the main contributors to the environmental impact of the company: production, transportation and installation of entities. Using SimaPro 7.3.2, a LCI analysis was performed. The environmental impacts obtained and used in the model are described in appendix b.

4.4. Social assessment

For this case-study, the regional factor (μ_r) is selected based on the current Portuguese economic reality, where a social benefit would arise from job creation in the inland regions, less populated. In a bigger scale this would move people away from the overpopulated areas, developing these inland regions, while increasing the quality of life in both areas (improving access to public service facilities and homogenising the ecological footprint of the population). Therefore, for this case study, μ_r is given by Equation (23).

$$\mu_r = \frac{pd_{\text{Total}}}{pd_r} \tag{23}$$

where pd_{Total} represents the population density of continental Portugal and pd_r the population density of region r. $\mu_r \approx 0$ represents an overpopulated region while $\mu_r > 1$ indicates an underpopulated region, when compared to the population density of continental Portugal. The bigger the factor μ_r, the less populated the region is. Therefore, the developed model, described in Equation (19), uses the maximization of the Social Benefit indicator in the objective function. In this way, when deciding on facility location, the model prefers underpopulated regions to install facilities. It should be noted that some of the underpopulated regions might be underpopulated due to geographical or physical factors (e.g. scarcity of water, irregular topography or absence of infrastructures). Hence, the possible locations were chosen already taken this into account and making sure that all necessary conditions were gathered.

Since the company was only available to support a maximum number of warehouses an additional constraint represented by Equation (24) was added to the model, where mw corresponds to 13 warehouses, the number of warehouses already existent in the real case.

$$\sum_i Y_i \leq mw, i \in I_a \tag{24}$$

5. Results

5.1. Single objective optimization

The model is initially solved considering each objective function individually. Four different scenarios are considered:

- Scenario A: the real scenario, which assumes the 13 current entities of the supply chain of the company (12 warehouses plus the factory which has a warehouse associated) as fixed and opened. As results it was aimed to quantify the supply chain minimum costs;
- Scenario B1: an optimal solution, obtained when minimizing cost;
- Scenario B2: an optimal solution, obtained when minimizing environmental impact;
- Scenario B3: an optimal solution, obtained when maximizing social benefit.

Fig. 4 shows the warehouse locations obtained for each of the considered scenarios.

When minimizing cost (scenario B1) the model returns a network of only 7 warehouses (including the one belonging to the factory). When minimizing environmental impact (scenario B2) the model returns the exact same network as obtained through

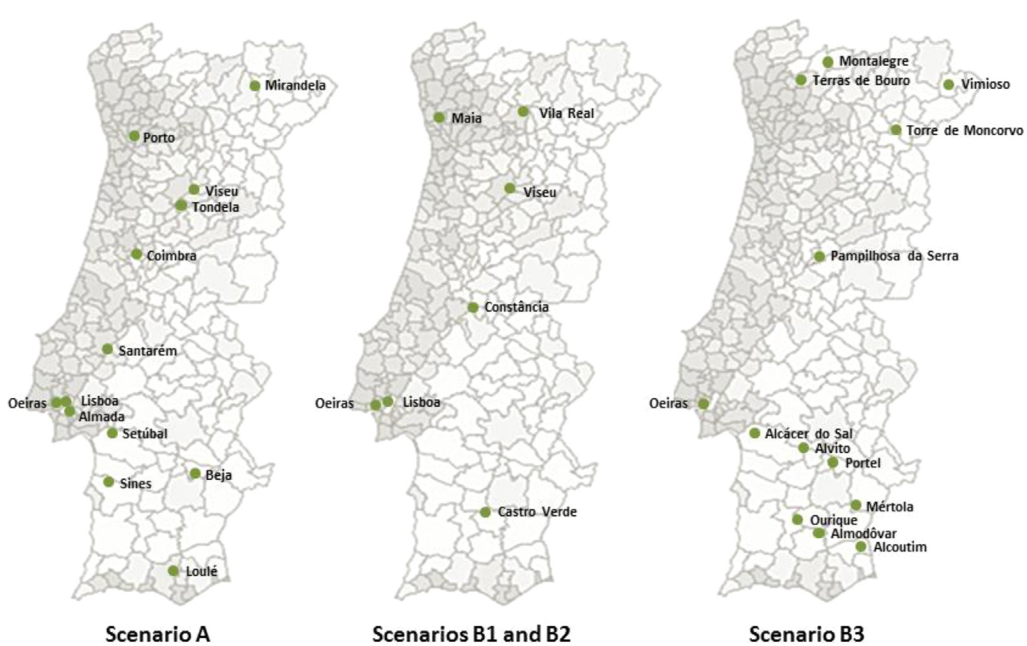
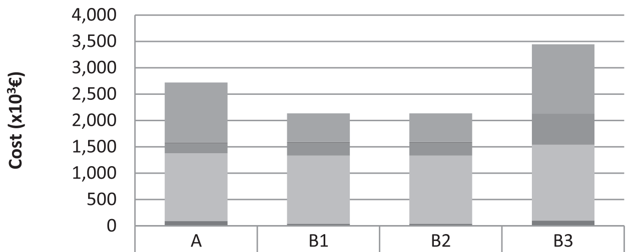
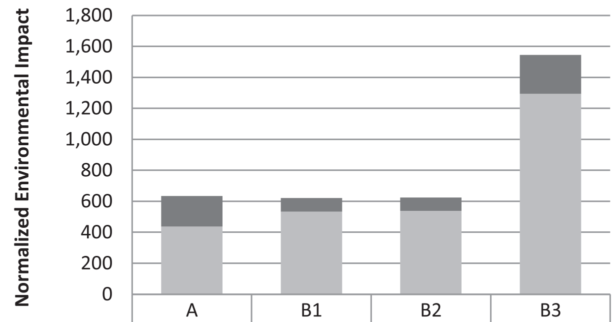


Fig. 4. Warehouse location in scenarios A, B1, B2 and B3. The darker regions indicate higher population density.



	A	B1	B2	B3
Human resources	11,42,400	5,46,000	5,46,000	13,10,400
Battery recovery	17,404	17,404	17,404	1,923
Transportation	1,82,881	2,41,238	2,41,384	5,93,447
Raw materials	12,88,991	12,88,991	12,88,991	14,37,383
Warehouses	89,365	41,805	41,805	1,00,332

Fig. 5. Cost distribution for scenarios A, B1, B2 and B3.



	A	B1	B2	B3
Entities	197	88	88	250
Transportation	437	533	537	1,294

Fig. 7. Normalized environmental impact of entities and transportation for scenarios A, B1, B2 and B3. Production and battery recovery are not included since the total impact is maintained between scenarios.

scenario B1. On the other hand, when maximizing social benefit (scenario B3), the model returns 13 warehouses, the maximum amount allowed, clearly favouring those in the inland and less populated regions (the lighter regions in Fig. 4).

Comparing the costs of the different scenarios and their distribution, as shown in Fig. 5, we see that higher social benefit comes with higher costs. This is due not only to the fact of having more warehouses, which comes with higher rent costs and the need for extra human resources, but also to higher transportation costs. It is also important to mention that a lower amount of recovered batteries is obtained, which leads to higher costs of raw materials. All these aspects make the solution obtained in scenario B3 non implementable at the company level. When minimizing cost (scenario B1), Fig. 5 shows that it is in fact possible to achieve a significant cost reduction compared to the real scenario (21.5%), even though at the cost of a lower social benefit.

On the environmental aspects and as seen in Fig. 6, all scenarios present human toxicity (HT) as the most affected midpoint category, followed by marine ecotoxicity (MET) and freshwater eutrophication (FE), given the high contribution of production to the environmental impact. For the same reason, it is also clear that there is not a significant difference in environmental impact across the different scenarios since production impact surpasses the remaining ones and is almost constant along the different scenarios (not shown). Still, in scenario B2 the environmental impact decreases by 0.16% when compared to the real scenario.

In order to examine if the high weight of production on environmental impact is causing a scaling issue and biasing the resulting network, a scenario where the environmental impact of production is not included was tested. No significant changes were verified (Fig. 7). It can now be seen that, without considering production, the model can decrease the environmental impact by 1.26% when compared to the real scenario. This is achieved by decreasing the impact of entities but increasing that of transportation. For scenario B3, the significant increase in total environmental impact compared to scenario A (12.5%) is mostly due to the increase in transportation (an increase of 196%).

5.2. *Multi-objective approach*

As seen before, some of the solutions through single objective optimization might not be viable to implement. Hence, it becomes necessary to analyse all three objectives simultaneously so as to establish possible solutions of compromise. However, in this case-study, the environmental impact varies little, as shown before and proven ahead in Figs. 9 and 10 for more significantly different network solutions. The multi-objective approach was then applied solely to the economic and social objectives, which offer a higher challenge regarding the necessary trade-offs.

5.2.1. *ABC analysis*

Due to the large computing time necessary to obtain data using the entire superstructure as well as due to the computational impossibility to perform a lexicographic optimization, it became necessary to reduce the possible warehouses locations.

In order to reduce the risk associated with the fluctuation of demand, an approach inspired on the inventory ABC analysis was performed on the customers in order to identify those with more impact on the company sales. The 80-20 Pareto principle (Pareto

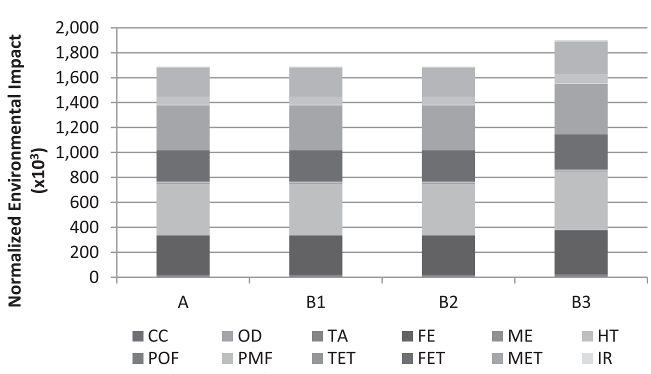


Fig. 6. Environmental impact distribution for scenarios A, B1, B2 and B3.

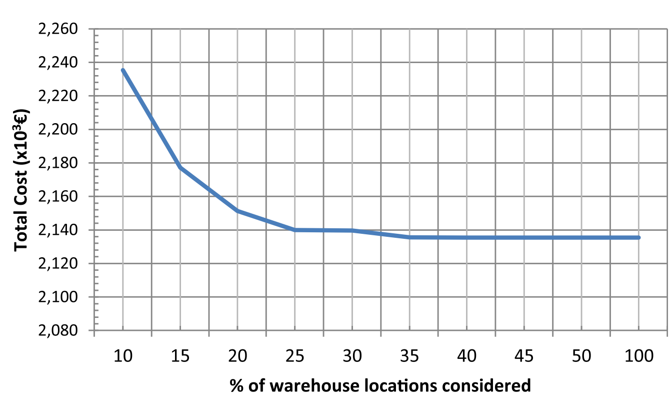


Fig. 8. Sensitivity analysis on the percentage of warehouses considered.

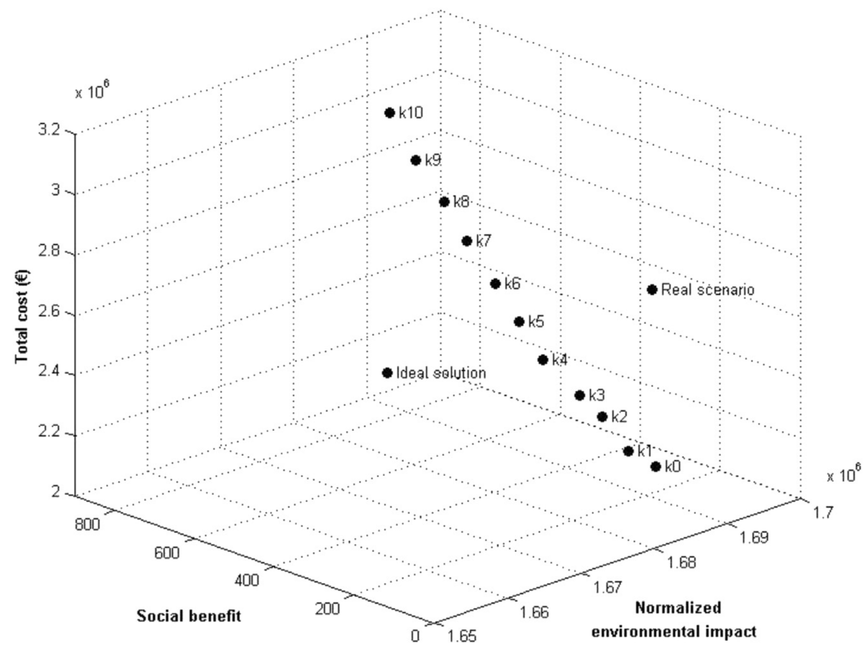


Fig. 9. Multi-objective approach for the maximization of Social Benefit with cost limitation, with lexicographic optimization and a superstructure of 84 possible locations. The real scenario and the ideal solution are also represented for comparison.

and Page, 1971) was verified with around 80% of the annual sales coming from 20% of the customers. Knowing this, it is clear that there is a percentage of clients with a higher economic importance for the company, whose location should be included in the reduced superstructure (note that possible warehouse locations are given by existent costumer locations).

Being the economic performance at the top of the decision makers' concerns, an adequate percentage of warehouses (organized by the corresponding customers' annual sales amount) would guaranty an improved economic performance. Hence, a sensitivity analysis is performed on the total cost obtained with different percentages of warehouses (ordered according to the ABC analysis), as shown in Fig. 8. It can be concluded that at 35% of potential warehouse locations the minimum cost is attained, since the warehouses which return the minimum cost solution are included.

This analysis supports the reduction of the number of possible locations for the company's facilities to 84, 35% of the total customers' locations and accounting for 91% of the total sales (as retrieved from the performed ABC analysis).

With the superstructure reduced from 278 to 84 possibilities for the location of the warehouses, the Ɛ-constraint method was applied considering the two objective functions – cost and social benefit – with lexicographic optimization. The results obtained are shown in Fig. 9.

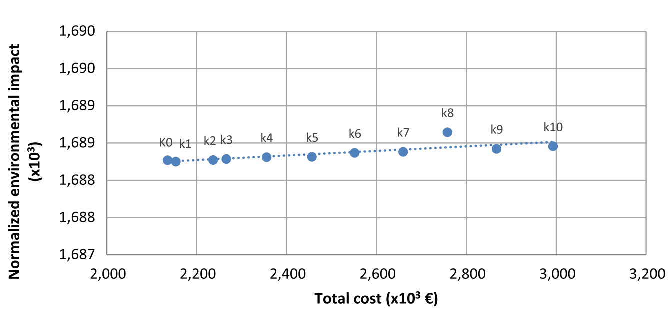


Fig. 10. Total cost versus normalized environmental impact, evidencing the little variation of the environmental impact indicator between the different solutions.

One of the first conclusions that can be taken from these results is that there is little variation of environmental impact, due to the large impact of production, as mentioned before, which is not subject to any decision to be taken by the model. Furthermore, as evidenced in Fig. 10, the environmental impact varies linearly with total cost. Hence the extra computational effort necessary to perform the multi-objective optimization taking into consideration all three dimensions simultaneously would not contribute to improved results in terms of environmental performance.

Continuing with the analysis of Fig. 9 it is clear that a significant improvement can be obtained both from the economic and the social points of view when compared to the real scenario. Maintaining roughly the same social benefit of the real scenario, a cost reduction of 22% could be obtained. On the other hand, maintaining approximately the same cost, an increase of social benefit in over 300% could be obtained, as can be confirmed from Table 1.

Table 1
Multi-objective solutions analysis based on three criteria: economic and social performance improvement, minimum network variation, and minimum distance.

Solutions	1st criterion: Economic and social performance improvement		2nd criterion: Minimum network variation	3rd criterion: minimum distance
	Gain in cost (%)	Gain in social benefit (%)	Warehouses maintained from the real scenario	Normalized distance
k0	22	−4	–	–
k1	21	42	3	0.74
k2	18	85	2	–
k3	17	135	3	0.57
k4	13	184	0	–
k5	10	224	0	–
k6	6	263	0	–
k7	2	312	0	–
k8	−1	353	–	–
k9	−5	397	–	–
k10	−10	442	–	–

The selection of a solution of compromise is performed according to the company's economic and social goals as well as risk perception, and it is based on three criteria:

- The first criterion is that the selected solution has to be translated into a gain in the economic as well as in the social performance, when compared to the real scenario. This criterion removes solutions k0, k8, k9 and k10 from the eligible ones.
- The second criterion is minimum network variation, again compared to real scenario, so as to further reduce the risk of the decision. Solutions k1 and k3 perform better in this criterion as they maintain 3 of the initial warehouses.
- With the third and final criterion we wish to select the solution, which is closer to the ideal solution, if it existed (minimum cost and maximum social benefit). As can be confirmed in Table 1, solution k3 is the one that presents the minimum normalized distance, guarantying the best economic/social outcome among the possible solutions.

6. Conclusions

This work contributes to answering the question: How to integrate sustainability into supply chain design and planning? It does so in the following ways:

- It presents a generic multi-objective mathematical programming model for the design of planning of supply chains, incorporating the three dimensions of sustainability;
- It integrates the ReCiPe LCA methodology, which to the best of the authors knowledge had never been used before in supply chain design models, even though it is indicated in the literature and by the European Commission as the most developed one currently available;
- A social indicator is created and incorporated into the model, which allows to study the impact of facility location decisions according to societal issues on the economic performance of the company, and the level of municipal economic incentives that would compensate relocating;
- The developed model is applied to a real case-study and clear strategies to select the best solution, taking risk minimization into account, are presented to decision makers.

From the case-study we can conclude that the developed model allows improvements in all the three dimensions of sustainability and offers important managerial insights. A significant cost reduction can be obtained by reducing the number of warehouses and increasing transportation. A reduction in the environmental impact can be obtained following the same strategy as the one used for cost minimization. Prioritization of action in reducing environmental impact is given to production, followed by transportation. With a small compromise of the economic performance, an improvement of the social contribution can be achieved, indicating that governmental economic incentives should be analysed as they could provide a further increase in the economic performance.

Even though important aspects have been studied along this paper there is still a lot of work to be done to answer in more detail the proposed research question. Future work should include improving the developed social indicator so as to be possible to evaluate the social dimension of a supply chain on its own, which is now a limitation of this work. Furthermore, focusing on a single indicator and on a single supply chain might miss the complex nature of the problem given the interconnectivity of the factors involved. Other regional development indicators and other case studies should be explored and analysed in a systems thinking approach in an attempt to fully capture the dimension of the problem. At the model level, further aspects should be considered such as the possible dynamic behaviour of the network as well as the presence of uncertainty at the strategic level in some of the parameters assumed, as for instance levels of returns and/or demand.

Acknowledgements

The authors acknowledge the Portuguese National Science Foundation (FCT) for Grants SFRH/BD/51947/2012 and SFRH/BPD/63668/2009, and Projects PTDC/SEN-ENR/102869/2008, PEst-OE/MAT/UI0297/2011 and PTDC/EMS-SIS/1982/2012.

Environmental glossary

ALO	Agricultural Land Occupation
CC	Climate Change
FRD	Fossil Depletion
FET	Freshwater Ecotoxicity
FE	Freshwater Eutrophication
HT	Human Toxicity
IR	Ionising Radiation
MET	Marine Ecotoxicity
ME	Marine Eutrophication
MRD	Metal Depletion
NLT	Natural Land Transformation
OD	Ozone Depletion
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
TA	Terrestrial Acidification
TET	Terrestrial Ecotoxicity
ULO	Urban Land Occupation

APPENDIX A. Model formulation

Let the supply chain be represented by a graph $G=(V,A)$ with a set of nodes (V) and a set of arcs (A), as described in Salema et al. (2010).

Sets

Consider the indices:

i, j as entities,
$m, \overline{m}$ as products, and
k as vehicles/means of transport.

Entities

Each level of the supply chain is defined by just one kind of entity (factory, warehouse, customer, recovery center), thus node set V is divided into the following subsets:

I_f location of factory, $i \in I_f \subseteq V$
I_a possible locations for warehouses, $i \in I_a \subseteq V$
I_c locations of customers, $i \in I_c \subseteq V$
I_r possible locations for recovery centers, $i \in I_r \subseteq V$

Set $I = I_f \cup I_a$ contains all entities for which a maximum limit is imposed on inventories.

Products

Consider the following subsets of M, each one referring to a different product:

M_f factory outbound products, $m \in M_f \subseteq M$
M_a warehouses outbound products to the customers, $m \in M_a \subseteq M$

M_r customers outbound products, $m \in M_r \subseteq M$
M_c warehouses outbound products to the factory, $m \in M_c \subseteq M$

Extended entities
Extended entities are defined by the pair product-entity since entities and products are related:

$\widehat{V}_f = \{(m,i) : m \in M_f \wedge i \in I_f\}$
$\widehat{V}_a = \{(m,i) : m \in M_a \wedge i \in I_a\}$
$\widehat{V}_c = \{(m,i) : m \in M_r \wedge i \in I_c\}$
$\widehat{V}_r = \{(m,i) : m \in M_c \wedge i \in I_r\}$
$\check{V}_f = \{(m,i) : m \in M_c \wedge i \in I_f\}$ inbound product set for factories
$\check{V}_c = \{(m,i) : m \in M_a \wedge i \in I_c\}$ inbound product set for customers
$V_{nos} = \check{V}_f \cup \widehat{V}_a \cup \widehat{V}_c \cup \widehat{V}_r$

Flows
Flows are defined by the pair entity–entity, representing the edges of the graph.
Let A be the set of all network flows: $A = \cup_{k \in K} A_k, K = \{f_1, f_2, r_1, r_2\}$. Each echelon is defined as:

$A_{f_1} = \{(i,j) : i \in I_f \wedge j \in I_a\}$
$A_{f_2} = \{(i,j) : i \in I_a \wedge j \in I_c\}$
$A_{r_1} = \{(i,j) : i \in I_c \wedge j \in I_a\}$
$A_{r_2} = \{(i,j) : i \in I_a \wedge j \in I_f\}$

Suppliers are also integrated in this model. They are represented by a fictitious entity whose formulation is achieved by creating a factory internal flow: $A_s = \{(i,i) : i \in I_f\}$.
Set A_{out} is defined as: $A_{out} = A_{f_1} \cup A_{r_2}$.

Extended flows
As for entities, flows and products are also related. Extended flows are defined by the pair product-entity:

$F_{f_1} = \{(m,i,j) : m \in M_f \wedge (i,j) \in A_{f_1}\}$
$F_{f_2} = \{(m,i,j) : m \in M_a \wedge (i,j) \in A_{f_2}\}$
$F_{r_1} = \{(m,i,j) : m \in M_r \wedge (i,j) \in A_{r_1}\}$
$F_{r_2} = \{(m,i,j) : m \in M_c \wedge (i,j) \in A_{r_2}\}$
$F_s = \{(m,i,i) : m \in M_c \wedge (i,i) \in A_s\}$

Set F_{out} is defined as: $F_{\text{out}} = F_{f_1} \cup F_{r_2}$

Network super-structure
The super-structure of the network is defined by set: $F = \cup_{k \in K} F_k, K = \{f_1, f_2, r_1, r_2, s\}$.
Time
Consider t as index for time units. Let set T be defined as: $T = \{t_1, t_2, \ldots, t_h\}$.

Scalars

BigM large number
mk maximum number of kilometres per vehicle per micro period
mw maximum number of warehouses

Parameters

cf_i fixed cost of entity $i \in I_a$
cs_{mit} unit cost of product m acquired in entity i for period t, $i \in I_f$
ct_{ij} transportation cost, per kilometer, from entity i to entity j, $(i,j) \in A$
d_{ij} distance between entity i and entity j, in kilometres, $(i,j) \in A$
cp_{mit} unit cost of product m collected in entity i, at period t, $i \in I_c$
chr_i costs with human resources in entity $i \in I$
$rp_{m\overline{m}}$ relation between product m and $\overline{m}$, $(m, \overline{m}) \in$ M
pd_{mit} product m demand for entity i for period t, $i \in I_c$
msc_i maximum storage capacity of entity $i \in I$
mst_i minimum stock level in entity $i \in I_f$
cv_{ij} capacity of each vehicle that operates between entity i and entity j
I_{ac} environmental impact for activity a (e.g. production, transport) in impact category c
A_i area of entity i
w_i number of workers in entity i
μ_i regional factor in entity i

Variables

Continuous variables

X_{mijt} amount of product m served by entity $i$to entity j, at time t
S_{mit} amount of product $m$stocked in entity i, over period t

Binary variables

$Y_i =$ 1if entity $i$is opened/served, 0 otherwise

Integer variables

Z_{ijt} number of trips from entity i to entity$j$, at time t

APPENDIX B. Environmental impact data

Table B. 1 depicts the environmental impact data used in the model. For production, the environmental impact of a battery with 19 Kg is considered. The option selected is *Battery, LiIo, rechargeable, prismatic, at plant/GLO S* as it is the most adequate within the database. Human Toxicity is the most affected impact category, followed by Marine Ecotoxicity and Freshwater Eutrophication.

Regarding transportation, the environmental impact of two vehicles is considered – one that accounts for primary distribution and the other for secondary distribution. The options *Operation, lorry 3.5-7.5t, EURO4/RER S* and *Operation, van < 3,5t/RER S* are chosen from Ecoinvent database to simulate primary and secondary distribution, respectively. These options include fuel consumption, direct airborne emissions of gaseous substances, particulate matters and heavy metals, as well as heavy metal emissions to soil and water caused by tyre abrasion. The lorry, responsible for primary distribution, has an overall bigger impact than the van, responsible for secondary distribution. Marine Ecotoxicity and Natural Land Transformation are the most affected impact categories.

Although the warehouses are rented, the environmental impact of installation is considered. This choice was made based on the fact that the usage of the warehouses implies a previous construction. Therefore, the option selected is *Building Hall/CH/I S*. As described in the Ecoinvent database, it includes the most important materials used and their disposal, the transportation of the parts to the building site and to the final disposal at the end of life. Also included is the requirement of electricity for construction, maintenance and demolition. These impacts are then amortized uniformly over a 15 year period (the average lifetime of a warehouse) (Zaks, 2010). Freshwater Ecotoxicity and Marine Ecotoxicity are the most affected impact categories.

The impact caused by the factory is left out of the model since no decision is to be taken concerning this entity. Therefore, for the comparative analysis to be performed this value would not affect the conclusions.

Table B. 1
Environmental impact inputs used in the model. The most affected impact categories are highlighted in bold.

Abbr. impact category	Units	Battery with 19 Kg, per unit		Vehicles used for the primary and secondary distribution, per km				Warehouse, per m^2	
		Env. impact	Norm. env. impact	Env. impact		Norm. env. impact		Env. impact	Norm. env. impact
				Primary distribution	Secondary distribution	Primary distribution	Secondary distribution		
CC	Kg CO_2 eq	1.11E+02	9.87E-03	3.65E-01	2.83E-01	3.25E-05	2.52E-05	2.97E+02	2.65E-02
OD	Kg CFC-11 eq	9.52E-06	4.33E-04	5.34E-08	4.23E-08	2.43E-06	1.92E-06	2.60E-05	1.18E-03
HT	Kg 1,4-DB eq	5.45E+02	**9.21E-01**	1.23E-02	1.27E-02	2.08E-05	2.14E-05	1.36E+02	2.29E-01
POF	Kg NMVOC	5.36E-01	1.01E-02	1.98E-03	1.82E-03	3.73E-05	3.43E-05	1.42E+00	2.66E-02
PMF	Kg PM10 eq	3.97E-01	2.66E-02	5.72E-04	4.83E-04	3.84E-05	3.24E-05	1.00E+00	6.71E-02
IR	Kg U235 eq	3.16E+01	5.05E-03	6.62E-03	5.55E-03	1.06E-06	8.88E-07	5.76E+01	9.22E-03
TA	Kg SO_2 eq	1.05E+00	3.07E-02	1.29E-03	1.00E-03	3.75E-05	2.91E-05	2.70E+00	7.86E-02
FE	Kg P eq	2.95E-01	**7.11E-01**	8.06E-06	6.79E-06	1.94E-05	1.64E-05	9.12E-02	2.20E-01
ME	Kg N eq	4.74E-02	5.58E-03	7.13E-05	5.38E-05	8.39E-06	6.33E-06	1.17E-01	1.38E-02
TET	Kg 1,4-DB eq	3.85E-02	4.69E-03	9.50E-05	4.47E-05	1.16E-05	5.45E-06	6.75E-02	8.23E-03
FET	Kg 1,4-DB eq	6.13E+00	5.63E-01	3.04E-04	2.35E-04	2.80E-05	2.16E-05	3.37E+00	**3.10E-01**
MET	Kg 1,4-DB eq	6.82E+00	**8.02E-01**	7.86E-04	4.29E-04	**9.25E-05**	**5.05E-05**	2.59E+00	**3.04E-01**
ALO	m^2a	3.21E+00	7.11E-04	1.99E-04	1.70E-04	4.40E-08	3.76E-08	1.40E+02	3.09E-02
ULO	m^2a	2.23E+00	5.48E-03	5.53E-04	4.56E-04	1.36E-06	1.12E-06	4.15E+00	1.02E-02
NLT	m^2	2.29E-02	1.42E-01	1.26E-04	1.03E-04	**7.81E-04**	**6.38E-04**	3.48E-02	2.16E-01
MRD	Kg Fe eq	3.71E+02	5.21E-01	1.28E-03	1.08E-03	1.79E-06	1.51E-06	4.48E+01	6.28E-02
FRD	Kg oil eq	3.75E+01	2.26E-02	1.21E-01	9.72E-02	7.27E-05	5.84E-05	8.36E+01	5.03E-02

APPENDIX C. Computational results

The model was solved through GAMS 23.6, using CPLEX 12.0, in a two Intel Xeon X5680, 3.33 GHz computer with 12 GB RAM. The computational results for the real scenario and for the scenarios using the complete superstructure for each objective function are given in Table C.1. The optimum scenarios range from 10 to 21 h, depending on the objective function. Once the superstructure is reduced to 35%, from the ABC analysis, the computational time is reduced to an average of 30 min.

Table C. 1
Computational results.

Scenarios	Objective function	Total variables	Binary variables	Constraints	CPU (s)	GAP (%)	Objective value
Real (A)	Minimize Cost	153,128	74,880	194,623	418.82	0.0192	2,720,553
Optimum (B1)	Minimize Cost	851,334	421,390	2,345,456	37,542	0.0199	2,135,439
Optimum (B2)	Minimize Environmental Impact	851,334	421,390	2,345,456	76,343	0.0009	1,689,253
Optimum (B3)	Maximize Social Benefit	851,334	421,390	2,345,456	67,272	0.0192	1,737

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