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Multi-Directional Local Search for Sustainable Supply Chain Network Design

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Abstract

In this paper, we propose a bi-objective MILP formulation to minimize logistics costs as well as CO₂ emissions in a supply chain network design problem with multiple layers of facilities, technology levels and transportation mode decisions. The proposed model aims at investigating the trade-off between cost and CO₂ emissions through supply chain activities (i.e., raw material supply, manufacturing, warehousing, and transportation). To this end, a multi-directional local search (MDLS) metaheuristic is developed. The proposed method provides a limited set of non-dominated solutions ranging from a purely cost effective solution to a purely environmentally effective one. Each iteration of the MDLS consists in performing local searches from all non-dominated solutions. To do so, a Large Neighborhood Search (LNS) algorithm is used. Extensive experiments based on randomly generated instances of various sizes and features are described. Three classic performance measures are used to compare the set of non-dominated solutions obtained by the MDLS algorithm and by directly solving the MILP model with the epsilon-constraint approach. This paper is concluded by managerial insights about the impact of using greener technology on the supply chain

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topology.

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DESIGN ; LARGE NEIGHBORHOOD SEARCH ; MULTI DIRECTIONAL LOCAL
SEARCH

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1. Introduction

In this paper, we consider a Supply Chain Network Design (SCND) problem with four-layers and multiple commodities. This SCND model considers the locations of facilities at the two intermediate layers: production facilities and distribution centers. It also determines the choice between several technology levels at any facility and transportation modes on every arc of the network.

Technology levels and transportation modes highly influence the level of CO₂ emissions. The use of “green” technology may reduce the amount of CO₂ emissions through supply chains. Green technology might be achieved by deploying technology principles such as renewable energy, renewable raw materials, life-cycle assessment, biotechnology approach, and so forth (Doble and Kruthiventi, 2007). For example, within the biomass supply chain, fast pyrolysis followed by hydroprocessing as the biomass conversion technology is more effective in reducing GHG emissions over gasification followed by Fischer–Tropsch synthesis (Gao and You, 2017).

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15 Supply chain network design has mostly incorporated four policies to integrate environ-
mental issues: carbon cap, carbon offset, cap-and-trade and carbon tax. All four policies suc-
ceed to achieve substantial emission reductions with a slight increase in total cost; mostly by
configuring the supply chain to use lower-emitting resources (Waltho et al., 2019). However,
such compromise solutions can be easily missed using traditional single objective methods
20 (Harris et al., 2014).

Therefore, we consider a mixed integer linear program (MILP) with two objectives. The
first objective function is the minimization of logistics costs expressed as the sum of fa-
cility fixed costs, production costs, and transportation costs. The second objective is the
minimization of CO₂ emissions arising from production and logistics operations.

25 Although supply chain network design is intrinsically a multi-objective problem, the num-
ber of multi-objective SCND related publications has grown up quite lately. They represent
only 9% of the papers cited in the review by Melo et al. (2009) about facility location and
supply chain management. In their survey on multiple criteria facility location problems,
Zanjirani Farahani et al. (2010), studied 730 source titles. Since then, the field has known
30 a tremendous growth, mainly due to the huge literature in sustainable supply chain (Eskan-
darpour et al., 2015). Customer service and risk related objectives are also more and more
studied.

The literature on multi-objective optimization often distinguishes between single-solution
methods and methods providing decision makers with a set of mutually non-dominated so-
35 lutions.

Single-solution methods convert multi-objective formulations into single objective formu-
lations. In this category, models with weighted sum of objectives can be solved by any
classical solution methods, e.g. Tabu Search (Cardona-Valdés et al., 2014; Caballero et al.,
2007), and Variable Neighborhood Search (Eskandarpour et al., 2013, 2014).

40 Single-solution methods can be used to find a set of mutually non-dominated solutions,

at the price of being run multiple times with different parameters. This can become a computational burden for large instances. Therefore, developing heuristic methods is inevitable to find trade-off solutions (Zanjirani Farahani et al., 2010). Population based methods offer a choice between several trade-off solutions within a single run, providing decision makers with
45 sufficient options necessary to balance all objectives (Guillén-Gosálbez, 2011; Harris et al., 2014). Table 1 shows examples of recent population based method references.

Meta-heuristic	Reference papers
Genetic	Altiparmak et al. (2006); Dehghanian and Mansour (2009); Liao et al. (2011); Demirel et al. (2014); Harris et al. (2014); Robles et al. (2016); Tiwari et al. (2016); Kumar et al. (2017); Shi et al. (2017); Zhang et al. (2017); Alavidooost et al. (2018); Ebrahimi (2018)
Memetic	Jamshidi et al. (2012); Pishvaei et al. (2010)
Particle swarm	Canales-Bustos et al. (2017); Kadambala et al. (2017); Moncayo-Martínez and Mastrocinque (2016); Zhang et al. (2016); Shankar et al. (2013b,a); Ganguly et al. (2011)
Scatter search	Olivares-Benitez et al. (2013)
NSGA II	Alizadeh Afrouzy et al. (2018); Arabzad et al. (2015)
Hybrid	Devika et al. (2014); Govindan et al. (2015)

Table 1: Examples of multi-objective population based methods for SCND

The bi-objective SCND problem is solved with the multi-directional local search (MDLS) algorithm originally proposed by Tricoire (2012). MDLS is a multi-objective optimization framework which generalizes the concept of local search to multiple objectives. Its key idea is
50 to use different local searches, each of them working on a single objective. It considers a set of non-dominated solutions, called *non-dominated set*, which is updated through the solution process. More precisely, a local search is performed in order to improve non-dominated solutions with respect to each objective function separately. An iteration consists in (i) selecting a solution, (ii) performing local search on this solution for each objective/direction,
55 thus producing a new solution in each direction and (iii) accepting or rejecting the newly produced solutions.

In Tricoire (2012), MDLS has been applied to several multi-objective problems such as the multi-objective multi-dimensional knapsack problem, the bi-objective set packing problem and the bi-objective orienteering problem. It has been later applied to intermodal train loading planning (Heggen et al., 2018) and several variants of the travelling salesman problem (Defryn and Sörensen, 2018) and vehicle routing problems (Kovacs et al., 2015; Molenbruch et al., 2017; Lehuédé et al., 2019). A variant of the original MDLS, called Improved Multi-Directional Local Search (IMDLS) was proposed by Lian et al. (2016). IMDLS limits the size of the non-dominated set. This size limitation allows the algorithm to perform parallel local searches from each non-dominated solution without any memory issue. An enhanced version of the IMDLS algorithm is proposed in Eskandarpour et al. (2019).

To the best of our knowledge, MDLS has never been used for solving facility location and more generally SCND problems. The main contributions of this paper are therefore: (i) to propose a bi-objective extension of the model proposed in Eskandarpour et al. (2017), with environmental assessment and technology levels (Section 2) (ii) to solve this problem with an MDLS approach limiting the number of trade-off solutions as proposed by Lian et al. (2016) (Section 3) (iii) to compare the results of the MDLS algorithm with an ε -constraint method (Section 4) and (iv) to propose managerial insights based on the analysis of solutions to our model (Section 5).

2. Problem definition and modeling

2.1. Problem settings

We consider a bi-objective SCND model based on a logistics network with four layers: suppliers, production plants, distribution centers (DCs) and customers. The location of suppliers and customers are known, whereas those of plants and DCs have to be determined from a list of candidate locations. Customer demand is assumed deterministic.

Decision makers choose *where to locate plants and DCs* as well as *which technology to*

install at selected locations. Thus, for each location, we consider a list of candidate technologies. The generic term technology may refer to distinct generations or variants of the same type of machine or to competing technological choices. Each technology has its own capacity, production cost and CO₂ emissions. If a technology is less effective than another technology both from the economic and environmental point of view, it will never be selected. Thus, we consider only technologies that do not dominate each other, i.e greener technologies are considered to require a larger initial fixed cost. This is why the integration of technological choices is perfectly adapted to a bi-objective model.

As products move through the supply chain, their carbon footprint increases. Raw material sourcing, manufacturing, handling, transportation, and storage contribute to the emissions a product directly or indirectly is responsible for (Waltho et al., 2019). In particular, when it comes to investigate the source of CO₂ emissions within supply chains, warehousing operations and logistics centers have received little attention (Freis et al., 2016). Warehouses have significant amount of energy consumption due to lighting, heating, cooling and air conditioning as well as material handling equipment (Ries et al., 2017). Environmental assessment becomes particularly crucial in automated warehouses (Tappia et al., 2015).”

To this end, the environmental impact is assessed by the quantity of CO₂ emissions in the whole network, arising from two main sources: (i) product processing, for which the amount of emissions depends on the technology installed and is assumed proportional to the amount of products processed by the facility (ii) product transportation, for which the emissions are based on the distance travelled and the type of transportation mode used. Although far from being exhaustive, this assessment is considered relevant since transport and industrial facilities account for 22% and 20% of global CO₂ emissions, respectively (OECD/IEA, 2012). Moreover, it can be easily measured and integrated into mathematical models, which can explain its large use in academic papers (Wang et al., 2011).

We assume that a restricted list of suitable transportation modes has been *a priori* iden-

tified for each pair of nodes, with respect to criteria such as availability and safety, shipping costs, CO₂ emissions, shipment capacities, speed and frequency. Hence, for each arc, one
110 or several transportation modes are available, such as road, rail, inland navigation or air transport. At the strategic level, the cost and emissions of most transportation modes are assumed linear with respect to the quantity carried. Some transportation modes incur a fixed charge.

With respect to the above-mentioned description, the SCND model proposed in this
115 paper aims at determining the number, location, and technology level at plants and DCs, the suitable transportation modes, and the product flows between facilities. The goal is to minimize two conflicting objectives: the total cost and the environmental impact expressed by amount of CO₂ emissions. In the following, we present the mathematical formulation of this problem, as extended from Eskandarpour et al. (2017) including CO₂ emissions and
120 technology levels.

2.2. Data, sets, parameters and variables

The sets, parameters and decision variables used in the mathematical model are given in Tables 2, 3 and 4 respectively. The SCND problem is defined on a directed graph $\psi = (V, A)$ where $V = I \cup J \cup K \cup L$ and the set A of arcs defines all possible links between two successive
125 layers.

2.3. Mathematical formulation

The economic objective (1) encompasses all fixed and variable costs in the network. The first term is the sum of all opening fixed costs. The second and third terms correspond to processing costs. The fourth term represents the fixed costs of using each transportation
130 mode between each pair of nodes. The last term refers to the variable transportation cost between each pair of nodes.

Set	Description
I	suppliers
J	candidate plants
K	candidate DCs
L	customers
$J^o \subset J$	open (selected) plants
$K^o \subset K$	open (selected) DCs
P	products
M	transportation modes
T	technologies

Table 2: Data sets

Parameter	Description
d_l^p	demand of customer $l \in L$ for product $p \in P$
c_j^t	fixed cost of opening a facility $j \in J \cup K$ using technology $t \in T$
a_i^p	unit processing cost of product $p \in P$ at supplier $i \in I$
e_i^{pt}	unit processing cost of product $p \in P$ at $i \in J \cup K$ with technology $t \in T$
cap_i	capacity of facility $i \in I \cup J \cup K$
g_{ij}^m	fixed cost of using transportation mode $m \in M$ along arc $(i, j) \in A$
v_{ij}^{mp}	variable transportation cost of a unit of product $p \in P$ on arc $(i, j) \in A$ by mode $m \in M$
\underline{V}_{ij}^m	minimum threshold volume for using transportation mode $m \in M$ along arc $(i, j) \in A$
\bar{V}_{ij}^m	capacity of transportation mode $m \in M$ along arc $(i, j) \in A$
b_i^p	unitary CO ₂ emissions at supplier $i \in I$ for each product $p \in P$
q_i^{pt}	CO ₂ emissions caused by the manufacturing or warehousing of one unit product $p \in P$ at $j \in J \cup K$ with technology $t \in T$
r_{ij}^{mp}	CO ₂ emissions caused by the transportation of one unit of product $p \in P$ along arc $(i, j) \in A$ by mode $m \in M$

Table 3: Parameters

Name	Type	Description
y_j^t	binary	= 1 if facility $j \in J \cup K$ with technology level t is open and 0 otherwise
u_{ij}^m	binary	= 1 if transportation mode $m \in M$ is selected for arc $(i, j) \in A$ and 0 otherwise
x_{ij}^{mp}	continuous	flow of product $p \in P$ on arc $(i, j) \in A$ using transportation mode $m \in M$
h_i^{pt}	continuous	amount of product $p \in P$ processed with technology level $t \in T$ at facility $i \in J \cup K$.

Table 4: Decision variables

$$\begin{aligned}
\min z_1 = & \sum_{j \in J \cup K} \sum_{t \in T} c_j^t y_j^t + \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} \sum_{p \in P} a_i^p x_{ij}^{mp} + \sum_{i \in J \cup K} \sum_{t \in T} \sum_{p \in P} e_i^{pt} h_i^{pt} + \\
& \sum_{(i,j) \in A} \sum_{m \in M} g_{ij}^m u_{ij}^m + \sum_{(i,j) \in A} \sum_{m \in M} \sum_{p \in P} v_{ij}^{mp} x_{ij}^{mp}. \quad (1)
\end{aligned}$$

The environmental objective (2) consists of three terms representing the CO₂ emissions due to purchasing and supplying of products from suppliers to plants, the CO₂ emissions at plants and DC, and the CO₂ emissions arising from transportation modes, respectively.

$$\begin{aligned}
\min z_2 = & \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} \sum_{p \in P} b_i^p x_{ij}^{mp} + \sum_{i \in J \cup K} \sum_{t \in T} \sum_{p \in P} q_i^{pt} h_i^{pt} + \\
& \sum_{(i,j) \in A} \sum_{m \in M} \sum_{p \in P} r_{ij}^{mp} x_{ij}^{mp}. \quad (2)
\end{aligned}$$

135

Constraints (3) are the flow conservation constraints through the network.

$$\sum_{i \in V} \sum_{m \in M} x_{ij}^{mp} = \sum_{k \in V} \sum_{m \in M} x_{jk}^{mp} \quad \forall j \in J \cup K, p \in P. \quad (3)$$

Constraints (4) and (5) calculate the amount of product entering in each facility.

$$\sum_{t \in T} h_j^{tp} = \sum_{i \in I} \sum_{m \in M} x_{ij}^{mp} \quad \forall j \in J, p \in P \quad (4)$$

$$\sum_{t \in T} h_k^{tp} = \sum_{j \in J} \sum_{m \in M} x_{jk}^{mp} \quad \forall k \in K, p \in P. \quad (5)$$

Constraints (6) ensure the satisfaction of customers demands.

$$\sum_{k \in K} \sum_{m \in M} x_{kl}^{mp} \geq d_l^p \quad \forall l \in L, p \in P. \quad (6)$$

Constraints (7) and (8) force the model to satisfy capacity constraint at suppliers, plants and DCs respectively. In addition, constraints (8) state that the products can be shipped only to open facilities.

$$\sum_{j \in J} \sum_{m \in M} \sum_{p \in P} x_{ij}^{mp} \leq cap_i \quad \forall i \in I \quad (7)$$

$$\sum_{p \in P} h_i^{tp} \leq cap_i y_i^t \quad \forall j \in J \cup K, t \in T \quad (8)$$

140

Constraints (9) ensure that at most one technology level is selected for each facility.

$$\sum_{t \in T} y_j^t \leq 1 \quad \forall j \in J \cup K. \quad (9)$$

Constraints (10) ensure that at most one transportation mode is selected between two

connected nodes. Constraints (11) – (12) guarantee that the volume limitation of each given mode is satisfied.

$$\sum_{m \in M} u_{ij}^m \leq 1 \quad \forall (i, j) \in A \quad (10)$$

$$\sum_{p \in P} x_{ij}^{mp} \leq \bar{V}_{ij}^m u_{ij}^m \quad \forall (i, j) \in A, m \in M \quad (11)$$

$$\sum_{p \in P} x_{ij}^{mp} \geq \underline{V}_{ij}^m u_{ij}^m \quad \forall (i, j) \in A, m \in M. \quad (12)$$

Without loss of generality, we also consider possible restrictions on the number of open
 145 facilities. Decision makers or industrial experts are often able to *a priori* determine reasonably narrow ranges, denoted by $\{J_{min}, \dots, J_{max}\}$ and $\{K_{min}, \dots, K_{max}\}$, respectively, for the number of plants and DCs to be selected. Constraints (13)–(14) bound the number of open plants and DCs respectively. These constraints can be discarded by setting minimal values at 0 and maximal values at $+\infty$.

$$J_{min} \leq \sum_{j \in J} \sum_{t \in T} y_j^t \leq J_{max} \quad (13)$$

$$K_{min} \leq \sum_{k \in K} \sum_{t \in T} y_k^t \leq K_{max}. \quad (14)$$

Constraints (15) – (18) state binary and non-negativity restrictions on decision variables.

$$y_j^t \in \{0, 1\} \quad \forall j \in J \cup K, t \in T \quad (15)$$

$$u_{ij}^m \in \{0, 1\} \quad \forall (i, j) \in A, m \in M \quad (16)$$

$$x_{ij}^{mp} \geq 0 \quad \forall (i, j) \in A, p \in P, m \in M \quad (17)$$

$$h_i^{pt} \geq 0 \quad \forall i \in J \cup K, p \in P, t \in T. \quad (18)$$

150 3. Multi Directional Local Search (MDLS)

In this section, we introduce the MDLS metaheuristic for solving the bi-objective SCND model (1)–(18). Section 3.1 presents the main scheme of our implementation of the MDLS algorithm. The local search algorithm used within the MDLS framework is presented in Section 3.2. Subsequent sections detail the key steps of this algorithm. Finally, following 155 the ideas of Lian et al. (2016), Section 3.5 introduces a refinement of MDLS that restricts the number of solutions in the non-dominated set and intensifies the search around the least crowded areas.

3.1. The Multi-Directional Local Search algorithm for bi-objective SCND

The Algorithm 1 describes our implementation of the MDLS framework.

Algorithm 1 The MDLS algorithm for bi-objective SCND

```

1: Initialization of the non-dominated set:  $\mathcal{P} \leftarrow \mathcal{P}^0$ 
2: while the termination criterion is not satisfied do
3:    $\mathcal{P}' \leftarrow \mathcal{P}$ 
4:   for every solution  $p \in \mathcal{P}$  do
5:     for Objective  $o = 1 \rightarrow 2$  do
6:        $p_o = \text{singleObjectiveLocalSearch}(p)$ 
7:        $\mathcal{P}' \leftarrow \mathcal{P}' \cup \{p_o\}$ 
8:     end for
9:   end for
10:   $\mathcal{P} \leftarrow$  set of non-dominated solutions in  $\mathcal{P}'$ 
11: end while
12: Post-optimization:  $\mathcal{P}^* \leftarrow \text{Optimize\_product\_flows}(\mathcal{P})$ 
13: return  $\mathcal{P}^*$ 

```

160 The algorithm is initialized with an initial non-dominated set (see section 3.3). At every iteration, all solutions of the current non-dominated set are modified by running independent local searches (see section 3.2) with respect to each objective (cost and CO₂ emissions). In original MDLS developed by Tricoire (2012), the local search is applied only to one randomly

selected solution. Applying the LNS on all solutions $p \in \mathcal{P}$ in both directions yields a new
 165 set \mathcal{P}' of solutions. Since \mathcal{P}' may contain dominated solutions, the non-dominated set \mathcal{P}
 at next iteration is built by removing all dominated solutions in \mathcal{P}' (line 10). In line 12,
 a post-optimization step slightly improves the value of all continuous variables (see section
 3.4).

3.2. Single-objective local search

170 The local search method used in Line 6 of Algorithm 1 is the Large Neighborhood Search
 (LNS) metaheuristic (Pisinger and Ropke, 2010). The principle of the LNS is to iteratively
destroy and *repair* the current solution in order to progressively improve it. A destroy method
 destructs part of the current solution while a repair method rebuilds the destroyed solution
 so that a new feasible solution is found (Shaw, 1998). Problem specific *destroy and repair*
 175 *operators* (methods) have to be designed in order to efficiently solve the optimization problem
 considered. In this paper, we reuse the Large Neighborhood Search algorithm extensively
 described in Eskandarpour et al. (2017). In practice, any other single-objective local search
 method can be used instead. This LNS algorithm sets facility location decisions associated
 with plants and DCs. Transportation modes and product flow decisions are determined by a
 180 greedy heuristic consisting of assigning product flows to the nearest facility, via the cheapest
 transportation mode. The LNS algorithm embeds 6 destroy operators, 9 repair operators,
 and 2 combined (destroy + repair) operators. The determination of technology levels uses
 a biased roulette wheel giving much higher probability to the technologies with lower fixed
 costs (resp. CO₂ emissions). This approach helps diversify the search.

3.3. Initial non-dominated set

The initial non-dominated set \mathcal{P}^0 must contain mutually non-dominated solutions that
 preferably represents good diversity of solutions with respect with both objectives. This di-
 versity will help MDLS explore various areas of the solution space. Let $n_j = \sum_{j \in J} \sum_{t \in T} y_j^t$

and $nk = \sum_{k \in K} \sum_{t \in T} y_k^t$ represent the number of production facilities and DCs in a solution, respectively. For each possible value of the pair (nj, nk) we seek two solutions: one minimizing costs and the other one minimizing CO₂ emissions. To do so, we used a simplified version of the LNS algorithm described in Section . The following simplifications have been considered: (i) only two destroy operators and one repair operator are used, (ii) when considering cost (resp. CO₂ emissions) objective, the technology level with the lower fixed cost (resp. lower emission) is set at all selected facilities, (iii) this simplified version is run for only 100 iterations. \mathcal{P}^0 is built from the merger of by merging solutions obtained with all possible values of the pair (nj, nk) and removing dominated solutions.

3.4. Post-optimization of product flows

The local search algorithm sets transportation modes and product flows with by a greedy heuristic. The goal of this post-optimization is to slightly improve the value of the corresponding variables, by using a linear programming solver instead of the greedy heuristic.

This post-optimization might reduce the number of non-dominated solutions since neighboring solutions can merge. This is illustrated in Figure 1. Figure 1(a) displays a non-dominated set resulting from the previous steps of the MDLS algorithm. Figure 1(b) shows three non-dominated neighbors obtained by the post-optimization step. Figure 1(c) presents the set of final non-dominated solutions.

3.5. Improved Multi Directional Local Search (IMDLS)

A new idea introduced by Lian et al. (2016) is to limit the size of the non-dominated set to a predefined number, hereby denoted by P_{max} . In order to select the P_{max} active solutions, they measure crowding distance of each solution of the non-dominated set. The crowding distance of a solution measures the density of solutions around it ; higher values of crowding distance correspond to isolated solutions. In a bi-objective context, the crowding distance of a particular solution is simply obtained by calculating the average distances between this

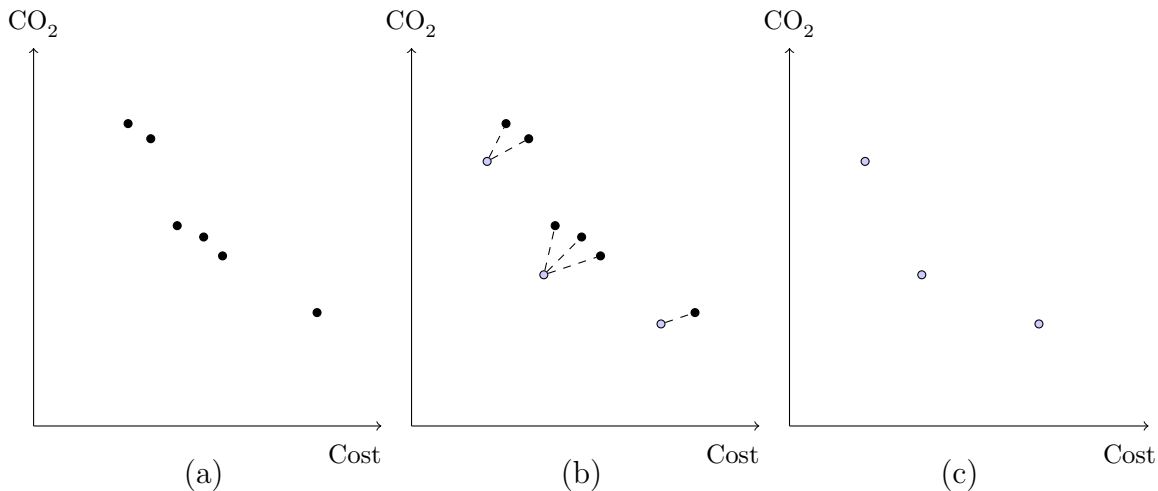


Figure 1: Post-optimization. (a) non-dominated set before post-optimization (b) Neighbors obtained by post-optimization. (c) Final non-dominated set.

solution and its two neighboring solutions along each of the objectives in the non-dominated
 set (i.e. the solutions that are just better than and just worse than it for both of the
 215 objectives) (Deb et al., 2002). This calculation takes place at every iteration of the main
 loop in Algorithm 1. Then, solutions are sorted in non-increasing order of their crowding
 distances and the first P_{max} solutions only are conserved. Note that the crowding distance of
 the two extremal solutions in the non-dominated set are artificially set to $+\infty$, so that they
 220 are kept in any case.

We implemented the IMLDS algorithm and added an intensification step. In IMDLS,
 local search is applied on each solution of the non-dominated set. Exactly one local search
 is performed from each non-dominated solution. (Caballero et al., 2007) formulated the
 intuitive idea that there is always a possibility that another non-dominated solution is still
 225 to be discovered around a non-dominated solution. The intensification process is based on
 the assumption that these "still to be discovered non-dominated solutions" are more likely
 to be found near the least crowded areas of the set \mathcal{P} . Hence, a small subset of $\tau < P_{max}$

solutions with highest crowding distances is selected. From these points, we perform several local searches (instead of one) and consider all solutions generated. This is illustrated by
 230 Example 1. Note that this intensification step makes sense only if the local search contains some stochastic components, so that distinct solutions are returned by successive calls.

Example 1. Consider 5 solutions denoted A , B , C , D and E respectively, and assume $P_{max} = 10$ and $\tau = 2$. Assume also that B and D have the largest crowding distances (Figure 2(a)).

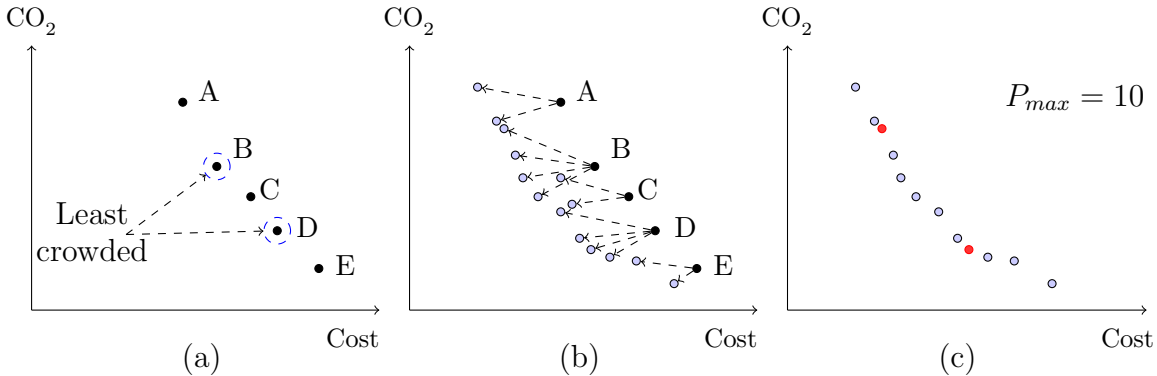


Figure 2: One MDLS iteration. (a) Starting set of solutions. (b) Neighbors obtained by MDLS around each solution. (c) Final non-dominated set.

Figure 2(b) shows 14 neighboring solutions obtained by applying one local search related
 235 to each objective starting from A , C and E , and two local searches related to each objective starting from B and D . Figure 2(c) presents the set of 12 mutually non-dominated solutions among these 14 solutions. Since $P_{max} = 10$, the solutions displayed in red are removed from the current set.

4. Computational experiments

240 We evaluate our MDLS implementation through a comparison with the results obtained with the classical ε -constraint method (denoted thereafter by EC) and with the IMDLS

framework proposed by Lian et al. (2016). All algorithms were coded in C++ and run on a computer with four Intel 3.0 GHz CPUs and 8 GB of RAM.

The numerical experiments rely on a set of generated instances that are detailed in Section 4.1. Then, Section 4.2 briefly recalls the principle of the ε -constraint method and lists the performance measures used to assess the quality of the MDLS. The parameter settings are given in Section 4.3. In Section 4.4, the contribution of the main components of the proposed MDLS is evaluated and its results are compared with those of the IMDLS. Lastly, Section 4.5 compares the non-dominated sets obtained with the MDLS and those provided by the EC.

4.1. Test instances

Our experiments are based on the 15 instances extensively described in Eskandarpour et al. (2017). The size of these instances is determined by the number of facilities in the logistics network and the upper limits J_{max} and K_{max} . Similarly to Cordeau et al. (2006), we set the number of potential suppliers and plants to $|I| = |J| = 0.1 \times |L|$. The number of potential DCs was set to $|K| = 0.2 \times |L|$. The values J_{max} and K_{max} were set to $0.5 \times |J|$ and $0.5 \times |K|$, respectively. Table 5 displays the instances' main features.

In addition, the number $|P|$ of products has been set to 5 and 2 available technology levels are considered at each facility.

CO₂ emissions originate from operations that take place at facilities and during transportation. Subsections 4.1.1 and 4.1.2 detail both cases.

4.1.1. Cost and emissions related to facilities

Technology levels installed in facilities influences the amount of CO₂ emissions as well as fixed costs and processing costs. We considered two potential technologies levels l_1 (lowest) and l_2 (highest) at each facility. For technology level l_1 , the processing CO₂ emissions at suppliers and facilities are modeled with a conversion factor φ randomly generated in the

Table 5: Test instances

<i>Instance</i>	$ I $	$ J $	$ K $	$ L $	J_{max}	K_{max}
<i>T1</i>	6	6	12	60	3	6
<i>T2</i>	7	7	14	70	4	7
<i>T3</i>	8	8	16	80	4	8
<i>T4</i>	9	9	18	90	5	9
<i>T5</i>	10	10	20	100	5	10
<i>T6</i>	12	12	24	120	6	12
<i>T7</i>	14	14	28	140	7	14
<i>T8</i>	16	16	32	160	8	16
<i>T9</i>	18	18	36	180	9	18
<i>T10</i>	20	20	40	200	10	20
<i>T11</i>	22	22	44	220	11	22
<i>T12</i>	24	24	48	240	12	24
<i>T13</i>	26	26	52	260	13	26
<i>T14</i>	28	28	56	280	14	28
<i>T15</i>	30	30	60	300	15	30

interval $[2.5, 4.5]$ (unit: kg CO₂ equiv./ton of product) for each type of product. As indicated by Table 6, we assume that the highest technology results in higher fixed cost but lower processing cost and CO₂ emissions.

Table 6: Features of technology levels

Technology level	l_1	l_2
Fixed cost	=	+20%
Processing cost	=	-10%
Processing emission	=	-20%

270 4.1.2. Cost and emissions related to transportation

We assumed three transportation modes in the network. Each mode includes fixed cost and variable costs as well as CO₂ emissions. Without loss of generality, mode 1 could be an internal fleet of trucks. Fixed cost of mode 1 was assumed to be 10000. Mode 2 could represent an outsourced fleet of trucks (3PL) for the delivery of goods to customers. Variable

275 cost of mode 2 was defined as 20% more expensive than that of mode 1. On the other
hand, 3PL companies have the ability to pool shipments from several companies, so that
they generally operate with higher truck fill rate and less empty truck repositioning, which
improves their environmental efficiency. Mode 3 could correspond to inland navigation or
rail transportation, for which fixed cost is assumed to be null and variable cost 80% of that
280 of mode 1.

In the context of supply chain network design, we consider quantities carried over long
time periods (e.g. one year), by a fleet of vehicles. The loads carried vary from one trip to
another, as well as the drivers and the traffic conditions. Thus, strategic models use averaged
values of speed, load and traffic conditions for each trip. Under this assumption, transporta-
285 tion costs and emissions are considered roughly proportional to the distance traveled. We
use conversion factors for half and full truckload, provided by the French Environment and
Energy Management Agency (ADEME). According to Tables 32 and 35 by ADEME (2010),
we consider conversion factors of 0.065 and 0.055 kg per km.ton for full and half truckload
respectively, as well as 0.006 kg per km.ton mode 3. Finally, overall emissions on each arc are
290 calculated by multiplying the arc length by the conversion factor and the amount of products
shipped.¹

4.2. The ε -constraint method and performance measures

4.2.1. Results with the ε -constraint method (EC)

The main principle of EC is to convert a bi-objective model with two objectives z_1 and z_2
295 to a model with single objective z_1 and the constraint $z_2 \leq \varepsilon$. Each value of the parameter ε
gives rise to a distinct MILP, which can be solved by any MILP solver or solution method.
We used IBM Ilog Cplex 12.6 concert technology (standard tuning) with a time limit of 3
hours for each value of ε .

¹A file detailing the generation of environmental factors along with test instances are accessible at
<https://data.mendeley.com/datasets/b2t84kg4wh/draft>

In our experiments, the value of ε varies between the minimum and maximal levels of the environmental objective found with the single objective model. This interval is decomposed into evenly spaced intermediate values of epsilon (see Demir et al. (2014); Devika et al. (2014); Du and Evans (2008)). In total, 10 values of epsilon were generated.

After solving the problem for each value of ε , the dominated solutions are filtered. For small instances, we obtained optimal solutions for each of the 10 MILPs associated with a particular value of ε . For larger instances, we obtain an approximation of these optimal solutions.

Table 7 displays the results obtained for all instances. Column 2 shows the size of the non-dominated set for each test instance. Column 3 presents the total run time (in seconds), i.e the sum of run times for the 10 MILPs solved. Column 4 shows the number of MILPs which could not be solved to optimality after 3h. The average optimality gap between the best solution found and the lower bound is reported in column 5.

Table 7: Results with the ε -constraint method

	<i>Size of non-dominated set</i>	<i>Total time (in seconds)</i>	<i>Sub-optimal solutions</i>	<i>Gap (in %)</i>
<i>T1</i>	10	757	0	0
<i>T2</i>	10	9268	0	0
<i>T3</i>	10	12916	0	0
<i>T4</i>	10	23621	0	0
<i>T5</i>	10	34713	1	0.07
<i>T6</i>	9	58866	2	0.35
<i>T7</i>	10	79168	4	2.49
<i>T8</i>	10	30h	10	5.82
<i>T9</i>	9	30h	10	5.06
<i>T10</i>	10	30h	10	4.09
<i>T11</i>	10	30h	10	3.01
<i>T12</i>	9	30h	10	6.54
<i>T13</i>	10	30h	10	5.59
<i>T14</i>	10	30h	10	3.26
<i>T15</i>	9	30h	10	5.75

Table 7 shows the practical limits of the MILP solver. Small instances can be solved to optimality, at the price of high computational time. Solving realistic size instances requires using heuristic or meta-heuristic algorithms.

315 4.2.2. Performance measures

In this section, we compare the quality of the solutions obtained with MDLS with those obtained by EC. We used three classic performance measures: the *hypervolume*, the *unary ϵ indicator* and the *ratio of Pareto optimal solutions*.

Each measure partially reflects the performance of non-dominated set. Since all measures
320 have some drawbacks, using several measures at the same time can help fairly comparing several fronts (Tricoire, 2012).

- *The hypervolume measure H* (Zitzler et al., 2003) represents the surface covered by a set of non-dominated solutions with respect to a reference point (here the Nadir Point). Thus, larger hypervolume measure indicates better quality of the non-dominated set.
- 325 • *The unary ϵ indicator* (Zitzler et al., 2003) is defined as the smallest multiplicative coefficient to apply to an approximate set so as to completely dominate the reference set. Its smallest value is 1 and smaller values are better.
- *The ratio of Pareto optimal solutions (R)* (Altıparmak et al., 2006): given solutions sets S_1 and S_2 obtained by two methods, this ratio shows the percentage of solutions
330 from set S_1 not dominated by any member of set $S_1 \cup S_2$. The higher this ratio is, the better the solution set.

4.3. Parameter Settings

The parameters of MDLS have been determined based on preliminary computational experiments, with the goal of keeping good trade-off between the solution quality and computational time. The MDLS algorithm is stopped after 15000 iterations. The value of parameter
335

τ has been set to 2 and local searched are applied 5 times on each of the τ solutions. The maximum size of the non-dominated set has been set to $P_{max} = 10$.

4.4. Evaluating components of Algorithm 1

Table 8 shows the contribution of three important components of Algorithm 1: initialization (line 1), the main MDLS loop (lines 2–1) and post-optimization (line 12).

Table 8: Contribution of each phase of the algorithm

Instance	Initialization		Main loop			Post-optimization		
	# sol	CPU (s)	# sol	Ratio	CPU (s)	# sol	Ratio	CPU (s)
T1	5.2	1	6.4	1	1127	5	1	1
T2	6.0	2	5.4	1	1577	4.6	1	2
T3	6.4	2	5.6	0.83	1926	5.2	1	1
T4	8.0	2	7.2	1	2815	4.8	1	1
T5	5.8	3	6.6	0.67	3093	5.8	1	1
T6	9.4	9	5.4	1	4400	5	1	7
T7	9.0	18	9.8	1	6596	8.8	0.9	9
T8	8.8	41	5.6	1	8059	5.4	1	26
T9	7.4	45	9.2	1	9403	9.2	1	16
T10	8.2	79	9.6	0.82	12277	9.2	1	31
T11	9.2	98	7.6	0.80	14872	7.6	1	70
T12	7.2	178	7.8	1	17998	5.4	1	89
T13	10.0	288	7.6	1	21712	7.6	1	201
T14	9.4	456	9.2	1	26558	9.2	1	302
T15	9.8	532	8.6	0.83	30871	8	1	418
Average	8.0	117	7.4	0.93	10885	6.7	0.99	78

The MDLS was run 5 times on each instance. Columns 2, 4 and 7 report the average number of solutions (# sol) in the non-dominated set. Columns 3, 6 and 9 indicate the running time (in seconds). As stated earlier, the number of non-dominated solutions is slightly decreased by the post-optimization step, since calculating optimal product flows enables merging some neighboring non-dominated solutions. Regarding computing times, the initialization and the post-optimization require less than 2% of the total time. Columns 5 and 8 report the ratio of Pareto optimal solutions associated with the MDLS iterations and the post-optimization steps. The average values of 0.93 and 0.99) indicate that each component of the algorithm significantly improves the results of the preceding one.

350 One main difference between MDLS proposed in this study and in Lian et al. (2016) with the original one in Tricoire (2012) is to provide a non-dominated set with a small set of solutions. Providing a reasonable number of representative solutions to decision makers might be more desirable (Govindan et al., 2015). We also show that this speeds up the convergence to the Pareto set. We run MDLS with either $P_{max} = 10$ or $P_{max} = +\infty$, with a time limit of 355 10 hours. The results presented in Table 9 show the superiority of the MDLS with $P_{max} = 10$ (denoted MDLS (10)) over the one with unlimited non-dominated set (denoted MDLS (∞)).

Table 9: Impact of the non-dominated set limitation

<i>Instance</i>	# sol		<i>R</i>	
	MDLS (10)	MDLS (∞)	MDLS (10)	MDLS (∞)
<i>T1</i>	5	34	1	0.79
<i>T2</i>	5	72	1	0.60
<i>T3</i>	7	48	1	0.73
<i>T4</i>	4	62	1	0.48
<i>T5</i>	7	53	1	0.42
<i>T6</i>	6	57	1	0.09
<i>T7</i>	10	86	1	0.55
<i>T8</i>	5	57	1	0.53
<i>T9</i>	9	51	1	0.20
<i>T10</i>	10	89	1	0.47
<i>T11</i>	5	54	1	0.94
<i>T12</i>	6	58	1	0.52
<i>T13</i>	7	87	1	0.46
<i>T14</i>	10	56	1	0.45
<i>T15</i>	6	88	1	0.47
average	6.8	63.5	1	0.51

Columns 2 and 3 show the size of the non-dominated set obtained with both variants. Columns 4 and represent the ratio of Pareto optimal solutions corresponding to MDLS(10) and MDLS(∞). Limiting the set of solutions acts as an intensification of the algorithm.

360 Unlike the IMDLS, our approach aggressively explores the solution space around the least crowded areas. Table 10 compares the result of one single run of our MDLS implementation

and IMDLS in terms of number of non-dominated solutions, ratio and CPU time.

Table 10: Comparison between MDLS and IMDLS

<i>Instance</i>	# sol		<i>R</i>		CPU (s)	
	<i>MDLS</i>	<i>IMDLS</i>	<i>MDLS</i>	<i>IMDLS</i>	<i>MDLS</i>	<i>IMDLS</i>
<i>T1</i>	5	7	0.61	0.68	1083	1061
<i>T2</i>	5	5	0.62	0.75	1517	1396
<i>T3</i>	7	9	0.71	0.67	1871	1759
<i>T4</i>	4	4	0.61	0.49	2733	2433
<i>T5</i>	7	5	0.8	0.75	2911	2852
<i>T6</i>	6	8	0.62	0.78	4063	3982
<i>T7</i>	10	5	0.63	0.8	6821	6480
<i>T8</i>	5	5	0.84	0.7	8207	7304
<i>T9</i>	9	7	0.71	0.74	9274	8440
<i>T10</i>	10	10	0.72	0.62	12511	11260
<i>T11</i>	5	5	0.71	0.69	15491	15181
<i>T12</i>	6	8	0.64	0.48	18082	16997
<i>T13</i>	7	4	0.77	0.64	22645	20834
<i>T14</i>	10	6	0.83	0.67	28409	25568
<i>T15</i>	6	9	0.76	0.63	32776	31792
<i>Average</i>	6.80	6.47	0.71	0.67	11226	10489

The overall results do not show significant difference between both approaches. However, as the instances size grow, the performance of MDLS tends to improve. For instance, the average ratio R of MDLS and IMDLS for instances T11 to T15 are 0.74 and 0.62 respectively.

4.5. Computational results

To compare the non-dominated set found by MDLS and EC, we ran both methods 5 times with 10 different values of ε and a time limit of 3 hours for each value of ε . The solutions provided by EC are Pareto optimal when the corresponding MILPs are solved to optimality. Hence, some solutions obtained with the MDLS may dominate those obtained by EC.

Table 11 reports the three performance measures described above. Columns 2 and 3 show the average ratio (R) for each method. Columns 4 and 5 show the value of unary ϵ indicators. Column 6 shows the gap between the hypervolume value of MDLS and EC. To

measure the ratio R and the unary ϵ indicator, the non-dominated sets are compared with a
 375 common reference set, which consists of the set of all non-dominated solutions provided by
 these methods.

Table 11: Comparison between MDLS and EC

<i>Instance</i>	<i>R</i>		Unary ϵ		<i>H%</i>
	MDLS	EC	MDLS	EC	
<i>T1</i>	0.48	1	1.95	1.63	-1.33
<i>T2</i>	0.64	1	1.84	1.63	-0.81
<i>T3</i>	0.34	1	1.84	1.7	-0.16
<i>T4</i>	0.21	1	1.51	1.41	-0.49
<i>T5</i>	0.38	1	1.91	1.67	-0.14
<i>Average</i>	0.41	1	1.81	1.61	-0.59
<i>T6</i>	0.32	1	1.8	1.62	-0.34
<i>T7</i>	0.34	0.85	1.3	1.66	-0.26
<i>T8</i>	0.46	0.8	1.58	1.73	-0.64
<i>T9</i>	0.61	0.79	1.49	1.67	0.21
<i>T10</i>	0.67	0.73	1.36	1.63	-0.22
<i>Average</i>	0.48	0.83	1.50	1.66	-0.25
<i>T11</i>	0.72	0.68	1.68	1.64	0.43
<i>T12</i>	0.66	0.7	1.43	1.83	0.75
<i>T13</i>	0.81	0.7	1.37	1.59	0.64
<i>T14</i>	0.72	0.65	1.47	1.62	0.24
<i>T15</i>	0.69	0.72	1.63	1.72	0.41
<i>Average</i>	0.72	0.69	1.51	1.68	0.49
<i>Overall Average</i>	0.54	0.84	1.61	1.65	-0.11

By definition, a solution from the MDLS set is dominated in a one to one comparison
 with an optimal point provided by EC. Thus, the ratio R associated with EC is much higher
 (0.84 against 0.54). Nonetheless, as the size of instances increases, the ratio associated with
 380 MDLS tends to increase while the ratio associated with EC decreases.

MDLS has a slightly better average unary ϵ than the EC (1.61 versus 1.65). Especially
 for large datasets, MDLS has more ability to find several solutions that minimize the second
 objective, so that the tail of the EC front is dominated by MDLS. This is illustrated by

Figure 3 representing instance T14. Eventually, the hypervolume indicator shows that MDLS
 385 is outperformed by EC for small and medium sized instances, but its performance increases
 when the instance size increases.

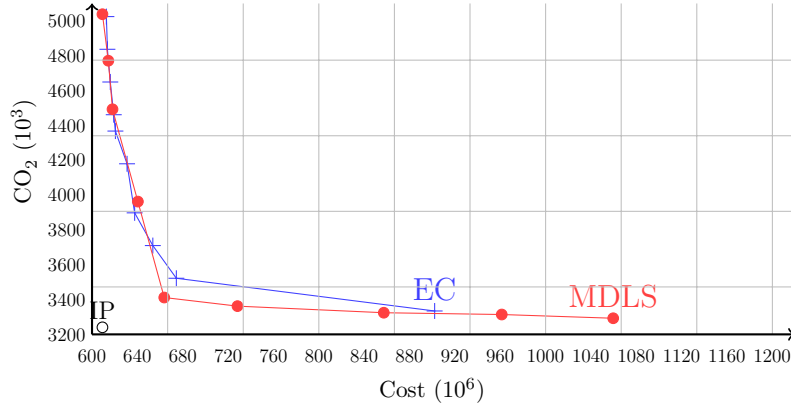


Figure 3: Comparison of the non-dominated sets for instance T14

5. Managerial insights and conclusion

Our experiments also showed that the supply chain topology can vary from one non-
 dominated solution to another one. As an example, Figure 4 represents an non-dominated
 390 set obtained for instance T4 (with 9 suppliers, 9 potential plants, 18 potential DCs, and 90
 customer).

The Figure 5 represents the selected plants and DCs corresponding to three particular
 solutions: solution A minimizing cost, a trade-off solution B and the *greenest* solution C,
 respectively. The technology levels used at each facility are represented with distinct colors.

395 Solutions A, B and C have completely different topologies. For example, there are 4 plants
 and 6 DCs in solution A, most of them having the lower technology level. Solution B is quite
 similar to solution A, the main difference comes from the improvement of technology levels.
 On the other side, cost is not a criterion in solution C. Thus all candidate facilities are open,
 with the highest technology level. This confirms the conclusion of Du and Evans (2008), who

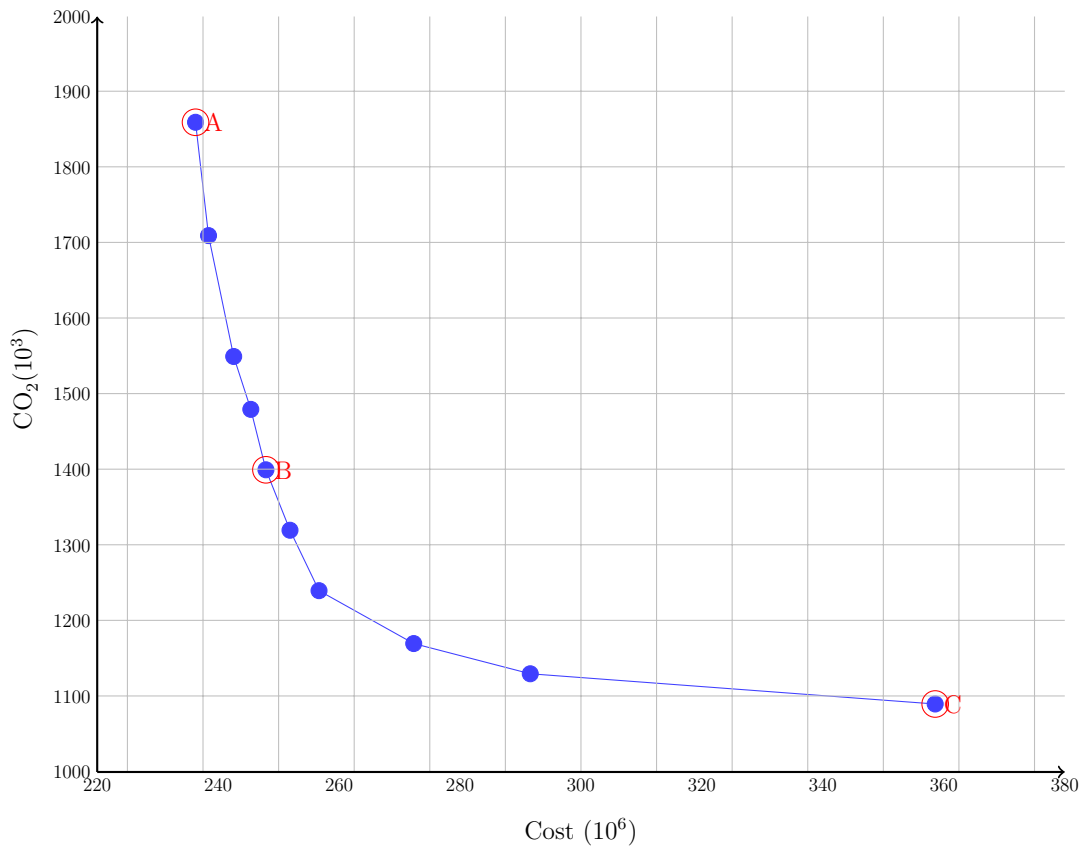


Figure 4: non-dominated set for instance T4

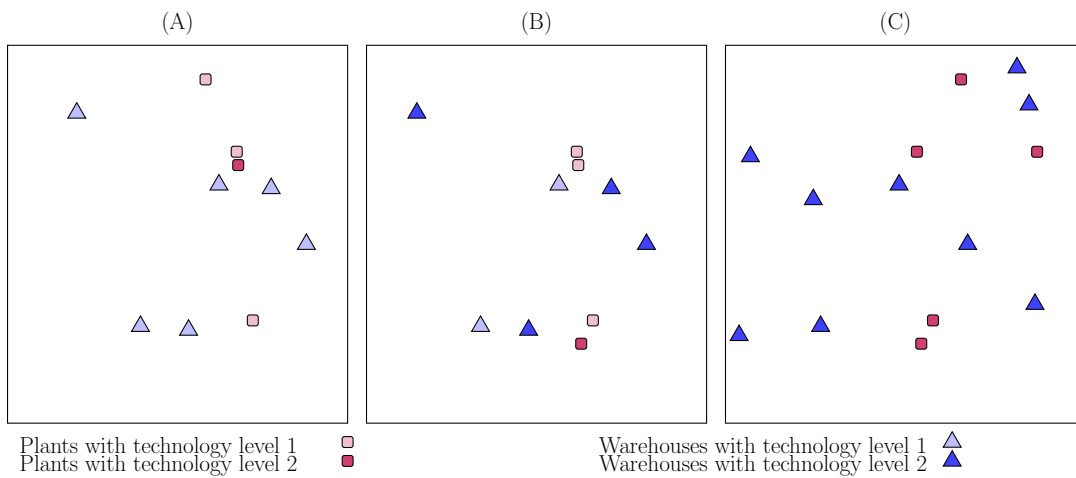


Figure 5: Supply chain topologies in solutions A to C

400 observed that the optimization for the first objective function leads to a centralized network structure; the optimization for the second objective function results in a decentralized network structure.

Greening the supply chain consists of two independent decisions: improving technology and modifying the supply chain. This example may suggest that decision makers first upgrade
405 a subset of key facilities, and then replace facilities with lower technologies by new facilities with higher technology. With this idea in mind, it can be worth identifying a subset of *robust* locations, i.e. locations that will remain selected whatever the environmental policy of the company and strategic decisions. We investigated the individual situation of each facility within the 10 non-dominated solutions presented in Figure 4. Figure 6 displays the total
410 number of occurrences of each facility within the 10 non-dominated solutions. Two plants and two DCs are selected in all 10 solutions. In other words, they can be considered as very *robust* facilities in term of both objectives. On the contrary, five DCs and one plant are never selected. These indications suggest that the analysis of the non-dominated set can be used as an *a posteriori* tool to refine the set of candidate locations and, thus, to focus on the core
415 of the decision making problem.

6. Conclusion

In this paper, we considered a bi-objective Supply Chain Network Design (SCND) problem and proposed an MILP model minimizing both economic and environmental performance criteria. Our goal was to solve this problem by exhibiting a set of efficient solutions consti-
420 tuting a non-dominated set. We therefore designed a solution procedure based on the MDLS framework proposed by Tricoire (2012). Each iteration of the MDLS uses the LNS as a local search method for both objectives. We exploited the idea of crowding distance to better intensify the search as well as limiting the number of solutions in the non-dominated set.

Using three indicators, we compared the quality of solutions obtained with our MDLS

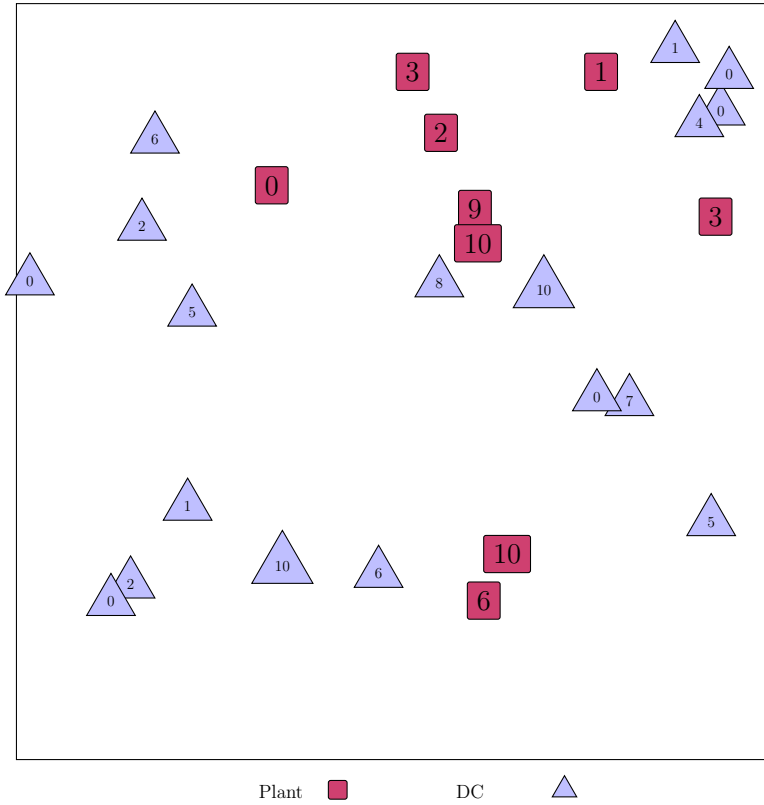


Figure 6: Number of occurrences of each facility location in all non-dominated solutions

425 procedure and those obtained with Cplex by solving the MILP model with the ε -constraint method. Our experiments show that the MDLS outperforms the ε -constraint method, and this outperformance becomes more obvious as the size of instances grows.

Sustainable SCND problems are complex in nature because they address the three dimensions of sustainable development. Our work could lead to many extensions and further
430 researches for a more comprehensive handling of economic, environmental as well as quantifiable social criteria by extending the procedures to multiple dimensions. For example, one may investigate the impact of the incentives offered by governments to promote the use of cleaner technologies. Another promising research direction is to analyse the complex nature of emissions considering aspects such as nonlinear tax rates, multivariate emission functions
435 and uncertainty (Waltho et al., 2019). The integration of social criteria such as the impact on employment or social life-cycle analysis would also lead to a challenging optimisation problem.

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