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A DECISION-MAKING MODEL TO DESIGN A SUSTAINABLE CONTAINER DEPOT LOGISTIC NETWORK: THE CASE OF THE PORT OF VALENCIA

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Abstract. In this paper, the design of a maritime container depot logistic network in a hinterland is studied. Containers are a basic tool in multimodal product transportation and all related operations have an impact on the environment due to different externalities such as noise, atmospheric and visual pollution. A three objective optimization model is used to minimize the total network cost, the environmental impact generated by the road transport operations associated with the depots (TI) and the environmental impact generated by the setting up and maintenance of the depots (FI). To determine the environmental impacts of each depot, Fuzzy Analytic Hierarchy Process (F-AHP) is used in both cases. In addition, a fuzzy multiobjective optimization approach has been used to solve the problem. The application case study is based on the Port of Valencia (Spain).

Keywords: environmental impact; sustainable supply chain management; reverse logistics; maritime transportation; container depots; fuzzy multiobjective optimization.

Introduction

Import and export operations have grown considerably in the last decades. Maritime containers have become a basic tool for these multimodal operations. In addition, containers are very useful due to their characteristics, such as standardization, flexibility and possibility of reuse. The latter is probably the most interesting characteristic of containers and what adds complexity to its management.

Before a container is reused, it needs some intermediate operations and a place to be stored. Since the storage capacity of ports is limited and, in many cases, the ports are far away from the shippers, it is necessary to store the empty containers somewhere so as to minimize time and costs of delivering the empty containers to the shippers who need them (Furió *et al.* 2013). However, in addition to cost effectiveness, there are other reasons for empty containers storage; for example, the import and export operations are not balanced or that the number of available containers in the world is double the total capacity of container vessels (Furió *et al.* 2006). For all these reasons, it is generally necessary to store empty containers in container depots.

Container depots are generally large ground extensions near ports or industrial areas where empty containers are stored waiting to be distributed to shippers. In addition, in these facilities different activities are performed, such as the cleaning and repairing of containers. These operations, as well as the container transport operations between shippers/consignees and depots, imply costs that companies try to minimize.

The concern for the environment, the inclusion of several factors in trying to estimate environmental impacts and the necessity to search for more sustainable networks, make the design of a logistic network more and more complex. For this reason, Decision Support Systems (DSSs) are increasing their importance as a suitable solution in this field. Thus, several researchers have designed DSSs for the operation, planning or design of container terminals (Murty *et al.* 2005; Harit *et al.* 1997; Van Hee, Wijbrands 1988). DSSs try to find out what would happen when making a series of decisions and then provide decisions or suggestions to managers. The main architecture of a DSS is similar to the 3-tier architecture of an Information System. This architecture was named DMM – Data, Dialog, Model – by Sprague and Watson (1995). We are going to focus our DSS de-

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scription on the intelligence component, i.e. the model tier, which is the base for helping the user to make more informed and effective decisions. Therefore, our aim is to model the design of a container depot network in a hinterland, by trying to decide the best location for each depot, and taking into account not only cost-related objectives but also the environmental impacts generated by the location and operation of the depots.

With regard to those environmental impacts, all the activities carried out in a depot as well as the containers' transportation have an impact on the surrounding area due to the factors such as greenhouse gas emissions, noise, wastewater (resulting from container cleaning) and other externalities. Thus, the setting up of a depot requires the use of heavy equipment that generates noise and atmospheric pollution, and increases the traffic congestion of the area. Moreover, a container depot logistic network generates a large amount of traffic due to the transportation trucks. Trucks' engines generate greenhouse gases with consequent effects on health and ecosystems, among other factors (Figliozzi 2011). But the main externalities generated by the road transport are: traffic congestion at peak times (which decreases overall productivity); the likelihood of accidents (road traffic causes over 1.2 million deaths each year worldwide (Toroyan, Peden 2009)); atmospheric pollution; noise pollution generated by the heavy traffic (which is partly responsible for the fact that nearly 80 million people in the European Union are exposed to noise levels exceeding the acceptable level of 65 dB (EC 1996)); visual pollution that alters the aesthetics of the rural and urban landscape, etc.

Obtaining data about the environmental impact generated by the transport operations and setting up and maintenance of the depots is a particularly difficult task. An alternative could be to use estimations of the marginal external costs of the transportation activity, such as those collected by Maibach *et al.* (2008) and Korzhenevych *et al.* (2014) under the auspices of the European Commission. These estimations could be included in a cost-based model, analysing the whole behaviour of the system. In this paper, however, a multiobjective optimization approach that makes the tradeoffs between the objectives more visible and explicit is proposed. Therefore, to handle these environmental impacts, a feasible way that could fit our goal, having so many different impact sources, has been found to be the use of a Fuzzy Analytic Hierarchy Process (F-AHP). In that way, the opinion of a number of experts is taken into account, summarizing all those heterogeneous effects.

It is noted that the flow capacity of a depot (i.e., the number of container movements it can handle per year) is an important factor when estimating the environmental impact generated by the transport operations carried out, and by the setting up and maintenance of the depot itself. It is as well a very important factor affecting the facility competitiveness. Do Ngoc and Moon (2011) developed a model for the decision of expanding a depot capacity, assuming the importance of operating at the correct size. Due to the difficulty of obtaining exact values for these flow capacities when designing a general network, we decided to consider them as fuzzy data. In this way, the flow capacity of depots is considered as a fuzzy constraint within the fuzzy multiobjective optimization approach used to solve the problem.

Summarizing, in this paper, a three objective fuzzy optimization approach based on the Multicommodity Capacitated Location Problem with Balancing Requirements (Crainic *et al.* 1989) is proposed. In order to identify the best container depot logistic network in a hinterland we aim not only to minimize the total cost of the network but also to minimize the total environmental impact generated by the transport operations associated with the depots network (TI) and the total environmental impact generated by the setting up and maintenance of those depots (FI).The proposed approach is applied to the case of the hinterland of the port of Valencia, Spain.

A previous work by the authors (Palacio *et al.* 2014) dealt with this type of container depot location problem by considering the environmental impacts on a single objective function. In that work, the authors used deterministic (i.e. without uncertainty) information both about the environmental impacts and depots' flow capacity. Under such circumstances the problem can be solved using the ε-constraints method and giving a Pareto frontier as a solution. This research improves upon that work by separately considering the environmental impacts of the setting up and maintenance of a depot from those of its operation, thus removing the need to aggregate them (something which required the use of a parameter for weighing the values of both impacts). In addition, uncertainties in the estimation of the environmental impact and low capacities data have been taken into account, thus increasing the realism and applicability of the solution approach. Finally, the use of a fuzzy multiobjective optimization approach leads to determining a single solution instead of a collection of potential solutions (Zimmermann 1978).

1. Literature Review

The depot location problem appears when deciding what to do with empty containers once consignees have downloaded their wares from the containers that have arrived from a port. This problem, known in the literature as the Multicommodity Capacitated Location Problem with Balancing Requirements (MCLB), was initially studied by Crainic *et al.* (1989). The following authors used several techniques to solve the problem such as branch and bound (Crainic *et al.* 1993a; Gendron, Crainic 1995, 1997; Bourbeau *et al.* 2000), tabu search (Crainic *et al.* 1993b) or goal programming (Badri 1999). Crainic *et al.* (1993a) did not find an optimal solution in a reasonable time using branch-and-bound and showed that standard methods are not efficient for this problem.

Similarly, Gendron *et al.* (2003a) showed that problems with a large number of variables of the MCLB could not be solved by mixed-integer programming solvers at that time. They combined slope scaling and tabu search and obtained good solutions. Representing N as the set of nodes and A as the set of arcs, they considered a network $G = (N, A)$ with two kind of nodes, the customers and the depots, with the arcs representing the existence of flows between these nodes. They minimized the total cost of the problem, satisfying the demand of each node. Gendron *et al.* (2003b) used a parallel hybrid heuristic for solving the MCLB problem.

More recently, Palacio *et al.* (2014) designed a model to find the best location for a container depot by considering the minimization of the total environmental impact as an additional objective function. They solved the problem using the ε-constraints method, obtaining a Pareto frontier, but they could not determine to what extent the environmental impact generated by the depots themselves is relevant for the final location within the network.

Apart from the above container depot location papers, there are a number of research works on empty container management in the literature. Thus, for example, Li *et al.* (2004) showed that there exists an optimal (U, D) policy for the management of empty containers in a port with stochastic demand. If there are fewer than U containers they are imported up to U but if there are more than D they are exported down to D. They also used multi-ports applications. Similarly, Dong and Song (2009) considered multi-vessel, multi-port and multi-voyage shipping systems with uncertain and unbalanced demands. They used Genetic Algorithms and Evolutionary Strategies to solve their problem. Other authors (Mittal *et al.* 2013) focused on the demand uncertainty characteristic of the problem when locating depots, while Boile *et al.* (2008) applied their model for location of new container depots and the repositioning of empty containers to the New York-New Jersey port region, based on the idea of building them close to customer clusters. Braekers *et al.* (2011) presented a good review about planning models for the empty container repositioning problem, focusing not only on strategic and tactical decisions (what was the most common approach in the first researches), but also on planning models dealing at strategic, tactical and operational levels.

It is important to note that all these papers only consider one objective, namely the minimization of the total cost of the logistic network. In this paper two additional objective functions are considered: the environmental impact generated by the setting up and maintenance of the depots (TI) and the impact generated by the transport operations associated with the depots (FI).

2. Problem Modelling

As mentioned before, the goal of this work is to design a container depot logistic network that minimizes the total cost of the system, the environmental impact generated by the transport operations associated to this network, and the environmental impact generated by the setting up and maintenance of the depots in the network. In this way, a crisp optimization model can be designed by extending the model proposed by Gendron *et al.* (2003a, 2003b) by introducing two new objective functions and considering three kinds of nodes instead of two: depots, terminals and shippers/consignees. The decision variables are a set of binary variables (that determine whether to open a depot) plus some continuous variables (to define the empty container flows). The notation for this model is shown in Table 1.

Table 1. Notation for model parameters and variables

Data	
T	– set containing all terminals in the system under study
D	– set containing all depots in the system under study
S	– set containing all shippers in the system under study
R	– set containing all consignees in the system under study
$S(t)$	– subset of shippers that can be supplied from terminal t
$R(t)$	– subset of consignees that can send empty containers to terminal t
$D(t)$	– depots that work with terminal t
$S(d)$	– subset of shippers that can be supplied from depot d
$R(d)$	– subset of consignees that can send empty containers to depot d
$T(d)$	– terminals that work with depot d
$D(r)$	– depots where consignee r can send its empty containers
$T(r)$	– terminals where consignee r can send its empty containers
$D(s)$	– depots that can send empty containers to shipper s
$T(s)$	– terminals that can send empty containers to shipper s
I_{rt}	– containers imported by consignee r through terminal t every year
E_{st}	– containers exported by shipper s through terminal t every year
K_d	– flow capacity limit of depot d
K_t	– flow capacity limit of terminal t
C_d	– storage capacity of depot d
f_d	– fixed operation cost of depot d
c_{rt}	– unit transport cost between consignee r and terminal t
c_{ts}	– unit transport cost between terminal t and shipper s
c_{rd}	– unit transport cost between consignee r and depot d
c_{ds}	– unit transport cost between depot d and shipper s
c_{td}	– unit transport cost between terminal t and depot d
w_d	– environmental impact per unit flow from/to depot d
v_d	– environmental impact per stored unit in depot d
Decision variables	
x_{rt}	– container flow from consignee r to terminal t
x_{ts}	– container flow from terminal t to shipper s
x_{rd}	– container flow from consignee r to depot d
x_{ds}	– container flow from depot d to shipper s
x_{td}	– container flow from terminal t to depot d
x_{dt}	– container flow from depot d to terminal t
δ_d	– binary variable that indicates if depot d opens or not

$$\min \sum_d f_d \delta_d + \sum_r \sum_{t \in T(r)} c_{rt} x_{rt} + \sum_t \sum_{s \in S(t)} c_{ts} x_{ts} + \sum_t \sum_{d \in D(t)} c_{td} \left(x_{td} + x_{dt} \right) + \sum_r \sum_{d \in D(r)} c_{rd} x_{rd} + \sum_d \sum_{s \in S(\mathrm{d})} c_{ds} x_{ds}; \quad (1)$$

$$\min 2 \sum_d w_d \left(\sum_{r \in R(d)} x_{rd} + \sum_{t \in T(d)} x_{td} \right); \quad (2)$$

$$\min \sum_d C_d v_d \delta_d \quad (3)$$

subject to:

$$\sum_{r \in R(t)} x_{rt} + \sum_{d \in D(t)} x_{dt} + \sum_s E_{st} = \sum_{s \in S(t)} x_{ts} + \sum_{d \in D(t)} x_{td} + \sum_r I_{rt} \ \forall t \in T; \quad (4)$$

$$\sum_{r \in R(d)} x_{rd} + \sum_{t \in T(d)} x_{td} = \sum_{s \in S(d)} x_{ds} + \sum_{t \in T(d)} x_{dt}, \ \forall d \in D; \quad (5)$$

$$\sum_{t \in T(r)} x_{rt} + \sum_{d \in D(r)} x_{rd} = \sum_{t \in T(s)} I_{rt}, \ \forall r \in R; \quad (6)$$

$$\sum_{t \in T(s)} x_{ts} + \sum_{d \in D(s)} x_{ds} = \sum_{t \in T(s)} E_{st}, \ \forall s \in S; \quad (7)$$

$$\sum_{r \in R(t)} x_{rt} + \sum_{d \in D(t)} x_{dt} + \sum_{s \in S(t)} x_{ts} + \sum_{d \in D(t)} x_{td} \le K_t, \ \forall t \in T; \quad (8)$$

$$2 \left(\sum_{r \in R(d)} x_{rd} + \sum_{t \in T(d)} x_{td} \right) \le K_d \delta_d, \ \forall d \in D \quad (9)$$

$\delta_d \in \{0,1\}, \ \forall d \in D$ all other variables non-negative. (10)

The total cost of the network is considered in the first objective function: the first term is the setting up and maintenance cost of the depots; the second term is the total cost of the container movements between each shipper/consignee and terminal; the third term is the total cost of the container movements between each terminal and depot, and the last term is the total cost of the container movements between each shipper/consignee and depot. In the second objective function the total impact associated with the container movements from/to each depot is considered. The coefficient (2) comes from the fact that, as imposed by constraints (5), the total number of movements of empty containers into a depot is equal to the total number of movements out of that depot. Hence, the sum of inward and outward movements is two times the number of inwards movements. The last objective function is associated with the total impact generated by the maintenance and setting up of each depot.

Regarding the seven blocks of constraints, constraints (4) and (5) guarantee that the number of containers arriving at a terminal or depot is equal to the number of containers that leave that same terminal or depot; constraints (6) and (7) ensure that each container imported or exported by a consignee/shipper is stored or received from a depot or a terminal; constraints (8) and (9) guarantee that the number of container movements in a terminal or a depot does not exceed the container movement capacity of that terminal or depot. Note that constraints (9) use a coefficient 2 for the same reason that objective function (2), i.e. because the total flow into/from a depot is two times the inward flow. Finally, constraint (10) imposes that variables δ_d are binary.

Regarding constraint (9), we note that the flow capacity of a depot is not actually an exact number so that a parameter τ is needed that determines by how much the capacity of a depot can potentially be increased from its nominal value. In that way and to use a fuzzy multiobjective optimization approach, a new constraint is introduced to replace constraint (9). Thus, constraint (9′) imposes that there cannot be container movements to/from a depot when it is not open:

$$2 \left(\sum_{r \in R(d)} x_{rd} + \sum_{t \in T(d)} x_{td} \right) \le \tau K_d \delta_d, \ \forall d \in D. \quad (9')$$

A reasonable value for parameter τ may be, for example, τ=1.15; that means the flow of each depot can rise up to a limit 15% above its nominal capacity.

Let λ_1 be the cost membership function, λ_2 the environmental impact generated by the transport operations membership function and λ_3 the environmental impact generated by the setting up and maintenance of the depots membership function. Denoting the three objective functions (1) to (3) as $f_i(x,\delta)$, $i = 1, 2, 3$ the proposed fuzzy multiobjective model is:

$$\max \sum_{i=1}^{3} \lambda_i \quad (11)$$

subject to:

$$\lambda_i \le \frac{z_i^+ - f_i(x,\delta)}{z_i^+ - z_i^-}, \ \forall i = 1, \ldots, 3; \quad (12)$$

$$\gamma_d \le \frac{\tau K_d - g_d(x,\delta)}{(\tau - 1) \cdot K_d}, \ \forall d. \quad (13)$$

Constraints (4)–(8), (9′), (10):

$\delta_d \in \{0,1\}, \ \forall d$;

$\lambda_i, \gamma_d \in [0,1]$, $\forall i$, $\forall d$ and all variables non-negative, (14)

where: $g_d(x,\delta)$ is the left hand side of constraint (9'); z_i^- is the optimal objective function value of the model min $f_i(x,\delta)$ subject to (4)–(8), (9'), (10) for i = 1, …, 3; z_i^+ is the optimal objective function value of the model max

$f_i(x,\delta)$ subject to (4)–(8), (9'), (10) for i = 1, …, 3. In other words, z_i^- and z_i^+ are, respectively, the minimum and maximum values of the i-th objective function when it is optimized separately. Note that in this model the three objectives have been assigned the same importance. To assign different importance to the objectives some constraint prioritizing the membership functions λ_i can be introduced. For example, if cost minimization is given no less importance than the other two objectives, then these constraints should be added $\lambda_1 \geq \lambda_2$ and $\lambda_1 \geq \lambda_3$.

The optimal solution of the above model $\left(x^*,\delta^*,\lambda_1^*,\lambda_2^*,\lambda_3^*,\gamma^*\right)$ has an associated cost $f_1\left(x^*,\delta^*\right)$, an associated environmental impact generated by the transport $f_2\left(x^*,\delta^*\right)$ and an environmental impact generated by the setting up and maintenance of the depots $f_3\left(x^*,\delta^*\right)$. With these three values and changing in the model above the objective function $\max\sum_{i=1}^{3}\lambda_i$ by $\max\sum_{d}\gamma_d$ and replacing constraints (12) by new constraints imposing that the values of the three objectives cannot be worse than those computed before, i.e. $f_i\left(x,\delta\right) \leq f_i\left(x^*,\delta^*\right)$, the model is solved again giving the final solution. This second phase, once the optimal objective function values have been determined, aims at maximizing the membership function values of the different flow capacity constraints. This makes the solution to balance the empty container flows so that these exceed the nominal capacity of the depots at the minimum.

3. Application to the Hinterland of Valencia

The above model was developed for the port of Valencia, one of the largest ports on the Mediterranean Sea and the most important container port in Spain. It offers a network of regular, transoceanic and regional connections with major ports around the world and in 2010 its maritime container traffic reached 4.21 million TEUs (Twenty-foot Equivalent Unit, the capacity unit of a standard container of 20 feet) (Valenciaport 2010).

Currently, the logistic network of the hinterland of Valencia includes eight empty container depots. These depots have a flow capacity between 50000 and 125000 container movements per year and a storage capacity between 1000 and 14000 containers. To improve the design of this logistic network an additional set of potential depot locations have been considered. Thus, based on the distribution of the shippers/consignees that must be serviced, 11 potential new depot locations have been selected. As experimental data for these potential depots, a nominal flow capacity of 95000 container movements per year and a storage capacity of 8800 containers was designed (Table 2).

Another factor to consider in the problem is the fixed cost of each depot and the cost per flow unit. Considering raw data coming from the real port used in this research, it was estimated that a depot with a flow capacity of 250000 containers per year has an operating cost of €1000000. Therefore, in this case study, proportional values according with the flow capacities of each

Table 2. Depot data

Depot	Location	Capacity	% of shippers within 50 km	Road distance to port [km]
1	Riba-Roja de Turia	125000	26.89	30.5
2	Náquera	50000	28.01	40.2
3	Alfafar	125000	30.53	12.5
4	Quart de Poblet	112500	29.13	15.7
5	Castellar	20000	29.97	6.5
6	Sagunto	95000	28.01	33.4
7	Port of Alicante	50000	18.21	172.0
8	Port of Cartagena	125000	7.56	273.0
9	Almussafes*	95000	32.49	25.7
10	Onda*	95000	12.32	75.0
11	L'Alcora*	95000	9.52	86.9
12	Albal*	95000	31.09	15.0
13	Villarreal*	95000	11.48	68.4
14	Novelda*	95000	17.65	155.0
15	Jumilla*	95000	3.36	161.0
16	Requena*	95000	3.08	77.2
17	Murcia*	95000	21.01	232.0
18	Ibi*	95000	24.37	126.0
19	Chiva*	95000	27.17	39.5

Note: * indicates potential location of depots not currently in operation, all of them with the same theoretical capacity.

depot are considered. Regarding the cost per flow unit, the distance between all the pairwise nodes has been calculated and multiplied by the unit cost per km of a standard container transport vehicle, which is estimated as 1.152 €/km (Ministerio de Fomento 2012).

4. Impact Estimation Using F-AHP

Due to the difficulty of obtaining quantitative environmental impact data, they have been estimated using F-AHP methodology. Triangular fuzzy numbers were used for making comparisons between each of the different alternatives considered, transforming the consensus fuzzy matrix into a crisp one by using the method proposed by Kwong and Bai (2003). This method is used to obtain the environmental impact data associated with the transportation operations w_d and with the setting up and maintenance v_d of each depot needed in the model. Five externalities associated with the environmental impact generated by the transport operations (atmospheric, visual and noise pollution, traffic congestion and likelihood of accident) have been considered. Six experts from the Port of Valencia were asked for their assessment of the environmental impact generated by the empty container transport.

The first step was to ask each expert to define a fuzzy matrix representing the pairwise comparisons of those five externalities. Matrices consistence was checked as well as the degree of consensus between those experts, using the procedure introduced by Bryson (1996). The consensus matrix was calculated using the geometric mean of each component of the triangular fuzzy numbers provided by each expert. Using the formulation proposed by Kwong and Bai (2003), this matrix was transformed into a crisp one, and to be sure that this transformation had not lost the matrix consistence, the final crisp matrix consistence was checked as well. Finally, to determine the normalized impact per flow unit generated by the transport operations of each potential depot location, three levels (low, medium, high) for each externality were considered and by using a 'ratings mode' the decision table was obtained. The calculation of this normalized impact per flow unit at each depot location is shown in Table 3.

On the other hand, for the impact generated by the setting up and maintenance of each depot, three externalities were considered: the setting up impact, the visual impact and the operations impact. Again, the normalized fixed impact per stored unit in each depot was calculated using the geometric mean of the expert assessments and the decision table using the 'ratings mode' as shown in Table 4.

5. Results

The model was programmed in LINGO. The maximum and minimum of the three objectives were previously calculated separately. The minimum cost of the network is 1212.98 (in thousand €) and the maximum

Table 3. Calculation of the normalized impact per flow unit for each depot

Depot	Atmospheric (0.1193)		Noise (0.5435)		Visual (0.0464)		Traffic (0.1247)		Likelihood of accidents (0.1661)		Total impact (w_d)
1	*M*	0.464	*M*	0.333	*M*	0.464	*H*	1.000	*M*	0.333	0.438
2	*L*	0.215	*M*	0.333	*M*	0.464	*L*	0.215	*L*	0.111	0.273
3	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	1.000
4	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	1.000
5	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	1.000
6	*M*	0.464	*M*	0.333	*L*	0.215	*L*	0.215	*H*	0.333	0.329
7	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	*H*	0.333	0.889
8	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	*H*	0.333	0.889
9	*M*	0.464	*M*	0.333	*M*	0.464	*H*	1.000	*H*	0.333	0.438
10	*M*	0.464	*M*	0.333	*M*	0.464	*H*	1.000	*H*	0.333	0.438
11	*M*	0.464	*M*	0.333	*L*	0.215	*H*	1.000	*H*	0.333	0.427
12	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	1.000
13	*M*	0.464	*M*	0.333	*M*	0.464	*H*	1.000	*H*	0.333	0.438
14	*M*	0.464	*M*	0.333	*L*	0.215	*M*	0.464	*H*	0.333	0.360
15	*M*	0.464	*M*	0.333	*M*	0.464	*L*	0.215	*H*	0.333	0.340
16	*M*	0.464	*M*	0.333	*M*	0.464	*M*	0.464	*H*	0.333	0.371
17	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	*H*	1.000	1.000
18	*M*	0.464	*M*	0.333	*L*	0.215	*M*	0.464	*H*	0.333	0.360
19	*M*	0.464	*M*	0.333	*M*	0.464	*M*	0.464	*H*	0.333	0.371

Notes: L – low, *M* – medium, *H* – high.

Table 4. Calculation of the normalized fixed impact per stored unit in each depot

Depot	Setting up impact (0.20)		Visual impact (0.08)		Operations impact (0.72)		Total impact (v_d)
1	*L*	0.215	*M*	0.464	*M*	0.333	0.320
2	*H*	1.000	*L*	0.215	*L*	0.111	0.297
3	*H*	1.000	*H*	1.000	*H*	1.000	1.000
4	*L*	0.215	*M*	0.464	*H*	1.000	0.800
5	*M*	0.464	*H*	1.000	*H*	1.000	0.893
6	*M*	0.464	*M*	0.464	*M*	0.333	0.370
7	*M*	0.464	*H*	1.000	*H*	1.000	0.893
8	*M*	0.464	*H*	1.000	*H*	1.000	0.893
9	*M*	0.464	*M*	0.464	*M*	0.333	0.370
10	*H*	1.000	*M*	0.464	*M*	0.333	0.477
11	*H*	1.000	*L*	0.215	*M*	0.333	0.457
12	*M*	0.464	*H*	1.000	*H*	1.000	0.893
13	*L*	0.215	*H*	1.000	*M*	0.333	0.363
14	*H*	1.000	*L*	0.215	*M*	0.333	0.457
15	*H*	1.000	*L*	0.215	*M*	0.333	0.457
16	*H*	1.000	*L*	0.215	*M*	0.3333	0.457
17	*M*	0.464	*H*	1.000	*H*	1.000	0.893
18	*H*	1.000	*M*	0.464	*M*	0.333	0.477
19	*M*	0.464	*L*	0.215	*M*	0.333	0.350

Notes: L – low, *M* – medium, *H* – high.

cost 9614.51. Regarding the environmental impacts, the minimum and maximum value for the transport operations were 10305.11 and 48854.9 respectively, and for the setting up and maintenance of the network were 774.13 and 3820.06 respectively. These values define the membership functions of our model (Fig. 1).

Once the three objective function membership functions have been determined, the fuzzy multiobjective optimization model of section 2 can be solved. In order to analyse the model performance more deeply, five cases were considered, depending on the different importance given to the three different objective function memberships:

- *Case 1:* The problem was run for the current situation in the hinterland of Valencia, i.e., we imposed that the open depots are just the existing eight depots (1–8). We can thus obtain the current cost and environmental impacts for further benchmarking.
- *Case 2:* The problem was solved without any restriction on the importance of the three objective functions, i.e., the three objectives are considered to have the same importance.
- *Case 3:* The problem was solved by giving more importance to the cost function than to the impact functions. Six different situations are considered depending on the relationship among the three objectives (cost more important than TI and FI; cost more important than TI and TI more important than FI; cost more important than FI and FI more important than TI; cost 2 times more important than TI and FI; cost 3/2 times more important than TI and TI 3/2 more important than FI; and cost 3/2 times more important than FI and FI (3/2) times more important than TI).
- *Case 4:* The problem was solved by giving more importance to the environmental impact generated by the transport operations than to the cost, and the setting up and maintenance impact. Again six different situations are considered (changing in the previous description the roles of cost and TI).
- *Case 5:* The problem was solved by giving more importance to the environmental impact generated by the setting up and maintenance of the depots than to the cost and transport operations impact. Again six different situations are considered (changing in the description of Case 3 the roles of cost and FI).

All the results can be seen in Table 5 and Fig. 2.

Results for Case 1. Considering the case that the currently operative depots are the only ones that are open, the solution computed by the model would have a cost of 1796.30 (in thousand €). The total impact generated by the transport operations would be 20584.66 and the total impact generated by the setting up and maintenance of the depots 1830.56. We are going to use this solution to make comparisons with the solutions found in every other case.

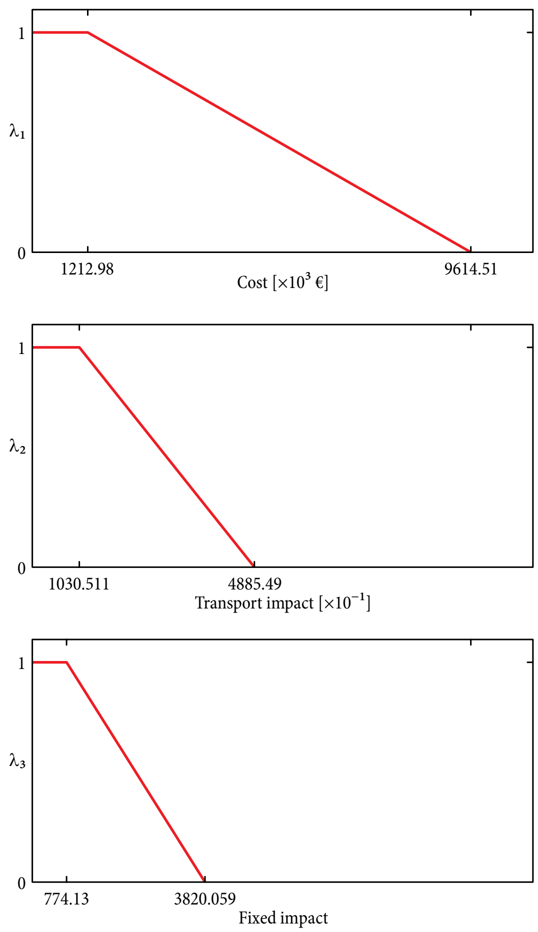

Fig. 1. Objective function membership functions

Results for Case 2. In this case all the objectives are considered with the same weight. This solution (Table 5) dominates the current situation, improving the cost by about 16% and TI and FI by about 50%. It opens new potential locations and closes some depots in the current situation.

Results for Case 3. In this case we consider that the cost objective has more importance than the other two objectives. Six subcases are explored (Table 5). The first two subcases have the same solution. This solution is similar to that of case 2, but opening depot 18 instead of depot 14. It is much better than the current situation, as it improves the three objective functions. The third subcase opens exactly the same depots as case 2 and also improves the current situation in all the objectives. The fourth subcase, in which the cost function is considered to be much more important than the other two, achieves the best cost value but obtains similar impact values as the current solution. Maintaining almost the same cost value of subcase 4, TI and FI can still be improved by about 16% in subcases 5 and 6 (Table 5).

Results for Case 4. Now, the most important objective is TI. In the first three subcases the solution obtained is the same as in case 2. The other three subcases open the same depots, but one of them dominates the other two. This solution improves the impact values of the current solution but almost doubles the cost value. It is important to note that this solution achieves the best possible transport impact values of all the solutions found.

Results for Case 5. In the last case of this study the most important objective is FI. The first three subcases

Table 5. Experimental results (dominated solutions by others in this set are shadowed; only 7 non-dominated solutions are found)

Sol. No.		Open depots 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Cost	Transport impact	Fixed impact	Objectives' importance
1	Case 1	1	1	1	1	1	1	1	1												1796.30	20584.66	1830.558	
2	Case 2		1				1	1		1				1	1	1				1	1515.58	11331.76	880.982	
3	Case 3		1				1	1		1				1		1			1	1	1490.22	11577.22	887.986	$\lambda_1>\lambda_2$; $\lambda_1>\lambda_3$
4			1				1	1		1				1		1			1	1	1490.22	11577.22	887.986	$\lambda_1>\lambda_2>\lambda_3$
5			1				1	1		1				1	1	1				1	1509.47	11665.51	880.982	$\lambda_1>\lambda_3>\lambda_2$
6		1	1		1			1		1		1	1	1		1		1	1		1212.98	25109.12	1981.064	$\lambda_1>2\lambda_2$; $\lambda_1>2\lambda_3$
7		1	1		1			1		1		1		1		1		1	1		1214.37	20825.47	1666.787	$\lambda_1>(3/2)\lambda_2;\lambda_2>(3/2)\lambda_3$
8		1	1		1			1		1		1		1		1		1	1		1214.37	20825.47	1666.787	$\lambda_1>(3/2)\lambda_3;\lambda_3>(3/2)\lambda_2$
9	Case 4		1				1	1		1				1	1	1				1	1515.58	11331.76	880.982	$\lambda_2>\lambda_1$; $\lambda_2>\lambda_3$
10			1				1	1		1				1	1	1				1	1515.58	11331.76	880.982	$\lambda_2>\lambda_1>\lambda_3$
11			1				1	1		1				1	1	1				1	1515.58	11331.76	880.982	$\lambda_2>\lambda_3>\lambda_1$
12			1				1					1			1	1	1		1	1	4111.82	10305.11	1077.079	$\lambda_2>2\lambda_1$; $\lambda_2>2\lambda_3$
13			1				1					1			1	1	1		1	1	3536.97	10305.11	1077.079	$\lambda_2>(3/2)\lambda_1;\lambda_1>(3/2)\lambda_3$
14			1				1					1			1	1	1		1	1	3788.81	10305.11	1077.079	$\lambda_2>(3/2)\lambda_3;\lambda_3>(3/2)\lambda_1$
15	Case 5		1				1	1		1				1	1	1				1	1509.50	11657.50	880.982	$\lambda_3>\lambda_1$; $\lambda_3>\lambda_2$
16			1				1	1		1				1	1	1				1	1509.50	11665.10	880.982	$\lambda_3>\lambda_1>\lambda_2$
17			1				1	1		1				1	1	1				1	1509.50	11657.50	880.982	$\lambda_3>\lambda_2>\lambda_1$
18		1	1			1	1	1		1				1						1	3390.70	14049.43	774.126	$\lambda_3>2\lambda_1$; $\lambda_3>2\lambda_2$
19		1	1			1	1	1		1				1						1	3616.43	14043.86	774.126	$\lambda_3>(3/2)\lambda_1;\lambda_1>(3/2)\lambda_2$
20		1	1			1	1	1		1				1						1	3176.32	14022.98	774.126	$\lambda_3>(3/2)\lambda_2;\lambda_2>(3/2)\lambda_1$

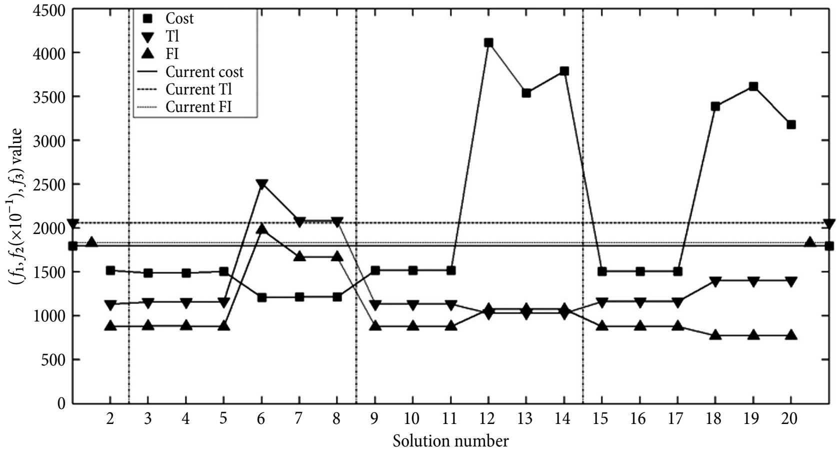

Fig. 2. Graphical representation of the objective function values of the 20 solutions found for the five cases considered

open the same depots. However, the second subcase is dominated by the other two, which have a lower TI value. This solution dominates the current one, with TI and FI values about 50% lower. The last three subcases also open the same depots but the last one dominates the other two. Moreover, this solution achieves the best possible FI function value of all the solutions found. This value improves the current fixed impact by 57.71% but with a big increase in the cost function value.

Regarding the question of which depots are open, note that depot 2 is always open in all the solutions found in these five cases while depots 3, 8 (both currently open) and 10 are not open in any solution. It is also important to mention that in the majority of the cases considered, the number of open depots is eight. Only the cases in which the cost function is considered much more important than the other two, is the number of depots opened increased to ten or eleven. This last case, in which eleven depots are open, is the one which achieves the best cost value for this case study.

As mentioned above, Palacio *et al.* (2014), using the ε-constraints method and considering just one aggregated environmental impact function and a more deterministic scenario, had computed different Pareto efficient sets of solutions. In order to compare the results from this paper with those solutions, we have taken their set of solutions corresponding to the parameter case in which the TI and the FI are similar and have evaluated it with the model of section 2. The results obtained are shown in Table 6.

Note that only 5 out of the 25 from Palacio *et al.* (2014) are non-dominated solutions. This reduction simplifies the decision making. If we compare these five solutions with the current situation, we obtain that they significantly improve the current one, as it can be seen from Table 7.

6. Discussion

From the results of the experiments, it has been observed that giving much more importance to one of the objectives than to the other two (subcases 4, 5 and 6) leads to the best value of the corresponding objective function at the expense of introducing a big penalty in the other two objective function values. In this way, if we pretend to obtain a balanced solution from the point of view of all three objectives, this option is not appropriate. Only if we truly want to focus our study on one main objective will this weighting scheme make sense. However, as the results of this case study show, these solutions do not generally dominate the current situation.

Attending to the non-dominated solutions obtained in the different cases and discarding the solutions that achieve the best value for one of the objective functions (due to the penalty in the other two objectives), only two depots selections were found to be solutions for the problem. These sets of open depots include three of the current depots (namely 2, 6 and 7) and five of the new potential sites (namely 9, 13, 14 or 18, 15 and 19). All these solutions completely dominate the current situation, clearly showing that it is inefficient especially as regards its environmental impacts, which can be improved by about 50%.

As mentioned above, considering all the non-dominated solutions, it has been found that depot 2 should always be open while depots 3, 8 and 10 should never be open. Regarding depots 3 and 8, the main reason for not being selected is because they have a very high fixed impact and the area where they are located also has a high TI value. On the other hand, depot 10 does not open because it is near depot 13 which is open for almost every solution and has a lower FI value. Depot 2 opens for every solution due to its good location and low TI and FI values.

It is worth noting that only in the case in which more importance is given to the environmental impact generated by the depots than to the other two objectives, more currently open depots than new depots are selected. This must be due to the fact that the currently open depots are in big industrial areas, so their FI is lower than others that can be opened in other, more populated areas.

As regards the solutions from Palacio *et al.* (2014), when evaluated with the model in section 2, we find that the current total cost of the system can be reduced by between 16.4% and 19.4%, TI between 44.34% and

47.54% and FI between 39.78% and 44.03%. It is interesting to note that one of the five non-dominated solutions obtained with the results of Palacio *et al.* (2014) opens just two of the eight current operative depots (namely 1 and 2) while it opens up to six of the new potential sites (namely 9, 11, 13, 14, 15 and 18). It can also be seen that these solutions achieve better cost results than the non-dominated solution found in the five cases studied. These solutions, however, are outperformed in terms of their FI values.

Table 6. Cost and impacts of the 25 solutions found by *Palacio et al.* (2014) evaluated with the model of section 2 (dominated solutions are shadowed)

Sol. No.	Open depots																			Cost	Transport impact	Fixed impact
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19			
*R*1	1			1		1	1		1		1	1	1		1		1	1		1566.39	11580.70	2099.40
*R*2	1			1		1	1		1		1		1		1		1	1	1	1562.66	11438.45	1908.35
*R*3	1			1		1	1		1		1		1		1		1	1		1551.19	11580.70	1785.13
*R*4	1	1				1	1		1		1	1	1		1		1	1		1553.09	11207.73	1733.59
*R*5	1	1			1	1	1		1		1		1		1		1	1	1	1561.37	11061.49	1578,25
*R*6	1	1				1	1		1		1		1		1		1	1	1	1553.37	11061.49	1542.53
*R*7	1	1				1	1		1		1		1		1		1	1		1537.89	11207.73	1419.31
*R*8	1	1					1		1		1		1		1		1	1		1524.39	11719.42	1289.08
*R*9	1	1				1	1		1		1				1		1	1		1537.08	11191.10	1291.50
*R*10	1	1				1	1		1				1		1		1	1		1542.71	11241.13	1258.36
*R*11	1	1				1			1		1				1		1	1		1527.08	11191.10	1255.79
*R*12	1	1				1			1		1			1	1		1			1500.17	11191.10	1248,79
*R*24	1	1				1			1				1		1		1	1		1532.71	11241.13	1222.65
*R*13	1	1				1			1				1	1	1		1			1505.79	11241.13	1215.65
*R*25	1	1				1							1		1		1	1	1	1606.53	10949.20	1215.65
*R*26	1	1				1							1	1	1		1		1	1581.63	10949.20	1208.64
*R*16	1	1				1	1		1		1		1		1			1		1522.69	11207.73	1105.03
*R*17	1	1					1		1		1		1		1			1	1	1526.08	11515.81	1098.03
*R*18	1	1				1	1		1		1				1			1	1	1535.20	11044.54	1100.45
*R*19	1	1							1		1		1	1	1			1		1447.88	11457.10	1100.04
*R*20	1	1				1			1		1			1	1			1		1464.47	10964.97	1102.46
*R*21	1	1				1			1				1	1	1			1		1471.86	11013.44	1069.32
*R*27		1			1	1			1				1	1	1			1	1	1498.54	10799.46	1048.93
*R*23	1	1				1							1	1	1			1	1	1502.91	10842.77	1062.32
*R*28	1	1				1			1				1	1	1				1	1501.71	11107.92	1024.59

Table 7. Percent improvement of the five non-dominated solutions with respect to the current situation

Sol. No.	Open depots																			Cost	%	Transport impact	%	Fixed impact	%
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19						
Case 1	1	1	1	1	1	1	1	1												1796.30	–	20584.66	–	1830.56	–
*R*19	1	1							1		1		1	1	1			1		1447.88	19.40	11457.10	44.34	1100.04	39.91
*R*20	1	1				1			1		1			1	1			1		1464.47	18.47	10964.97	46.73	1102.46	39.78
*R*21	1	1				1			1				1	1	1			1		1471.86	18.07	11013.44	46.50	1069,32	41.59
*R*27		1			1	1			1				1	1	1			1	1	1498.54	16.58	10799.46	47.54	1048.93	42.70
*R*28	1	1				1			1				1	1	1				1	1501.71	16.40	11107.92	46.04	1024.59	44.03

Conclusions

Designing a container depot network is a work that has not been widely addressed as a multiobjective problem. In this paper a three-objective, fuzzy optimization model is defined to find the best location for empty container depots in a hinterland. These objectives are the total cost of the network, the environmental impact generated by the transport operations associated with the depots, and the environmental impact generated by the setting up and maintenance of the depots. Due to the difficulty of obtaining impact data F-AHP was used to estimate, based on experts' judgement, the unit environmental impacts of the different depot locations. Also, as some of the data needed to have a certain degree of uncertainty, fuzzy constraints for the flow capacities of the depots were considered. The proposed approach was applied to the case of the hinterland of Valencia.

Regarding the results obtained in solving the multiobjective fuzzy optimization model without imposing which depots must be open, in all the cases studied at least one of the objectives improved the current situation. Moreover, a few solutions that improve the current situation in all three objectives were found. In these solutions the cost function can achieve around 17% improvement, the environmental impact generated by the transport operations (TI) around 45% improvement and the environmental impact generated by the depots themselves (FI) 50% improvement.

Regarding the results obtained imposing which depots must be open, it was found that only five of the 25 solutions from Palacio *et al.* (2014) are non-dominated. These solutions can improve the current one for each objective by around 17%, 45% and 40% respectively. Therefore, solving the problem with fuzzy multiobjective optimization reduces the number of alternatives than when obtaining the Pareto frontier with the ε-constraints method. In this way, we can reduce the 25 solutions found in Palacio *et al.* (2014) to only seven solutions that dominate the current situation: five from Palacio *et al.* (2014) plus two new solutions obtained by solving the model in section 2 without imposing which depots must be open.

Also, it can be seen that, in general, the solutions found tend to open more new locations than to preserve the currently open depots, indicating that the current container depot network in the hinterland of Valencia can significantly improve its overall performance.

It should be taken into account that this study has some limitations when talking about the estimation of the environmental impact. The opinions of the panel of experts consulted in order to obtain environmental impact data is a subjective method. Probably a method such as Life Cycle Assessment (see, e.g., Guinée 2002), is a more objective one to estimate the data but also involves an expensive and more difficult process. Also, multimodal transportation could be considered as a future research topic, adding higher complexity to the model. As indicated by one of the reviewers, the use of double container loads in the logistics of containers (e.g. Lai *et al.* 2013) is getting more and more common. It would be interesting to extend the proposed approach to this type operation.

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