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Redesigning a food bank supply chain network, Part II: Computational study

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Abstract

In Martins et al. (2016), we proposed a novel mixed-integer linear programming model to redesign a multi-echelon food bank supply chain network over a multi-period planning horizon. The three dimensions of sustainability, i.e. economic, environmental and social goals, were addressed by considering three conflicting objective functions in the model. In the present paper, which we refer to as Part II, we refine the mathematical formulation and present a computational study conducted on a set of test instances that reflect the characteristics of the food bank network managed by the Portuguese Federation of Food Banks in the south of Portugal. The trade-offs that occur under the three conflicting objectives are evaluated for a subset of non-dominated solutions obtained with lexicographic ordering. The insights drawn from several comparative analyses also contribute to a better understanding of the impacts of food collection and distribution.

Keywords: Food rescue and delivery, sustainability, supply chain network design, tri-objective problem, social impact, economic and environmental performance

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Contents

1. Model refinement

In this section, we describe the refinements introduced in our previously developed mixed-integer linear programming (MILP) formulation (see Martins et al. (2016)). They aim to represent more accurately the characteristics of the network of food banks managed by the Portuguese Federation of Food Banks (FPBA). The complete formulation is presented in Appendix A. In the following, we will adopt the same numbering for the objective functions and the constraints as used in Appendix A, unless stated otherwise.

A new set of auxiliary variables, denoted ξ_d^t, are defined for donors $d \in FD$ and time periods $t \in T \cup \{0\}$. These variables have been introduced in the original constraints (3) to represent the financial donations that are not used to make food purchases. Moreover, they are also included in the economic objective function.

$$\sum_{p \in P} \sum_{b \in B} \tau_p^t x_{pdb}^t + \xi_d^t = \widetilde{Q}_d^t + \xi_d^{t-1} \qquad d \in FD,\ t \in T \tag{6}$$

We note that financial donations not spent in a given time period are available in later periods. Naturally, $\xi_d^0 = 0$ for every $d \in FD$.

A very large positive constant $\mathcal{M}$ was used in the original constraints (9) and (10) to ensure that the acquisition of transport capacity by a food bank warehouse is only possible if that warehouse holds storage capacity for the same product family. It is now replaced by the total number of storage capacity levels that can be installed in a warehouse. Therefore, we have:

$$\sum_{\ell \in L} v_{\ell k b}^t \leq |L| \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{13}$$

$$\sum_{\ell \in L} v_{\ell k b}^t \leq |L| \left[\overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \right] b \in OB,\ k \in K,\ t \in T \tag{14}$$

The slack variables γ^t, which appear in the original budget constraints (11), are now unrestricted in sign (see constraints (15) and (41) in Appendix A). This allows us to identify those time periods with a spending below the reference budget as well as time periods in which additional capital will need to be raised to cover the location and capacity acquisition expenditures. Variables γ^t will be maximised over the planning horizon in the social objective function instead of the economic function as it was the case in the original formulation.

We have decided to remove the auxiliary variables δ^t_{pc} $(c \in C,\, p \in P,\, t \in T)$ that accounted for the unsatisfied demand of charities over the planning horizon and that were initially used in constraints (22) and (23). These variables are not required to assess the social impact of food redistribution. Variables δ^t, which appear in constraints (28) below and in the social objective function of the refined formulation, are sufficient to measure this social factor. Observe that the elimination of δ^t_{pc} results in a decrease of the total number of variables in the model.

$$x^t_{pbc} \leq R^t_{pc}\, z^t_{bc} \qquad b \in B,\, c \in C,\, p \in P,\, t \in T \tag{27}$$

$$\sum_{p \in P} \sum_{b \in B} \frac{R^t_{pc}\, z^t_{bc} - x^t_{pbc}}{R^t_{pc}} \leq \delta^t \qquad c \in C,\, t \in T \tag{28}$$

Two sets of new constraints were also added to the formulation. The first set limits the total number of status changes at food bank locations (opening/closing warehouses) in each time period.

$$\sum_{b \in B} y^t_b \leq \lceil \beta_1\, |B| \rceil \qquad t \in T \tag{8}$$

with β_1 denoting a pre-specified constant and $\beta_1 \in (0, 1]$.

According to the second set of new constraints, charities cannot be assigned to food banks that are outside their desired service area.

$$\sum_{t \in T} \sum_{c \in C_b} z^t_{bc} \leq 0 \qquad b \in B \tag{24}$$

where C_b is the set of charities whose distance to food bank b exceeds a pre-defined threshold.

Some changes were introduced in the original objective functions (36)-(38). The *economic objective function* now also includes the total revenue obtained at the end of the planning horizon as a consequence of not completely spending the available financial donations. This is in line with the focus given by food banks to the redistribution of food donations rather than to the purchase of food products. The term in the original economic objective related to the investment budget (γ^t) was moved to the social objective function.

$$\begin{aligned}
\text{Min } z_1 = & \sum_{t \in T} \sum_{b \in B} \sum_{c \in C} FC^t \, z_{bc}^t + \sum_{t \in T} \sum_{b \in OB} \sum_{k \in K} VS_{kb}^t \, \overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \\
& \sum_{t \in T} \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VS_{kb}^t \, M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} + \\
& \sum_{t \in T} \sum_{b \in B} \sum_{k \in K} \sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} VH_{kb}^t \, x_{pib}^t + \alpha_1 \sum_{t \in T} \sum_{b \in B} \sum_{k \in K} \theta_{kb}^t \\
& - \alpha_1 \sum_{d \in FD} \xi_d^{|T|}
\end{aligned} \tag{1}$$

Concerning the *environmental objective function*, and in accordance with industry practices, the unit food disposal cost (φ^t) is now assumed to be the same for every food product, regardless of the product family the item belongs to. The total cost of CO_2 emissions incurred by transports performed by food bank vehicles depends on the time period through parameter ω^t. Round trips are considered to collect food items from a specific donor or from another food bank. Therefore, a vehicle moving in a round trip between two locations travels empty on the outward journey and carries a load on the return journey. This is taken into account in the last component of the new objective function (2).

$$\begin{aligned}
\text{Min } z_2 = \alpha_2 & \sum_{t \in T} \sum_{p \in P} \varphi^t \left[\sum_{d \in DD} \left(Q_{pd}^t - \sum_{b \in B_d} x_{pdb}^t \right) + \sum_{d \in CD} \left(Q_{pd}^t - \sum_{b \in B} x_{pdb}^t \right) \right] + \\
\alpha_3 & \sum_{t \in T} \sum_{b \in B} \sum_{p \in P} \sum_{i \in CD \cup B \setminus \{b\}} \omega^t \, U_{ib} \, (1 + x_{pib}^t)
\end{aligned} \tag{2}$$

In contrast to the original MILP model, we have now opted to express the *social objective function* as a goal to be maximised. Furthermore, two additional components were included.

$$\text{Max } z_3 = \alpha_4 \sum_{t\in T}\sum_{b\in B}\sum_{c\in HC} z_{bc}^t + \alpha_5 \sum_{t\in T}\gamma^t + \sum_{t\in T}\alpha_6^t \left[\sum_{b\in OB}\sum_{k\in K}\overline{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} M_{lk}\sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}}\right] - \alpha_7 \sum_{t\in T}\delta^t - \alpha_8 \sum_{t\in T}\varepsilon^t \tag{3}$$

The first component in (3) accounts for the total number of charities that are removed from the waiting list and start to receive food assistance. The second component, which was originally considered in the economic objective, measures the total deviation from the reference budget for network redesign (see constraints (15) in Appendix A). A positive value represents the total amount of available capital that is not required to be procured by food banks. In contrast, a negative value indicates that the reference budget is insufficient and therefore additional capital will need to be raised. We observe that it takes a significant effort to raise funds to support the redesign of the existing supply chain network. This effort falls not only upon the food bank organisation but also upon the social partners that support its operation such as regional and national public entities and private patrons. We emphasize this aspect by including variables γ^t in the objective function (3).

The third component in (3) is new and represents the value of the social work created by the operation of food banks. It reflects the importance of volunteer engagement (human capital) which is critical for food banks in working toward their mission (Ataseven et al., 2017). Each factor α_6^t incorporates the monetary value of social work (see Section 3.1.6 for a detailed description) and is multiplied by the total storage capacity that is available in the network in each time period (the term inside the square brackets). Storage capacity is used as a surrogate for the business activities of food banks. The last two components in (3) penalise the highest level of unsatisfied demand and the excessive travel of charities to collect food products from their designated food banks.

The social objective function comprises five distinct goals that are keystones of the activity of food banks. They convey metrics suitable for the evaluation of the social performance of the food bank supply chain that have not yet been proposed in the literature. These metrics may also be appropriate for the social evaluation of other non-profit supply chains.

Since several components in the economic, environmental and social objective functions have different units of measurement, they are multiplied by positive normalising factors, denoted α_1, α_2, α_3, α_4, α_5, α_6^t $(t \in T)$, α_7, and α_8.

Finally, we note that the three objective functions quantify the performance of the food bank supply chain in accordance with selected standards developed by the Global Reporting Initiative (2016), and also include other tailored metrics developed by the authors for this study.

2. Solution methodology

Multi-objective optimisation methods can be divided into three categories to identify Pareto optimal solutions (Miettinen, 2008), depending on the moment in which the decision maker intervenes in the optimisation process. *A priori* methods require the decision maker to articulate preferences on the objectives before the solution process starts. In practice, it may be difficult for the decision maker to specify preferences beforehand. In contrast, no preferences are considered in *a posteriori* methods. These methods involve searching for all or at least a representative set of Pareto optimal solutions, from which the decision maker then selects the most adequate alternative. The generation of many (or all) Pareto optimal solutions is often computationally prohibitive. Moreover, the usually very large number of Pareto optimal solutions make it difficult for the decision maker to select a preferred alternative. The third category is comprised of interactive methods whereby the search towards promising solutions is guided by preference information specified and refined by the decision maker during this process.

This study is the first to apply a multi-objective optimisation methodology to address key strategic decisions faced by an institution like the FPBA. At this stage we are interested in identifying the main trade-offs that occur when economic, environmental and social goals are considered simultaneously, and in obtaining a number of solutions that can be used as reference points for strategic (re)positioning. This is accomplished by employing lexicographic ordering successively to find all lexicographic solutions (Miettinen, 2008). For a pre-defined ranking of the three objectives according to their relative importance, the method starts by optimising the objective given the highest preference subject to the original constraints. Then, the second most important objective is optimised by adding a new constraint that guarantees that the first objective function preserves its optimal value. The third and final step consists of optimising the least important objective subject to the original constraints extended with two constraints that ensure the preservation of the optimal values of the two most important objectives. It can be proved that the solution of lexicographic ordering is Pareto optimal (Ehrgott, 2005). We apply the lexicographic method to all possible combinations for ranking the three objective functions. In this way, six Pareto optimal solutions are identified. Figures 1–3 illustrate all single objective MILP problems that need to be solved in order to obtain these solutions.

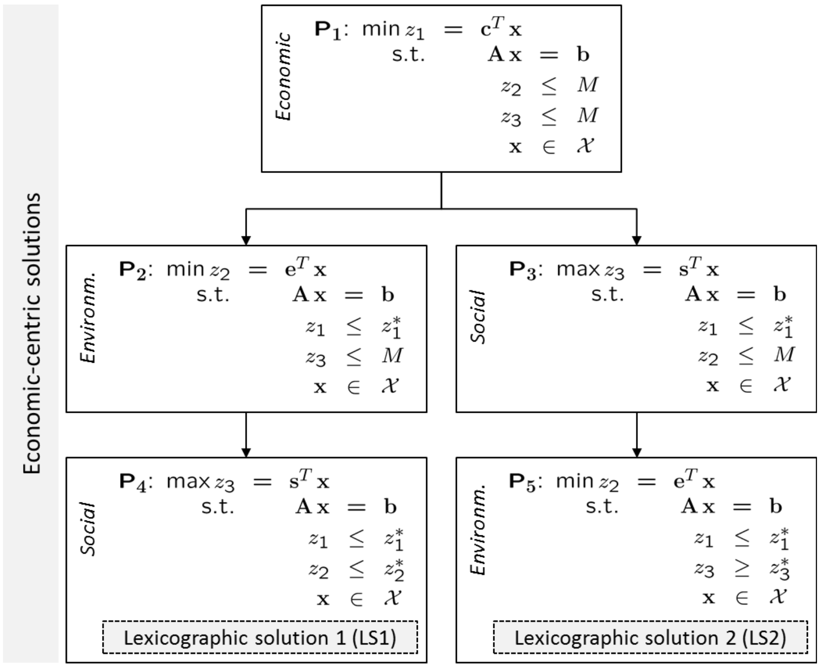

Figure 1: Lexicographic solutions obtained when the economic objective has the highest importance

We denote by $\mathbf{A}$ the matrix with the coefficients on the left-hand side of the functional constraints, while $\mathbf{b}$ represents the right-hand side vector. Here we assume that slack variables have been added to these constraints, if necessary, to make them all equalities. The vector with all variables is denoted by $\mathbf{x}$ and $\mathcal{X}$ describes the (integer) conditions satisfied by the variables.

Furthermore, the vectors with the coefficients of the economic, environmental and social objective functions are represented by $\mathbf{c}$, $\mathbf{e}$ and $\mathbf{s}$, respectively. Parameter M is a sufficiently large number.

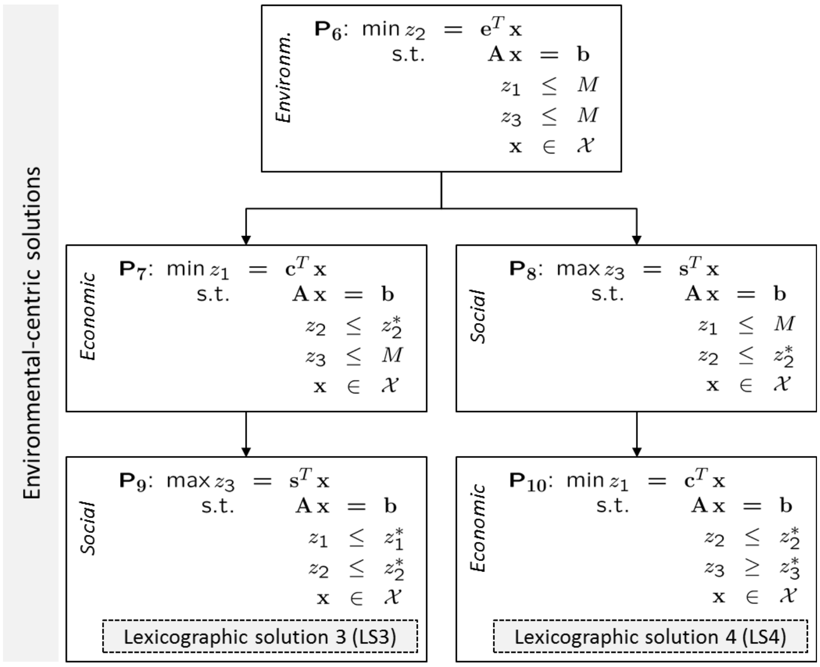

Figure 2: Lexicographic solutions obtained when the environmental objective has the highest importance

Two so-called *economic-centric* lexicographic solutions (LS1 and LS2) are obtained when the economic objective function (1) has the highest importance (see Figure 1). When the environmental objective function (2) is given the highest preference, two *environmental-centric* lexicographic solutions (LS3 and LS4) are identified as displayed in Figure 2. Finally, Figure 3 shows how the two *social-centric* lexicographic solutions (LS5 and LS6) are generated from assigning primary importance to the social objective function (3). Observe that the ideal vector is the outcome of solving problems $\mathbf{P}_1$, $\mathbf{P}_6$ and $\mathbf{P}_{11}$.

3. Computational study

This section is dedicated to a computational study based on real data provided by the FPBA. However, rather than just studying the particular case of the FPBA, we have opted

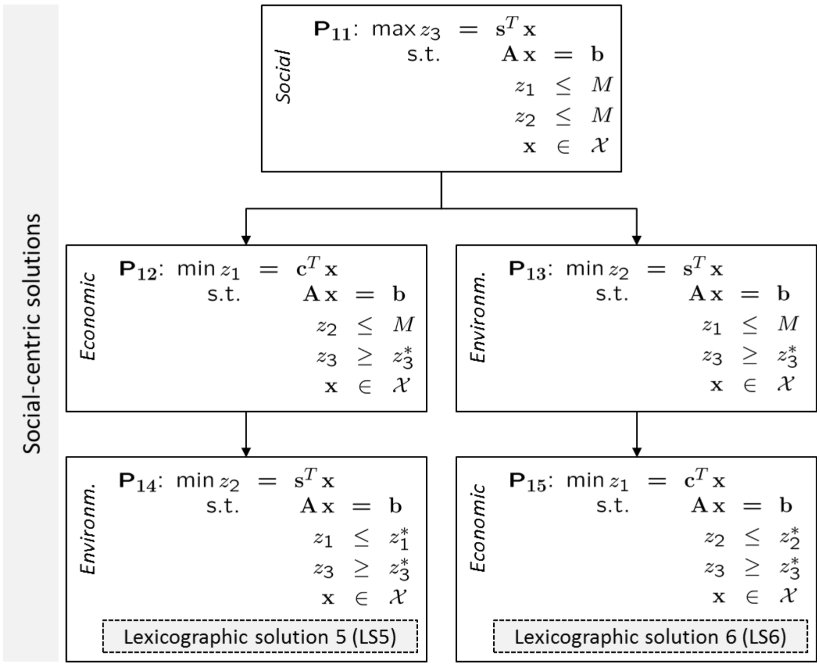

Figure 3: Lexicographic solutions obtained when the social objective has the highest importance

instead to generate a set of instances that reflect the structure and the characteristics of the current network operated by the FPBA in the south of Portugal, whilst creating diverse initial supply chain configurations. This will allow the generalisation of the insights derived from the results obtained to other food aid supply chains with similar settings.

An in-depth field work was conducted at the FPBA to become acquainted with this organisation, its drivers and operating practices. In addition, the logistics operations at the largest food bank, which is located in Lisbon, were also closely examined. As a result, the values of most of the parameters in our MILP model are supported by the real situation. However, some managerial practices captured by our model are currently not in place at the FPBA and in this case no data were available. This difficulty was overcome through data profiling and classification, which helped us to find suitable ranges for non-existent parameters. Some data were also drawn from official sources. The uniform distribution was used when the generation of random numbers was required.

In the remainder of this section we describe the data collection and processing steps in detail. This is followed by an analysis of the results obtained. Important managerial insights that illustrate the trade-offs achieved when the three dimensions of sustainability are considered simultaneously are also presented.

3.1. Data description

The FPBA network comprises 18 food banks in mainland Portugal. Computational limitations resulting from the software and hardware available prevented us from solving the problem for the entire network within a reasonable time limit. Consequently, we have decided to restrict the scope of our study to the region south of Lisbon, where currently four food banks with different sizes (a large, a medium and two small-sized facilities) are operated, and whose service area accounts for one-third of the total area covered by the FPBA in mainland Portugal.

Figure 4 shows the locations of the four existing facilities and of a potential site for a new food bank in all test instances. The current geographical dispersion of the FPBA facilities in the southern region of Portugal was used as a reference to semi-randomly generate the coordinates of the food banks in the rectangle $[0, 500] \times [0, 335]$. Considering that one unit in this rectangle

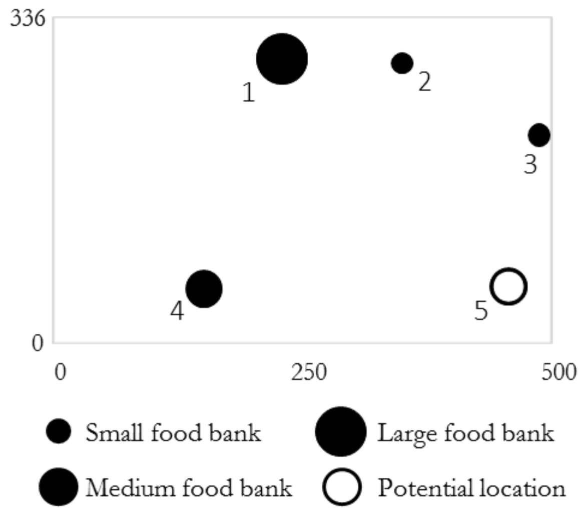

Figure 4: Locations of all food banks

corresponds to approximately 0.5 km, an area of around 41,875 km^2 is represented in each instance (i.e. 34% of the total area of mainland Portugal). Our instances retain the core design of the current FPBA network of food banks in the southern region of Portugal, even though the actual locations of the existing FPBA facilities do not match exactly those depicted in Figure 4. This will allow us to draw conclusions that are not only relevant to the FPBA but can also be generalized to other food aid supply chain networks.

Regarding the maximum number of allowed status changes at food bank locations (i.e. opening/closing facilities) per period, we have opted for the most flexible scenario and set $\beta_1 = 1$. Notice that in this case constraints (8) are redundant.

3.1.1. Donors, charities and food products

As shown in Table 1, a five-period planning horizon was considered. Assuming that each time period represents one year, this length of the planning horizon is appropriate in the context of the strategic decisions addressed by our model.

Parameter/Set	Value	Source
$\|T\|$	5	user-defined
$\|DD\|$	8	based on FPBA
$\|CD\|$	2	based on FPBA
$\|FD\|$	1	based on FPBA
$\|OB\|$	4	based on FPBA
$\|PB\|$	1	based on FPBA
B_d	$B_d = \{b \in OB \cup PB : U_{bd} \leq 250\}$	user-defined
$\|SC\|$	16	based on FPBA
$\|HC\|$	3	based on FPBA
C_b	$C_b = \{c \in HC \cup SC : U_{bc} \geq 250\}$	user-defined
$\|P\|$	5	based on FPBA
$\|K\|$	3 (1: dry, 2: fresh, 3: frozen)	based on FPBA
P_k	$P_1 = \{1, 2\},\ P_2 = \{3, 4\},\ P_3 = \{5\}$	based on FPBA
$\|L\|$	3	user-defined

Table 1: Index sets and their cardinalities

The analysis of the FPBA's historical data provided an overview of the organisations that donate food products and the charities that receive food assistance. Data aggregation was required due to the large number of entities involved in the supply chain. This step resulted in the values given in Table 1 and that were considered in our study.

According to the FPBA, in 2015 approximately 1,240 donors provided food items to the food banks in mainland Portugal, 2,000 charities received food assistance, and 400 agencies were on the waiting list. Since 16% of the Portuguese population lives in the southern region, we have considered that about 198 donors make food donations and 384 charities are involved in this region. These entities are represented in the test instances at a 1:20 scale by 10 donors and 19 charities, with the latter divided into $|SC| = 16$ and $|HC| = 3$. Typically, around 85% of the donors deliver food items to food banks, whereas the remaining 15% require donations to be collected. Accordingly, we have set $|DD| = 8$ and $|CD| = 2$. Furthermore, since the locations of individuals and businesses that make financial donations are not relevant for the purpose of our model, we have aggregated all such entities into a single financial donor. Our aggregation of charities yields a ratio of 1.6 between the number of served charities (16) and the number of donors (10), which reflects the real situation. The actual FPBA ratio ranged from 1.47 in 2013 to 1.85 in 2015. In each instance, the coordinates of every donor $d \in DD \cup CD$ and charity $c \in C$ were chosen randomly in the rectangle $[0, 500] \times [0, 335]$. The distance U_{ij} between origin i and destination j corresponds to the Euclidean distance for $(i, j) \in A$.

In total, 33 different food products are grouped into three product families - dry, fresh and frozen products - by the FPBA. Our instances include five products, which cover around 70% of all donations. They include: (1) milk, (2) rice, pasta, flour and purée, (3) fresh fruit, (4) fresh vegetables, and (5) frozen desserts and ice cream. The allocation of these products to families is given in Table 1.

Regarding the capacity options for storing and transporting food items, we have assumed that three capacity levels can be purchased, representing small, medium and large sizes. Further details are provided in the next section.

3.1.2. Warehouse and transport capacities

The data analysis has shown that the capacity of a storage area dedicated to a particular product family varies significantly among the facilities of the same size. Therefore, it was not possible to identify a standard capacity level per family and facility size. We have thus decided to randomly select the value of each parameter $\overline{M}_{kb}$ from an interval according to a uniform distribution. The limits of each interval shown in Table 2 are based on the actual minimum and maximum storage capacities over all existing food banks of a given size (i.e. small, medium or large), and for a specific family of products, as reported by the FPBA. Since five food products were considered (see Table 1), covering 67.4% of all food donations, we have reduced all capacities by this proportion.

		Product family					
	Existing	dry ($k = 1$)		fresh ($k = 2$)		frozen ($k = 3$)	
Parameter	food bank (b)	min.	max.	min.	max.	min.	max.
$\overline{M}_{kb}$	1 (large)	3639.60	4788.77	1122.21	4087.81	94.36	215.68
	$2, 3$ (small)	269.60	1533.35	23.59	208.94	3.37	10.11
	4 (medium)	930.12	2298.34	87.62	2470.21	20.22	43.81
$\overline{N}_{kb}$	1 (large)	1944.49	2594.90	0.00	1297.45	0.00	90.99
	$2, 3$ (small)	0.00	647.04	0.00	647.04	0.00	90.99
	4 (medium)	0.00	1297.45	0.00	1297.45	0.00	90.99

Table 2: Storage and transport capacity levels at existing warehouses (in tonnes)

Setting the interval limits required converting the size of a storage area (measured by square metres for dry products, and cubic metres for fresh and frozen products) into weight (tonnes). Based on the analysis of the volumetric features of a number of dry products stored at the Lisbon warehouse, we have adopted a conversion factor of 0.4737 square meters to one tonne per day. Furthermore, assuming a bimonthly storage period for dry products, this yields a conversion ratio of 2.8421 for calculating the annual capacity of a storage area. Fresh and frozen products are stored in pallets with a volume of 1.2 m^3 ($1 \times 1 \times 2$ m) and a maximum weight of 200 kg. Under an average duration of storage of one week (month) for fresh (frozen) food items, the conversion factor from cubic metres into annual tonnage is equal to $\frac{26}{3}$ (2.0) for fresh (frozen) products. A similar methodology was also adopted to set the values of the transport capacities, $\overline{N}_{kb}$. The limits of the intervals given in Table 2 for these parameters are based on the characteristics of the vehicles available at the food bank in Lisbon and assuming one trip on every work day.

Table 3 presents the sizes of the different capacity levels for storage ($M_{\ell k}$) and transportation ($N_{\ell k}$) of food products that can be installed at existing and new food bank locations. These values are defined with reference to the minimum and maximum capacity sizes at the existing food banks.

		Product family		
		dry	fresh	frozen
Parameter	Capacity level (ℓ)	($k = 1$)	($k = 2$)	($k = 3$)
$M_{\ell k}$	1 (small)	1011.00	168.50	6.74
	2 (medium)	2022.00	1348.00	33.70
	3 (large)	4044.00	2696.00	134.80
$N_{\ell k}$	1 (small)	168.50	134.80	16.85
	2 (medium)	337.00	269.60	33.70
	3 (large)	842.50	505.50	67.40

Table 3: Storage and transport capacity levels available (in tonnes)

While all large warehouses in the FPBA network have dedicated storage areas for the three product families, medium and small-sized facilities do not necessarily have the space and the equipment required to store and distribute all types of products. Table 4 presents the characteristics of the four existing facilities in each one of the 20 instances that were generated. They reflect the typical features of food banks with the same size that are currently operated by the FPBA. Storage and transport capacity for dry food items is available in every facility, whereas only a few existing warehouses can handle and distribute fresh and frozen products.

3.1.3. Financial parameters

The collection of data relative to investment and operating costs proved to be rather challenging, partly because the FPBA does not record financial information with the level of detail required for our model. Furthermore, a number of financial parameters are not available since they are associated with practices that are currently not followed by the FPBA. This is the

	Product	Instance																			
Food bank	family	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Dry	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
(large)	Fresh	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
	Frozen	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
2	Dry	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
(small)	Fresh	•	•			•			•	•	•	•	•	•		•				•	•
	Frozen	•				•	•		•			•									
3	Dry	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
(small)	Fresh			•	•								•			•	•				
	Frozen															•				•	•
4	Dry	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
(medium)	Fresh	•		•			•	•			•			•	•				•	•	
	Frozen								•		•			•							

Table 4: Types of storage areas available at existing food banks in the generated test instances

case, for example, with decisions related to the acquisition of storage and transport capacity. Typically, these decisions arise from donation opportunities created by municipalities and private donors, and contracts with preferred (private and public) companies that allow capacity to be rented under special rates and conditions. The estimation of financial parameters using commercial sources is not a viable option due to the distinctive nature of the activities pursued by food banks compared to for-profit businesses. Therefore, a top-down approach was used to estimate the missing data. In doing so, we have assumed an artificial monetary unit (m.u.) for most of the financial parameters. Since some parameters will be expressed in thousands of euros, rescaling factors can be used to ensure data consistency.

Under the top-down approach, the first parameter to be fixed is the annual budget available for expenditures on facility location and capacity acquisition. This parameter corresponds to the amount of capital that the organisation managing the food bank network expects to receive from institutional partners upon demand. It is assumed to be equal to 2,500 m.u. at the beginning of the planning horizon ($t = 0$). An annual growth rate of 2% is considered, meaning that $O^t = 1.02\, O^{t-1}$ ($t \in T$). The values of the financial parameters presented in Tables 5–7 are subject to the same variation unless stated otherwise. All parameters expressed in m.u. are defined with reference to O^0.

The unit purchasing costs of food products shown in Table 5 are based on price information

Parameter	Product (p)	Value	Unit
FI^0		1000*	m.u.
FU^0		500*	m.u.
FC^0		10*	m.u.
O^0		2500*	m.u.
τ_p^0	1 (milk)	0.4740	k€/tonne
	2 (rice, pasta, flour, purée)	0.8213	k€/tonne
	3 (fresh fruit)	0.7899	k€/tonne
	4 (fresh vegetables)	0.8406	k€/tonne
	5 (frozen desserts, ice cream)	4.4345	k€/tonne
φ^0		0.055**	k€/tonne
ω^0		0.00075**	k€/tonne-d.u.

Table 5: Values of some financial parameters at $t = 0$; *2% growth rate/period; **5% growth rate/period

provided by the FPBA for 2015. In this table, each value is the weighted sum of the prices for individual products. To take into account price volatility over the planning horizon, a price variation between -2% and +5% of the base price ($t = 0$) was considered. Therefore, in each time period, the unit price of product p is equal to the base value, τ_p^0, multiplied by a randomly generated number in the interval $[0.98, 1.05]$ according to a uniform distribution.

Disposal costs for unused donated products (φ^t) are supported by the respective donors. These costs are dictated by the (public or private) entities involved in waste disposal and by municipal taxes. We have fixed the unit disposal cost at 0.055 k€/tonne in accordance with Zacarias (2014). This figure is also consistent with the value estimated by the staff interviewed at the food bank in Lisbon. In order to convey the commitment of institutions like the FPBA to environmental goals, we have assumed an annual disposal cost increase of 5%.

Carbon dioxide emissions are considered for food bank vehicles engaged in the collection of food items from certain donors (defined by CD) and from other food banks. We disregard the emissions of vehicles of donors that deliver their donations to local food banks since these deliveries are often integrated in commercial distribution routes. Moreover, we also disregard the emissions caused by vehicles of the charities for the collection of food products at their designated food banks. Observe that the integration of the distance travelled by the charities into the social objective function (3) can also be seen as a surrogate for the environmental impact of these trips. The exact cost of CO_2 emissions has been the subject of much debate. The carbon market price, set either according to the Emissions Trading System or as a carbon tax, varies significantly across individual countries. There have been quite wide price fluctuations in recent years, and it remains unclear how prices will evolve (World Bank et al., 2016). We have assumed a high CO_2 cost of 20 €/tonne. In addition, for road freight transportation, the European Environment Agency estimates 75 grammes of CO_2 per tonne-km (European Environment Agency, 2015). This yields a CO_2 cost of 0.0015 k€/tonne-km for food bank vehicles. Knowing that one distance unit in the area depicted in Figure 4 corresponds to 0.5 km, the value of parameter ω^t has been set to 0.00075 k€/tonne-d.u. for $t = 0$. An annual growth rate of 5% was assumed to underline the concerns of the FPBA and similar institutions regarding this environmental factor.

As shown in Table 6, the unit capacity acquisition costs vary between 0.50 m.u./tonne and 10 m.u./tonne for storage capacity, and between 1 m.u./tonne and 10 m.u./tonne for transport capacity. Due to different storage and transport requirements by each of the product families, these costs are the lowest for dry food products and the highest for frozen products. Costs grow annually at a rate of 2%.

		Product family		
Parameter	Capacity level (ℓ)	dry ($k = 1$)	fresh ($k = 2$)	frozen ($k = 3$)
$VSI^0_{\ell k}$	1 (small)	1.00	5.00	10.00
	2 (medium)	0.75	1.50	5.00
	3 (large)	0.50	1.00	2.50
$VTI^0_{\ell k}$	1 (small)	2.00	7.50	10.00
	2 (medium)	1.50	5.00	6.00
	3 (large)	1.00	3.50	4.00
VU^0_k		0.25	0.50	1.25

Table 6: Costs for capacity acquisition and for capacity dismantling (m.u./tonne) at $t = 0$

While the cost parameters given in Tables 5–6 only depend on the type of product or family, operating and handling costs at warehouses also take into account regional differences in costs along with the specific characteristics of the three product families. Population density affects the availability of potential volunteers, which are the main source of labour for food banks. A shortage or excess of volunteer workers has a direct impact on the value of labour, and consequently on the cost of operating storage capacity and handling food items at warehouses. The large food bank in Figure 4 represents a FPBA facility located in a densely populated area, while the small facility 2 corresponds to a facility situated in one of the most sparsely populated regions. The remaining facilities are located in areas of intermediate population density. These differences are reflected in the costs shown in Table 7. In addition to regional cost structures, specific storage conditions (e.g. equipment, energy consumption) and handling equipment required by the different products also affect these costs. The operation of storage areas for frozen products incurs the highest costs, while the lowest costs are obtained for dry products. All costs rise at a rate of 2% per period.

		Product family		
Parameter	Food bank (b)	dry ($k=1$)	fresh ($k=2$)	frozen ($k=3$)
VS^0_{kb}	1	0.0250	0.05000	0.1250
	2	0.0500	0.10000	0.2500
	$3,4,5$	0.0375	0.07500	0.1875
VH^0_{kb}	1	0.1250	0.25000	0.6250
	2	0.2500	0.50000	1.2500
	$3,4,5$	0.1875	0.37500	0.9375

Table 7: Operating and handling costs at food banks (m.u.) at $t = 0$

Finally, the specification of the financial donations ($\widetilde{Q}^t_d$) is based on information provided by the FPBA regarding the quantity of products donated from 2010 until 2015. The available data were processed using a procedure that also allows to determine the quantities of the products supplied by each donor. This procedure is described in the next section.

3.1.4. Donations

In the period 2010–15, we estimate that the food banks operating in the southern region have processed about 3,750 to 4,500 tonnes of the five food products considered on our study. According to the FPBA, roughly 9% of these quantities were purchased using monetary donations. We now detail how we have used this information to specify the values of parameters Q^t_{pd} and $\widetilde{Q}^t_d$. In what follows, we denote by $U[a,b]$ the random generation of numbers in the interval $[a,b]$ according to a uniform distribution.

First, in Step 1 of the procedure described below, the quantity associated with financial donations (9%) is subtracted from the total quantity of food items secured by the FPBA. Next, in Step 2, the total quantity of each individual food product is randomly generated using the percent contributions provided by the FPBA as reported in Table 8. In Step 3, the assignment of product families to donors $d \in DD \cup CD$ is performed according to the distribution observed at the Lisbon food bank in 2015: 54.2% of the donors supplied dry products, 40.5% donated fresh products and the remaining 5.3% delivered frozen products. The intervals shown in Table 8 for each product family were defined with reference to these proportions. Although a few businesses, such as supermarkets and grocery chains, donate products from different families, most of the donors supply items of a single product family. The latter case is followed in Step 3 to define the number of donors that make available food items of a given family (s_k, $k = 1, 2, 3$). We note that due to the random selection process, it may be required to slightly adjust the values of parameters s_k in order to ensure $s_1 + s_2 + s_3 = |DD| + |CD|$. With the assignments obtained in this step and the distribution of products across the families (cf. Table 1), it is now straightforward to calculate the number of donors per product in Step 4, under the assumption that each donor supplies all items of a family. This information is used in Step 5 to obtain a reference value for the total quantity of each product donated by a donor. A variation rate of $+$/- 50% is introduced to generate parameters Q^0_{pd}. The actual quantities Q^t_{pd} used in our model are then randomly determined in Step 6 by considering a range of percentage change between 80% and 120% over the value for period $t = 0$. Finally, in Steps 7 and 8, the annual financial donations are calculated for the aggregate donor $d \in FD$ by taking into account the prices of the individual products. A variation of +/- 10% over the base value $\widetilde{Q}^0_{pd}$ is assumed.

Calculation of parameters Q^t_{pd} and $\widetilde{Q}^t_d$:

Step 1. Determine $Total$, the total quantity of food donations (in tonnes) in period $t = 0$, according to $Total = U\left[\frac{3750}{1.09}, \frac{4500}{1.09}\right]$.

Step 2. For each food product $p \in P$, select the total quantity of food donations, $Total_p = U[\overline{a}_p \times Total, \underline{a}_p \times Total]$ with $\overline{a}_p$ and $\underline{a}_p$ given in Table 8.

Step 3. Assign one product family k to each donor $d \in DD \cup CD$ in such a way that s_k donors provide all food products belonging to family k and $\sum_{k \in K} s_k = |DD| + |DC|$. The calculation of s_k is presented in Table 8.

Step 4. For each food item $p \in P$, determine the total number of donors of p, $\#donors_p$.

Step 5. Calculate the total quantity of food product $p \in P$ supplied by donor $d \in DD \cup CD$ in period $t = 0$ according to $Q^0_{pd} = U[0.5, 1.5] \times \frac{Total_p}{\#donors_p}$.

Step 6. Obtain the total quantity of food product $p \in P$ made available by donor $d \in DD \cup CD$ in period $t \in T$ as follows: $Q^t_{pd} = U[0.8, 1.2] \times Q^0_{pd}$.

Step 7. Calculate $TotalValue^t$, the total value of food donations in each time period $t \in T \cup \{0\}$ taking into account the individual product prices as follows: $TotalValue^t = \sum_{p \in P} \tau^t_p \sum_{d \in DD \cup CD} Q^t_{pd}$.

Step 8. Obtain the total value of financial donations in each time period t according to $\widetilde{Q}^0_d = 0.09 \times TotalValue^0$ and $\widetilde{Q}^t_d = 0.09 \times U[0.9, 1.1] \times TotalValue^t$ for $t \in T$. Recall that $d \in FD$ and $|FD| = 1$ (see Table 1).

3.1.5. Demand parameters

The FPBA primarily focuses on securing the greatest possible amount of food and redistributing it to as many charities as possible in an equitable manner, while minimising the food waste. To achieve a fair supply of all served charities, the available food products are delivered

Step	Product (p)	$[\overline{a}_p, \underline{a}_p]$	Step	Product family (k)	s_k
2	1	[0.120, 0.230]	3	1	$[0.500, 0.600] \times (\lvert DD\rvert + \lvert CD\rvert)$
	2	[0.100, 0.320]		2	$[0.350, 0.450] \times (\lvert DD\rvert + \lvert CD\rvert)$
	3	[0.270, 0.540]		3	$[0.025, 0.075] \times (\lvert DD\rvert + \lvert CD\rvert)$
	4	[0.130, 0.240]			
	5	[0.002, 0.020]			

Table 8: Parameters used in Steps 2 and 3

taking into account the specific nutritional needs of each agency and according to an allotment or *pro rata* process. However, our MILP model requires the demands of the charities to be specified for each product in each time period of the planning horizon. The assumptions made by the model could be adopted by the FPBA in the future through basing the distribution of the food products on the individual demands of the charities and not, as currently, on the amount of available donations and the underlying assumption of unlimited needs of the charities. In this case, only those products that would actually contribute to the satisfaction of known demands would be collected by the charities. To conciliate the two approaches, our demand estimations rely on parameters X^0_{pc} that give the actual quantities received by the charities in period $t = 0$. The values of these parameters are selected according to Steps 1–3 of the following procedure.

Calculation of parameters X^0_{pc} and R^t_{pc}:

Step 1. For each food product $p \in P$, calculate the total quantity of food purchases made with donated money in period $t = 0$ according to $\overline{Total_p} = U[\overline{a}_p, \underline{a}_p] \times \frac{\sum_{d \in FD} \widetilde{Q}^0_d}{\tau^0_p}$, with $\overline{a}_p$ and $\underline{a}_p$ given in Table 8.

Step 2. For each food product $p \in P$, determine the total quantity available in period $t = 0$ from in-kind donations and financial donations as follows: $Prod_p = Total_p + \overline{Total_p}$ with $Total_p$ obtained with the procedure described in Section 3.1.4.

Step 3. Determine the total quantity of food product $p \in P$ received by charity $c \in SC$ in period $t = 0$ according to $X^0_{pc} = U\left[0, \frac{2}{|SC|}\right] \times Prod_p$ for every $c = 1, \ldots, |SC| - 1$, and $X^0_{p|SC|} = \max\left\{0, Prod_p - \sum_{c=1}^{|SC|-1} X^0_{pc}\right\}$.

Step 4. Calculate the demand of all charities $c \in SC$ in each time period $t \in T$ as follows: $R_{pc}^t = U[0.90, 1.10] \times X_{pc}^0$.

Step 5. Obtain the average demand for food item $p \in P$ in each time period $t \in T$ per charity, i.e. $\overline{R}_p^t = \dfrac{\sum_{c \in SC} R_{pc}^t}{|SC|}$.

Step 6. Calculate the demand of each charity on the waiting list for every product $p \in P$ and period $t \in T$ according to $R_{pc}^t = U[0, 2] \times \overline{R}_p^t$ for $c = \{1, \ldots, |HC|-1\}$ and $R_{p|HC|}^t = \begin{cases} U[0, 2] \times \overline{R}_p^t & \text{if } \sum_{c \in SC} R_{pc}^t + \sum_{c=1}^{|HC|-1} R_{pc}^t \geq \sum_{d \in DD \cup CD} Q_{pd}^t \\ L_p^t & \text{otherwise} \end{cases}$.

First, food purchases made using financial donations are randomly defined in Step 1 taking into account the individual food prices. They are added in Step 2 to the total amount of in-kind donations in order to obtain the total quantity of each food item available at $t = 0$. The first $|SC| - 1$ charities receive a fraction of this total quantity, which does not exceed 12.5% for each charity (note that $2/|SC| = 2/16 = 0.125$). The last charity $c = |SC|$ is assigned the remaining quantity that was not distributed to the other agencies. Product demands over the planning horizon are obtained in Step 4 and vary between 90% and 110% of the reference values X_{pc}^0 previously fixed. We note that our demand generation procedure ensures that $R_{pc}^t \geq \beta_2 X_{pc}^0$ for every $t \in T$, $p \in P$ and $c \in SC$ (see Table 9 for the value of β_2). In the remaining Steps 5–6 of the above procedure the demand requirements of the charities on the waiting list (HC) are determined. The demands of these agencies, except the last one, can be at most twice the mean demand of the charities supplied at time $t = 0$. For the last charity $c = |HC|$, its demand is defined in such a way that in-kind donations are insufficient to meet the demands of all charitable agencies (SC and HC). Hence, if the inequality $\sum_{c \in SC} R_{pc}^t + \sum_{c=1}^{|HC|-1} R_{pc}^t < \sum_{d \in DD \cup CD} Q_{pd}^t$ holds for a given product p, a value L_p^t is selected to enforce an imbalance between supply and demand. The latter is randomly generated in the interval $[A_p^t, 2A_p^t]$ according to a uniform distribution and by taking $A_p^t = \sum_{d \in DD \cup CD} Q_{pd}^t - \sum_{c \in SC} R_{pc}^t - \sum_{c=1}^{|HC|-1} R_{pc}^t$. Otherwise, the demand of the last charity is obtained in the same way as for the other agencies on the waiting list.

Finally, the minimum levels of satisfied demand for the charities are given in Table 9.

Charities	Parameter	Value	Source
$c \in SC$	β_2	0.7	user-defined
$c \in HC$	β_3	0.5	user-defined

Table 9: Minimum demand satisfaction levels

3.1.6. Scaling factors

In all three objective functions, several positive factors are used, most of them for scaling purposes. Their values are presented in Table 10. Parameter α_1 is a penalty factor for unused transport capacity (θ_{kb}^t) and the residual value of financial donations at the last planning period ($\xi_d^{|T|}$). This parameter could also be used to convert the units of these two terms into the unit of the other components of the objective function (1) (m.u.). However, we have opted to set it equal to 0.0001.

Type of objective	Parameter	Value	Source
Economic	α_1	0.0001	user-defined
Environmental	α_2	$\{0.25, 0.50, 0.75\}$	user-defined
Environmental	α_3	$\{0.25, 0.50, 0.75\}$	user-defined
Social	α_4	$w_4 \times \frac{1}{\lvert HC\rvert \times \lvert T\rvert} \times 1{,}000$	user-defined
Social	α_5	$w_5 \times \frac{1}{\sum_{t\in T} O^t} \times 1{,}000$	user-defined
Social	$\alpha_6^t,\, t \in T$	$w_6^t \times \zeta^t \frac{1}{(\sum_{b\in OB}\sum_{k\in K} \overline{M}_{kb} + \lvert B\rvert \times \sum_{k\in K} M_{3k}) \times \lvert T\rvert} \times 1{,}000$	user-defined
		with $\zeta^0 = 0.0375916$	based on FPBA
Social	α_7	$w_7 \times \frac{1}{\lvert P\rvert \times \lvert T\rvert} \times 1{,}000$	user-defined
Social	α_8	$w_8 \times \frac{1}{\max\{U_{bc}\colon b\in B,\, c\in C\} \times \lvert T\rvert} \times 1{,}000$	user-defined

Table 10: Normalising factors with $w_i, w_6^t \in \{0.15, 0.20, 0.40\}$ for $i = 4, 5, 7, 8$ and $t \in T$

Factors α_2 and α_3 appear in the environmental objective function (2) to assert the preferences of the decision maker. Three different values were considered for these parameters. Setting $\alpha_2 = \alpha_3 = 0.5$ means that the minimisation of food waste and the minimisation of CO_2 emissions are equally important. Higher importance is given to avoiding food waste disposal by selecting $\alpha_2 = 0.75$ and $\alpha_3 = 0.25$. The opposite case corresponds to $\alpha_2 = 0.25$ and $\alpha_3 = 0.75$.

The purpose of the parameters that appear in the social objective function (3) are twofold. They are required to normalise the components in this function and also express the preferences of the decision maker in a similar way as the factors used in the environmental objective function. Preferences are conveyed by parameters w_i $(i = 4, 5, 7, 8)$ and w_6^t $(t \in T)$, which are in fact weights. Three values were considered $(0.15,\ 0.20$ and $0.40)$ and combined in five different ways that will be described in the next section. The total value of the social work created by the food aid supply chain in time period $t \in T$ is normalised through parameter α_6^t. The latter depends, in turn, on factor ζ^t that measures the value of work created per unit of storage capacity available in period t. For $t = 0$, this factor relies on the maximum storage capacity currently available in the FPBA network, the total number of fulltime workers and the mean annual salary of a worker. The workforce of the FPBA comprises volunteers (62%), employees (26%) and workers under social contracts (12%). The reference monthly salary is 1,096.70 € as reported by Pordata (2015). This information yields $\zeta^0 = 0.0375916$. An annual growth rate of 2% was considered for $t \in T$. Finally, the scaling factor α_8 depends on the maximum distance between a charity and a food bank. As depicted in Table 10, all factors used in the social objective function are multiplied by 1,000 for scaling purposes.

3.1.7. Generation of input scenarios

In total, 20 instances were generated. Each instance has 5,067 constraints and 5,420 variables, of which 950 are binary variables. The geographical locations of the facilities (i.e. four existing warehouses and a potential location for a new warehouse) are the same in all instances (see Figure 4). The initial warehouse and transport capacities, the locations of the donors and charities as well as their supply and demand quantities differ from instance to instance. Furthermore, eight different combinations for the weighting factors were considered according to Table 11. Each set of values indicates preferences given to the individual components of the environmental and social objective functions. Each instance was tested with the eight combinations. In order to identify all lexicographic solutions, in total $20 \times 8 \times 15 = 2,400$ problems were solved. Recall that it is necessary to solve 15 single objective problems to obtain all six lexicographic solutions of an instance (cf. Section 2).

	Parameter						
Case	α_2	α_3	w_4	w_5	$w_6^t\,(t \in T)$	w_7	w_8
1	0.50	0.50	0.20	0.20	0.20	0.20	0.20
2	0.75	0.25	0.20	0.20	0.20	0.20	0.20
3	0.25	0.75	0.20	0.20	0.20	0.20	0.20
4	0.50	0.50	0.40	0.15	0.15	0.15	0.15
5	0.50	0.50	0.15	0.40	0.15	0.15	0.15
6	0.50	0.50	0.15	0.15	0.40	0.15	0.15
7	0.50	0.50	0.15	0.15	0.15	0.40	0.15
8	0.50	0.50	0.15	0.15	0.15	0.15	0.40

Table 11: Combinations of weighting factors used in the environmental and social objectives

3.2. Analysis of results

The MILP model was coded in C^{++} using IBM ILOG Concert Technology and solved with IBM ILOG CPLEX 12.6.1.0. All experiments were conducted on a PC with a 2.6 GHz Intel® Core™ i7-6700HQ processor, 12 GB RAM (12,288 (8,192 + 4,096) MB DDR3L) and running Windows 7 (64-bit).

The computational time required to run a test instance is similar across all combinations of weighting factors and takes, on average, 1,634.63 seconds (approx. 27 minutes). Figure 5 displays the computational effort demanded by each choice of weighting factors. On average, a longer computational time (approx. 34 minutes) is required by combination 4 which gives preference to serving the highest possible number of charities on the waiting list compared to the other components in the social objective (3). In contrast, combination 7 takes on average the shortest computational time (approx. 24 minutes). In this case, the minimisation of the largest level of unsatisfied demand is the most important criterion in (3). Interestingly, more than half of the computational time is invested in obtaining the social-centric lexicographic solutions, LS5 and LS6. The identification of the economic-centric (environmental-centric) lexicographic solutions requires around 11% (38%) of the overall computational effort.

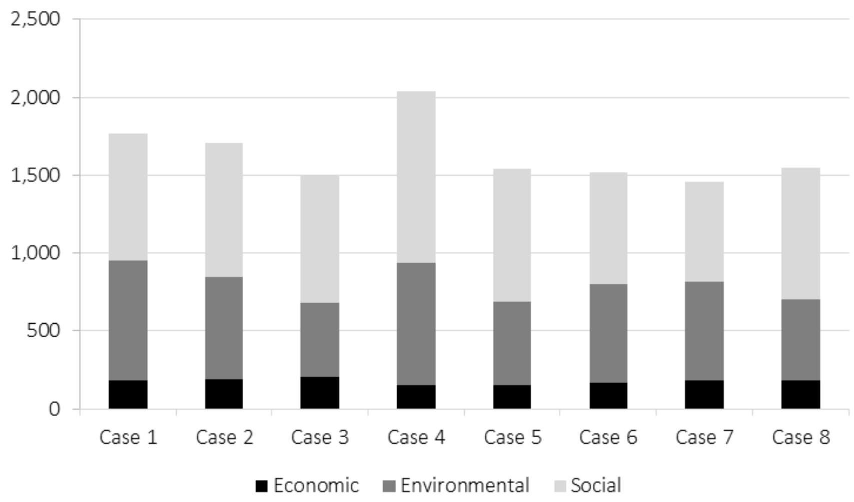

Figure 5: Average computational time (sec) for each choice of scaling factors and instance

3.2.1. Evaluation of lexicographic solutions

We have selected Case 1 from Table 11 to illustrate the main characteristics of the lexicographic solutions of the 20 test instances. Recall that in this case the individual components in the environmental objective are equally important, namely food waste disposal cost and CO_2 cost. Moreover, the five components in the social objective function (3) are assigned equal preference. Hence, Case 1 reflects a neutral attitude of the decision maker.

Table 12 summarizes the average objective function values of the lexicographic solutions. The average ideal values are shown in boldface. To highlight that the results differ across the 20 instances we have also included the average standard deviations from the ideal vector. These are particularly large for the environmental objective. For the economic-centric solutions (LS1 and LS2), a negative social outcome is obtained because in these cases the contribution of the first three components in the social function (i.e. the number of new charities supported, the total deviation from the reference budget and the value of the social work created) is smaller than the last two penalty components (see Section 3.2.2 for further details). In contrast, the social-centric solutions (LS5 and LS6) achieve the highest social value, as expected.

The trade-offs between the three criteria are shown in Figure 6. The largest differences from the ideal vector occur in the environmental and social objectives when the economic criterion

Lexicographic	Objective value (avg)			Standard deviation (avg %)		
solution	Economic	Environmental	Social	Economic	Environmental	Social
LS1	**6,690.34**	463.53	-91.73	14	89	18
LS2	**6,690.34**	477.20	-89.46	14	92	18
LS3	8,688.94	**166.82**	2.26	20	29	20
LS4	9,801.13	**166.82**	156.38	21	29	27
LS5	9,378.17	348.50	**241.49**	15	96	10
LS6	9,418.56	340.54	**241.49**	15	97	10

Table 12: Objective function values of lexicographic solutions

is the most important (solutions LS1 and LS2). This gives evidence of the extent to which economic considerations conflict with environmental and social factors, which is a valuable insight for a decision maker. Furthermore, the social-centric lexicographic solutions (LS5, LS6) also show a significant worsening of the environmental criterion. In contrast, the deterioration of the economic objective is less striking when the environmental or the social objective are first optimised. On average, the environmental-centric solution LS4 has the overall lowest deviation from the ideal vector and might, therefore, at first sight be an attractive alternative to be

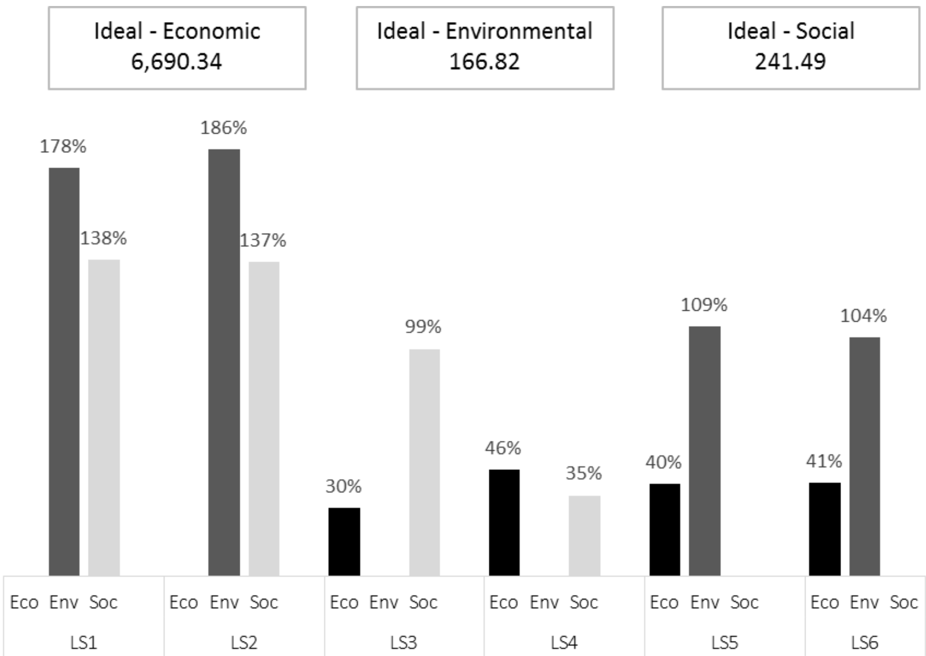

Figure 6: Deviation of the lexicographic solutions from the average ideal vector

implemented. Nevertheless, a deeper understanding of the individual features of each solution is required. This will be detailed in Section 3.2.2.

To illustrate the structure of the food bank supply chain network associated with each lexicographic solution, we have selected Instance 15 which is representative of the main characteristics of all instances. Figures 7-12 display the network configuration in the last period of the planning horizon for the six lexicographic solutions. The symbols that depict the network structure are defined at the bottom of Figure 7. Details of the individual features of these solutions are summarized in Table 21 in Appendix B.

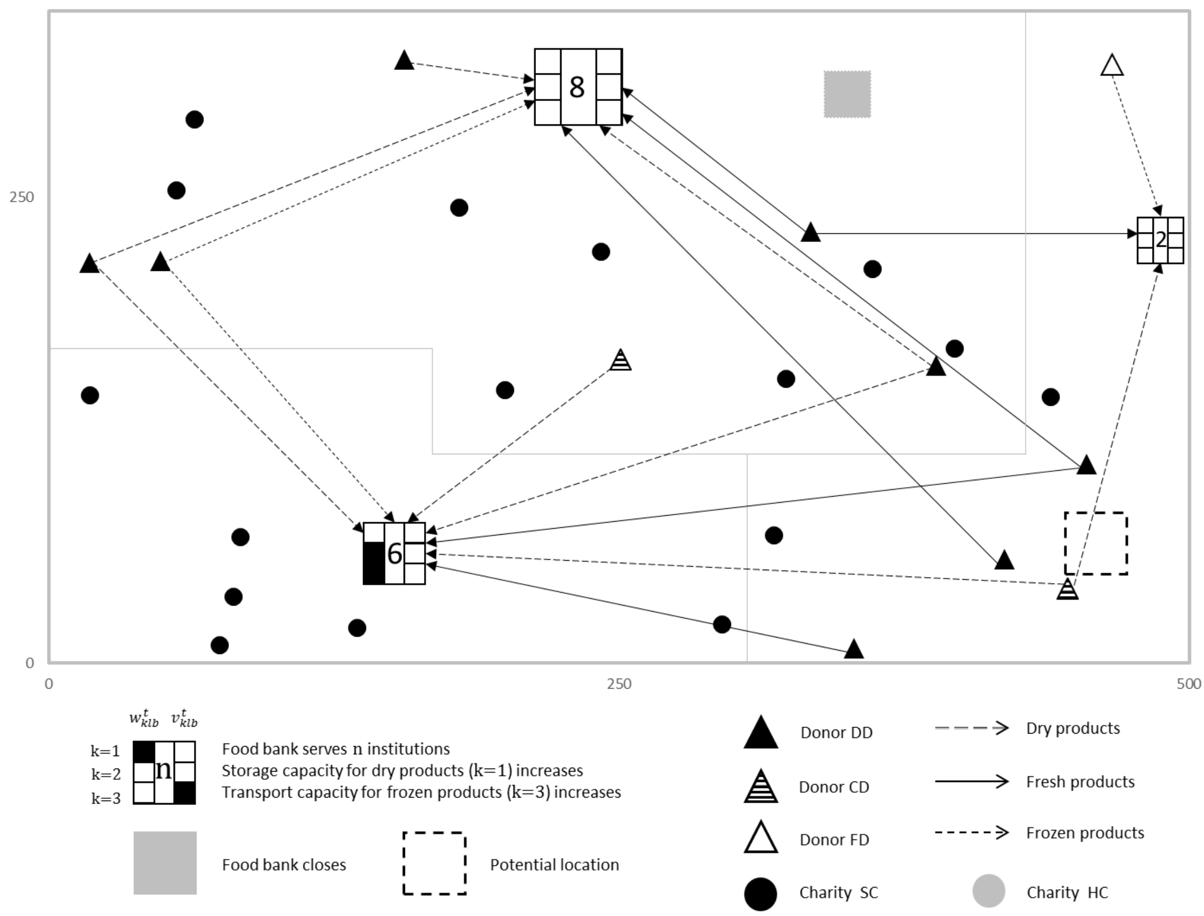

Figure 7: Supply chain configuration of LS1 (Instance 15)

Figure 7 shows that for LS1 three of the four existing food banks are operated, namely the large, the medium and one of the small facilities. Moreover, the medium-sized warehouse also has its storage capacity for fresh and frozen products extended in the first period, and in both cases a medium-sized storage space is installed. The available transport capacity at the three operating facilities is kept unchanged. The three charities on the waiting list do not receive any food assistance and only the minimum demand requirements of the charities in SC are satisfied (cf. Table 21). Financial donations for making food purchases are only used by the small food bank, accounting for merely 0.3% of the total quantity of food items processed by the network.

As displayed in Figure 8, the network associated with the second economic-centric solution LS2 has a similar structure to that of LS1, but the assignment of charities SC to the three operating food banks is slightly different. This is the outcome of giving higher preference to the social objective in LS2, which results in a smaller average distance travelled by a charity to its designated food bank (217.9 d.u. in LS2 versus 231.1 d.u. in LS1). Nevertheless, the environmental impact of LS2 is worse than that of LS1, chiefly due to the fact that all donations made available by donors CD are collected using food bank vehicles. This policy generates the highest CO_2 emissions over all lexicographic solutions (cf. Table 21).

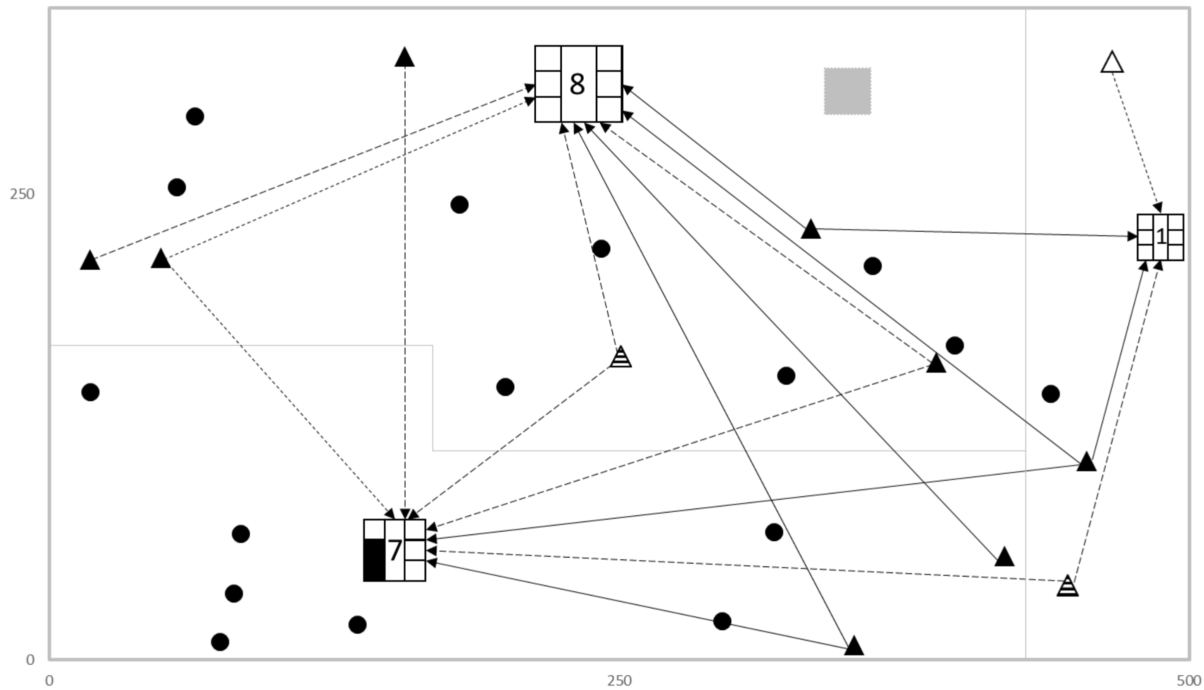

Figure 8: Supply chain configuration of LS2 (Instance 15)

Naturally, the best environmental performance is achieved by solutions LS3 and LS4. Figures 9 and 10 reveal that the configuration of the supply chain network greatly differs from that of the economic-centric solutions. In both cases, all facility location and capacity acquisition decisions are implemented in the first period and involve a significant investment spending. The large and medium-sized food banks are maintained, and a new warehouse is opened with storage capacity for all product families and transport capacity to collect donations of dry products. While in LS3 the two small facilities are closed, in LS4 they are kept and their storage capacities are even expanded through the acquisition of a small storage area (for fresh products in one case, and for frozen products in the other). Hence, in LS4 food banks are operated in all five locations. A common feature to the environmental-centric solutions is the fact that all charities on the waiting list receive assistance, even though their assignment to food banks changes in some cases from one period to the next. In LS4, these charities are supported throughout the whole planning horizon, whereas in LS3 two charities receive donations from the beginning of the time horizon and the third charity is only supported in the last period.

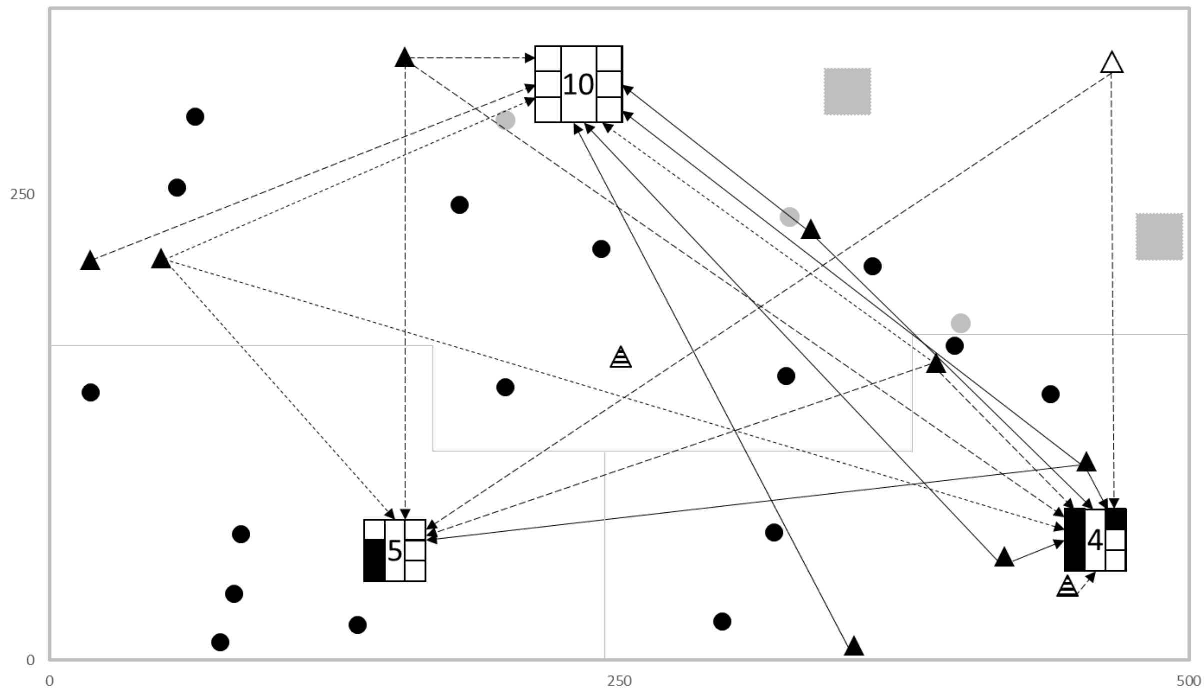

Figure 9: Supply chain configuration of LS3 (Instance 15)

Since food assistance is provided to all 19 charities in LS3 and LS4, significantly less food waste is generated compared with the economic-centric solutions. Furthermore, in order to keep the level of CO_2 emissions low, in-kind donations from donors DD are preferred to food collections from donors CD. Regarding the financial donations, these are completely used up in LS4 as a consequence of the higher relevance given to the social objective compared with LS3. As expected, the level of unsatisfied demand in LS4 is lower than in LS3 and more social work value is also created in LS4.

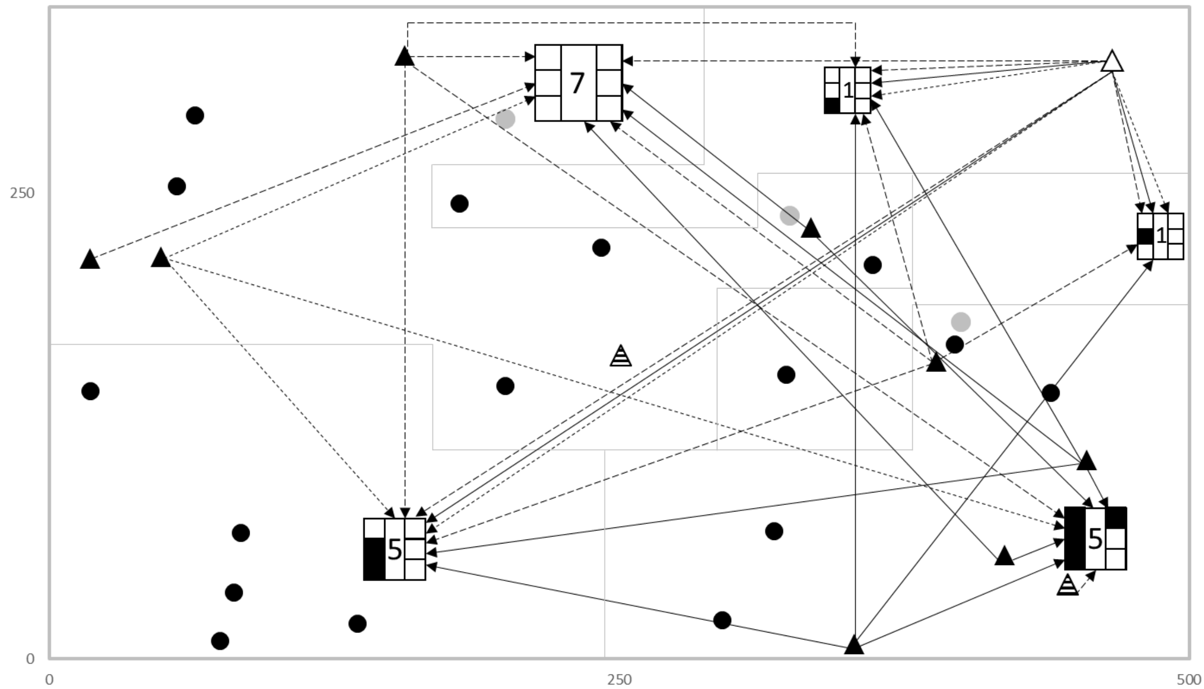

Figure 10: Supply chain configuration of LS4 (Instance 15)

The social-centric solutions exhibit the largest similarity with respect to their network configurations. As displayed in Figures 11 and 12, all existing warehouses are kept and no new facility is established. The storage capacity in the medium-sized food bank and in one of the small facilities is expanded in the first period, but additional transport capacity is not purchased. Since the existing food bank network is subjected to the least changes in LS5 and LS6, the effort to raise investment capital is also the lowest among all solutions. Furthermore, the highest level of food assistance is experienced by all charities (SC and HC) in every period, and their assignment to food banks coincides in LS5 and LS6. In fact, the total quantity of food products processed exceeds by almost 45% the volume handled by the supply chain networks of the economic-centric solutions. More than 90% of the distributed products are in-kind donations. Therefore, a high CO_2 cost for the collection of food items from donors CD is incurred and at the same time the lowest food disposal cost is observed (cf. Table 21).

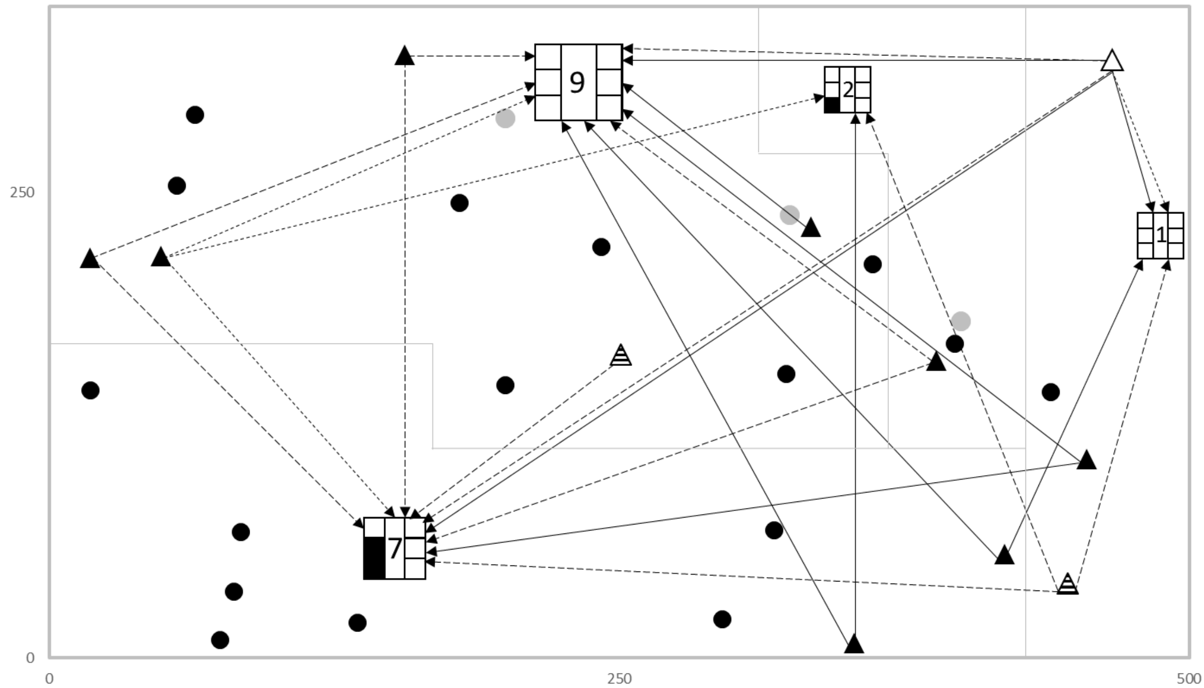

Figure 11: Supply chain configuration of LS5 (Instance 15)

The main difference between the two social-centric solutions and LS1, LS2, LS3 and LS4 involves the inter-warehouse shipment of food products, a feature that is absent from all other solutions. In particular, in LS5, frozen products are delivered from the large food bank to one of the small warehouses in the first four periods but not in the last period, and therefore this product flow is not shown in Figure 11. In contrast, in LS6, frozen products are transported from a small food bank to another small warehouse in all periods.

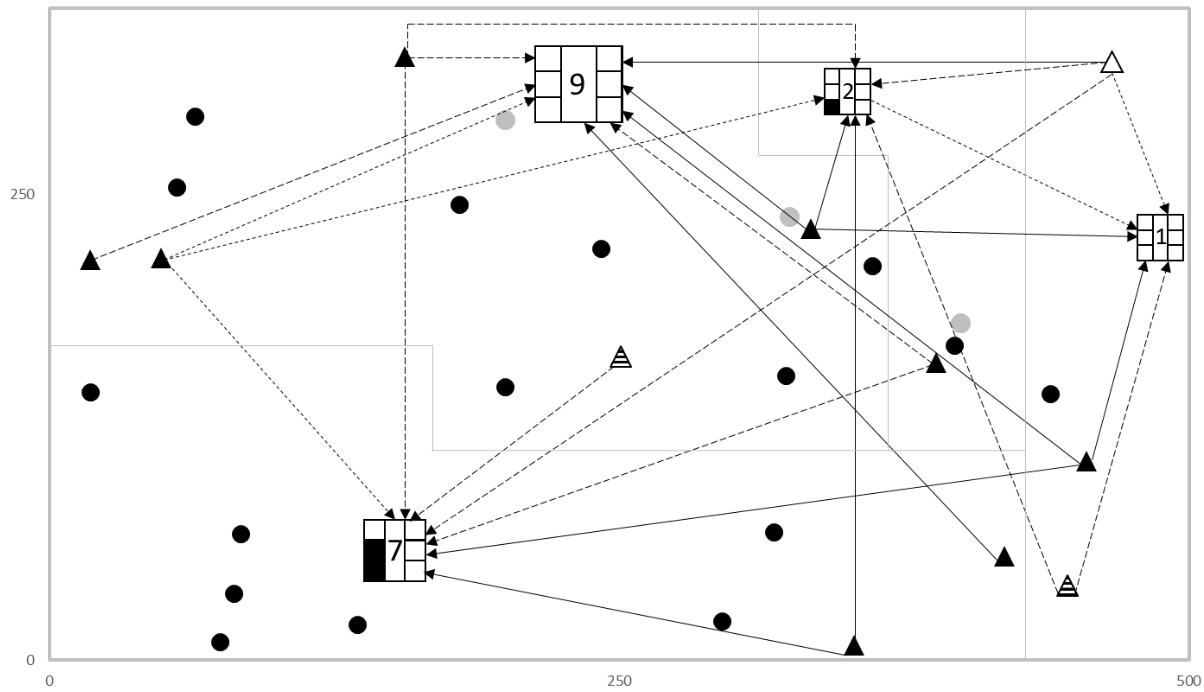

Figure 12: Supply chain configuration of LS6 (Instance 15)

3.2.2. Managerial insights

To gain a broader insight into the trade-offs between the three objectives, we evaluate next the lexicographic solutions according to the following eight key performance indicators (KPIs).

%Cost: Ratio to the largest economic objective function value.

%Storage: Ratio to the largest unused storage capacity at an operating food bank warehouse.

%Waste: Ratio to the largest level of unused in-kind food donations.

%CO2: Ratio to the largest total cost for CO_2 emissions.

%Demand: Ratio to the largest level of unsatisfied demand over all charities (SC and HC).

%Distance: Ratio to the largest distance between a charity and its designated food bank.

%Investment: Ratio to the largest investment capital required w.r.t the total reference budget ($\sum_{t \in t} O^t$).

%Work: 1 - ratio to the largest value of the social work created by the food aid supply chain.

These KPIs are depicted in Figure 13 for all solutions and represent averages over the results obtained for the 20 test instances. The worst possible value of each one of the first seven KPIs is 100%. For example, as reported in Table 12, the largest average value of the economic objective was observed for LS4. Hence, the KPI *%Cost* is 100% for this solution. All other values that appear in Figure 13 for this KPI are smaller than 100%. A different interpretation is associated with the last KPI *%Work*. In this case, the largest average social work value observed is 2,818.33 (see the second last row in Table 13). For LS1, the average social work value obtained is equal to 2,077.55, which corresponds to a KPI of 26% ($(1 - 2077.55/2818.33) \times 100$). Given the above definition of the KPIs, the larger the area of the web in the radar chart, the lower the quality of the corresponding solution.

The analysis in Section 3.2.1 of the trade-offs that arise in solutions LS1 and LS2 is emphasized by the two upper radar charts in Figure 13, which show the largest areas. In fact, these solutions exhibit the worst performance for the KPIs *%Demand*, *%Distance* and *%Work*. In addition, solutions LS1 also have the largest *%Waste* and solutions LS2 have the highest *%*CO_2. The environmental-centric solutions LS4, which apparently show the best average trade-offs in Figure 6, have a better social performance than LS3, whereas the latter solutions achieve superior results with respect to total cost and warehouse storage utilisation. Moreover, both LS3 and LS4 display the best performance regarding CO_2 cost. A closer look at the two radar charts at the bottom of Figure 13 reveals that the social-centric lexicographic solutions have the lowest levels of unused storage capacity, food waste and unsatisfied demand, the smallest maximum distance between a charity and its designated food bank, and the least effort to raise investment capital. However, these positive features seem to be overruled by a reduced economic performance and a high CO_2 cost.

Additional information on the lexicographic solutions is summarized in Table 13. The

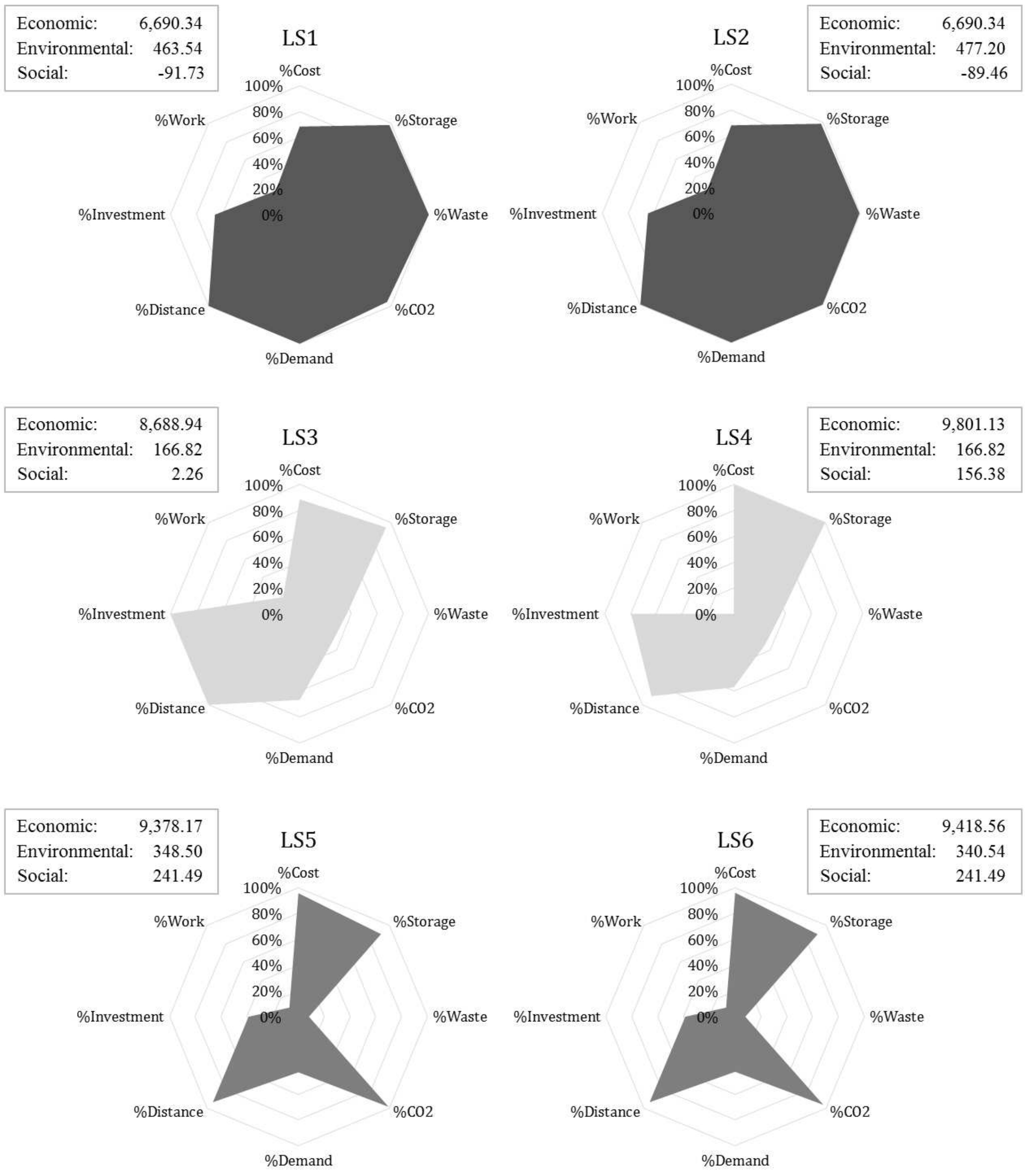

Figure 13: Comparison of selected KPIs for the lexicographic solutions

economic-centric solutions LS1 and LS2 are characterized by several changes in the configuration of the existing food bank network over the planning horizon that take the form of closing one or two small food banks and establishing a new facility with the profile of a small-sized food bank. As a result, a significant effort for procuring investment capital for facility location and capacity acquisition is demanded. The quantity of food products processed by the network is kept to the minimum possible level. This feature is reflected by not providing food assistance to any charity on the waiting list and by satisfying the minimum demand requirements of all other charities (SC). The impact of this strategy is also evidenced by a high percentage of unused food donations. In fact, almost one-quarter of all food items made available by donors are not redistributed to charities. This, in turn, leads to a large waste disposal cost. Solutions LS1 and LS2 also exhibit the largest average collection rate of food products from donors CD. This feature contributes to a significant cost for the CO_2 emissions of food bank vehicles engaged in food collection. A further characteristic of LS1 and LS2 is that most of the financial donations to make food purchases are not used.

The greatest difference to these features is conveyed by the social-centric solutions, LS5 and LS6. The existing food bank network is subjected to few changes, including never opening a new facility. This results in a low investment effort and in a higher utilisation of the available storage capacity. As expected, the largest collection and redistribution of food products occurs in these solutions. Not only all charities on the waiting list are served but also the quantity of food items received by all charities is clearly closer to their desired level of assistance. This is also accomplished by complementing in-kind donations with food purchases using financial donations. On the one hand, the least food waste is achieved with this policy, but on the other hand, food vehicles are engaged in more trips for collecting food donations and for inter-warehouse shipments. Consequently, larger CO_2 costs are incurred and these outweigh the low waste disposal costs. Not surprisingly, the food bank supply chains in LS5 and LS6 create a significant value of social work, which is surpassed by LS4.

Regarding the environmental-centric solutions LS3 and LS4, these demand the largest investment capital for opening/closing facilities and increasing the storage and transport capacity of food banks. Another distinctive feature of these solutions is the lowest level of CO_2 emissions which result from not engaging food vehicles in inter-warehouse transports and not collecting all food donations made available by donors CD. The latter aspect contributes to waste disposal costs that are higher than those in the social-centric solutions. In total, the quantity of food products secured by the food banks is in-between the values achieved by the other lexicographic solutions. Accordingly, the level of food assistance provided to charities SC and HC is significant, but not as high as that reached by LS5 and LS6, especially for those charities on the waiting list. Moreover, the assignment of a charity to different food banks over the planning horizon only occurs in these lexicographic solutions. Naturally, solutions LS3 share a few of the features of the economic-centric solutions, whereas solutions LS4 exhibit some of the characteristics of the social-centric solutions. This is explained by the ranking assigned to the objectives. In LS3, the economic objective is more important than the social objective, while the opposite occurs in LS4.

	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Food banks						
# banks closed	1.6	1.6	1.6	0.3	0.3	0.3
# new banks	0.6	0.6	0.8	0.5	-	-
# operating banks	3.0	3.0	3.2	4.3	3.8	3.8
Total storage capacity added (t)	1,574.5	1,574.5	3,153.0	3,002.7	1,511.4	1,511.4
Total transp. capacity added (t)	91.8	88.5	303.3	321.0	55.6	55.6
Storage capacity utilisation (%)						
dry products	18.1	18.1	22.3	18.0	22.1	22.1
fresh products	42.9	42.9	43.2	37.2	45.9	46.3
frozen products	22.2	22.2	25.7	24.3	32.2	32.3
Transport capacity utilisation (%)						
dry products	11.7	12.1	6.4	4.7	10.6	10.3
fresh products	30.6	31.2	15.1	12.4	31.1	30.9
frozen products	13.5	15.4	4.8	2.4	13.8	14.1
Flow between food banks (t)	2.7	2.7	-	-	184.6	170.4
Charities						
total # new served (HC)	-	-	1.8	2.8	3.0	3.0
Avg. satisfied demand (%)						
of charities SC	69.9	69.9	80.4	78.9	82.7	82.8
of new charities HC	-	-	50.2	67.8	80.8	81.1
of all charities C	59.1	59.1	72.7	76.7	82.4	82.6
min. # assigned to a bank	2.4	2.4	3.1	1.6	1.7	1.7
max. # assigned to a bank	10.5	10.5	9.2	8.8	10.2	10.1

	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
# changes in assignments						
banks-charities	-	-	1.9	0.9	-	-
# assignments to						
food bank 1	10.0	10.0	7.0	7.3	10.1	10.0
food bank 2	0.3	0.3	1.4	2.2	2.2	2.2
food bank 3	1.4	1.4	1.8	3.0	2.4	2.4
food bank 4	2.9	2.9	4.1	4.0	4.4	4.5
food bank 5	1.5	1.5	2.9	2.1	-	-
Max. distance to an assigned						
bank (d.u.)	236.8	236.1	236.3	213.8	222.1	222.1
Donations						
total food donations (kEUR)	11,019.7	11,019.7	13,676.1	14,382.5	15,373.3	15,411.2
total food donations (t)	13,774.3	13,774.3	16,940.5	17,852.8	19,131.7	19,178.1
from donors DD (%)	76.3	75.9	85.2	80.8	74.6	74.8
from donors CD (%)	22.1	22.6	11.0	10.4	16.8	16.4
from donor FD (%)	1.7	1.5	3.8	8.7	8.7	8.8
unused financial donations (kEUR)	1,063.0	1,069.4	706.4	-	7.8	-
unused financial donations (%)	79.6	80.3	54.1	-	0.5	-
Environmental indicators						
total food waste (kEUR)	278.3	276.5	102.9	102.9	27.5	26.4
total food waste (t)	4,358.0	4,330.3	1,613.0	1,612.9	427.9	409.2
total food waste (%)	24.4	24.2	8.9	8.9	2.0	1.9
at donors DD (%)	27.9	28.3	-	-	0.9	0.5
at donors CD (%)	8.7	6.1	53.0	53.0	4.4	6.3
CO_2 emissions (kEUR)	648.7	677.9	230.8	230.8	670.0	654.7
total CO_2 (t-d.u.)	747,820.7	779,489.7	265,194.1	265,196.7	770,730.1	753,600.4
Social indicators						
total value of social work						
created (kEUR)	2,077.5	2,077.5	2,305.3	2,818.3	2,538.4	2,538.4
total investment capital required						
(% of total reference budget)	42.7	42.0	65.0	51.7	25.1	25.1

Table 13: Characteristics of the lexicographic solutions (averages over 20 test instances)

Finally, a common feature to all lexicographic solutions is the operation of the large food bank 1, which serves more than half of the charities in most of the cases. The medium-sized food bank 4 is also present in all solutions and has the second largest service area. Decisions related to network reconfiguration are mostly taken in the first period. Interestingly, the transfer of food products between food banks accounts for less than 1% of the total quantity of food donations processed by the network. Table 14 summarizes the main findings of our analysis.

Economic-centric	Environmental-centric	Social-centric
Small network of food banks	Large network of food banks	Few changes in network design
Minimum level of food assistance	High level of food assistance	Highest level of food assistance
Least use of financial donations		High use of financial donations
Highest level of food waste	Low level of food waste	Lowest level of food waste
Large CO_2 emission cost	Lowest CO_2 emission cost	Large CO_2 emission cost
Large investment effort	Largest investment effort	Lowest investment effort
Low social work value creation	High social work value creation	High social work value creation

Table 14: Main features of lexicographic solutions

3.2.3. Comparison with existing network configuration

To be able to compare the results presented in the previous section with those associated with the configuration of the existing food aid supply chain, we have assumed that a number of conditions would remain unchanged over the planning horizon. Accordingly, the four existing food banks are operated with their initial capacities over all five time periods, and the acquisition of additional capacity (e.g. by opening a new warehouse) is not considered. Moreover, those charities served by food banks at the beginning of the planning horizon continue to receive food assistance and their requirements X^0_{pc} for each product $p \in P$ $(c \in SC)$ are satisfied. No charities on the waiting list are supported by the food banks. In order to be consistent with the profile of the FPA, we have assumed that each small food bank (i.e. facilities 2 and 3) processes 2.5% of the total food donations and the medium-sized food bank 4 processes 30%. The remaining 65% are handled by the large food bank 1. In total, 3,935.52 tonnes of food items are distributed in each period, 19.9% of product 1, 21.3% of product 2, 38.5% of product 3, 19.1% of product 4, and 1.2% of product 5. The total distributed amount is the average of $\sum_{p \in P} \sum_{c \in SC} X^0_{pc}$ over the 20 instances. Furthermore, all other input data were obtained by taking the corresponding averages over the test instances. Table 15 presents the values that were estimated for the three objective functions when the existing supply chain configuration (denoted "existing network") is maintained over the planning horizon. The percent deviations of the lexicographic solutions from these objective values are also shown in the table.

Estimated objective function values	Existing network	Lexicographic solutions					
		LS1	LS2	LS3	LS4	LS5	LS6
Economic (m.u.)	7,786.40	-14%	-14%	12%	26%	20%	21%
Environmental (kEUR)	329.81	41%	45%	-49%	-49%	6%	3%
Social	49.23	-286%	-282%	-95%	218%	391%	391%

Table 15: Comparison of lexicographic solutions with existing network configuration

Under the conditions described above, the estimated economic value of the existing network configuration is higher in all lexicographic solutions, except in the economic-centric. Concerning the environmental criterion, again the estimated value compares favourably with all solutions other than LS3 and LS4. The latter exhibit a significant lower total cost for food waste disposal and CO_2 emissions. Interestingly, the environmental performance of the social-centric solutions is in line with that of the existing network. Finally, the greatest differences between the lexicographic solutions and the estimated values occur in the social criterion. Since the social performance of the food bank supply chain is to be maximised, it can be seen that solutions LS5 and LS6 achieve a significantly greater gain than that estimated when the initial network design is maintained and food redistribution conditions are not changed.

The values shown in Table 15 also indicate that a policy that involves keeping the number of served charities at the initial level and supplying them with the same quantity of food products in all time periods, while not investing in the redesign of the food bank network, does not have inferior quality compared with the policies given by the lexicographic solutions. The three estimates provided in the table can also help decision makers to evaluate the impact of policy changes towards a more economic, environmental or social oriented management of the supply chain. This is illustrated in Figure 14 by comparing the best and worst objective function values of the lexicographic solutions with the estimates associated with operating the existing food bank supply chain.

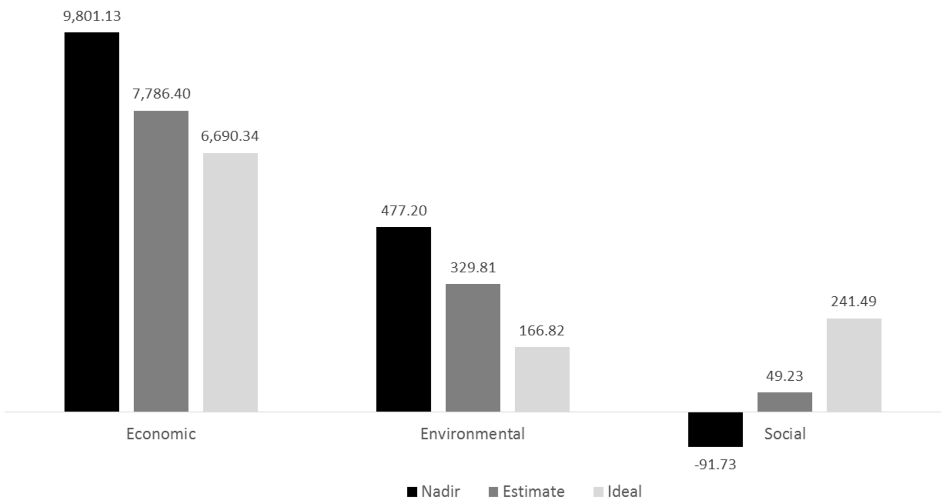

Figure 14: Comparison of ideal and nadir values with existing network configuration

3.2.4. Impact of scaling factors

In Section 3.2.1 we have presented the results obtained for a specific choice of weighting factors (Case 1) over the 20 test instances. We now analyse the outcome of the other seven groups of preferences that were given to the individual components of the environmental and social objective functions (recall Table 11). Figure 15 shows the average performance of the three objectives for Cases 2 and 3, and their comparison with Case 1. These three parameter combinations differ in the weighting factors assigned to the components of the environmental objective function, while the components of the social objective function are equally important. Regarding the economic results, the differences between Cases 2 and 3 compared with Case 1 are only observed in the environmental-centric solutions LS3 and LS4. In Case 2, these solutions have a higher economic cost than in Case 1, while the opposite occurs in Case 3. As for the social objective, both cases have a negative impact, with the exception of solution LS3 for which better results are obtained in Case 2 compared with Case 1. Concerning the environmental objective, and keeping in mind the different weight combinations that the two environmental components have in each case, the solutions obtained in Case 2 outperform those of Case 1. When higher relevance is given to food waste disposal than to the generation of CO2 emissions (Case 2), food assistance is provided to more charities and a larger quantity of food products is distributed, resulting in a lower level of food waste and a higher level of CO_2 emissions associated with trips to collect in-kind donations. The corresponding weighted environmental cost of all solutions of Case 2 is lower than the respective cost of Case 1. Reverse results are obtained for Case 3. Giving preference to the reduction of carbon footprint has a higher weighted ecological cost than a neutral policy with regard to the two environmental factors (Case 1).

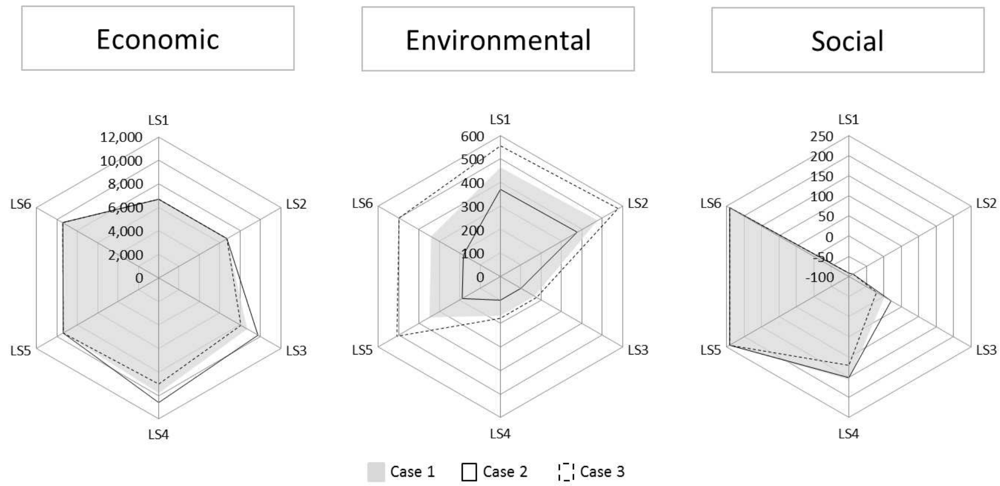

Figure 15: Comparison of lexicographic solutions for different scaling factors (Cases 1–3)

Figure 16 illustrates the results obtained for the remaining five parameter combinations. In each one of these, one of the individual components in the social objective function is given the highest preference. Furthermore, the scaling factors in the environmental objective take the same value (i.e. $\alpha_2 = \alpha_3 = 0.5$). It can be seen that the economic and environmental values of all solutions associated with these parameter combinations almost overlap, whereas differences in the social objective values occur. The social value of all solutions in Case 4, weighted to express a higher preference to supporting new charities, and Case 5, with weights that value most the investment spending indicator, is higher than in Case 1. In contrast, when the preferred social goals are the creation of social work (Case 6), the balance achieved in product distribution (Case 7), or the proximity of charities to food banks (Case 8), the corresponding weighted social value of the solutions is usually worse than in Case 1, the sole exceptions being solutions LS1 and LS2 of Case 6.

Finally, Figures 15 and 16 can play an instrumental role in the decision making process since they enable the evaluation of the impact of assigning higher preference to each one of the components in the environmental and social objective functions. Typically, benefits achieved on some features from specific preferences lead to a deterioration of other features.

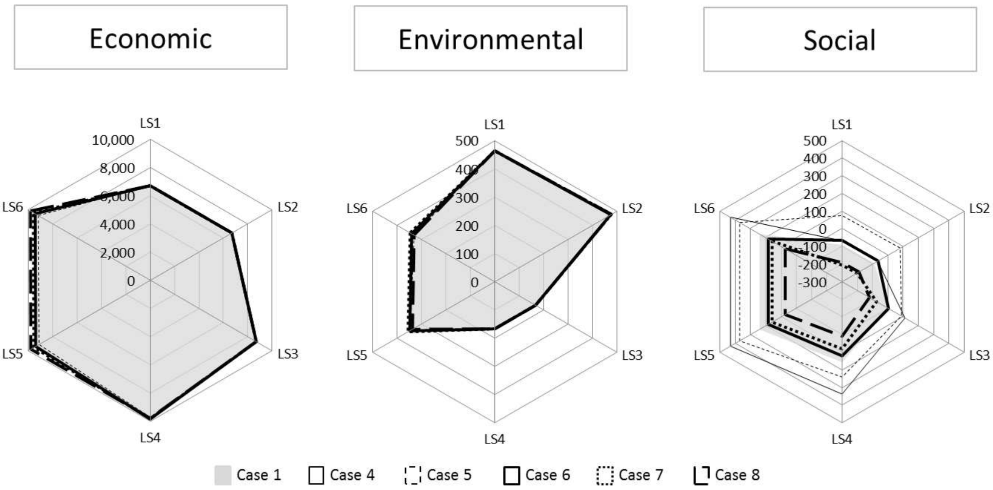

Figure 16: Comparison of lexicographic solutions for different scaling factors (Cases 1 and 4–8)

4. Conclusions

In the present research work, which comprises Part I (Martins et al. (2016)) and Part II, we addressed the problem of redesigning an existing multi-echelon food aid supply chain network over a multi-period planning horizon. Following a field study at the FPBA that helped to define the problem, we developed a multi-objective mixed-integer linear programming model to assist decision makers with location decisions involving food banks and with logistics decisions for food collection and distribution. The three dimensions of sustainability (i.e. economic, environmental and social) were integrated in the model. Based on information gathered from the field work and additional data drawn from official sources, we generated a set of instances that capture the main characteristics of the food bank network operated by the FPBA in the south of Portugal. Using the lexicographic method, we identified a subset of Pareto optimal solutions for each instance using CPLEX. Finally, we conducted a detailed analysis of these solutions and evaluated the trade-offs between the economic, environmental and social objectives.

Even though the lexicographic solutions reflect "extreme" situations due to the predominance of one objective over the other two, they provide critical reference points for defining the future positioning of the food aid supply chain. By highlighting the pros and cons of each lexicographic solution, we further assist decision makers in better understanding the consequences of different preference information. The comparison of the main features of the lexicographic solutions with the strategy currently adopted by the FPBA to manage its food bank network suggests that this organisation favours the social dimension. Indeed, the FPBA strives to secure the largest possible volume of food donations, to achieve zero food waste and to provide food assistance in the most equitable manner to as many charities as possible. This strategy also involves maintaining all existing food banks and making a very small investment in the expansion of their storage and transport capacities. Hence, a high value of social work is generated by operating all food banks. Being a social economy organisation, this is a natural strategic positioning for the FPBA. However, our computational results reveal that it is possible to consider alternative managerial policies that can offer a different compromise between the social, environmental and economic objectives in pursuit of a more sustainable supply chain.

Finally, we view the generation of lexicographic solutions as the first stage in a more evolving process to assist decision makers, especially those who are unfamiliar with mathematical optimisation. A future research venue would be to identify additional Pareto optimal solutions, for example, by applying the ε-constraint method, or even its augmented variant, a technique that is widely used in multi-objective optimisation (see e.g. Arampantzi and Minis (2017); Santibañez-Aguilar et al. (2014); Varsei and Polyakovskiy (2017)). This *a posteriori* approach can play a key role in further helping to understand the trade-offs when moving from one Pareto optimal solution to another. This knowledge is also very important in an interactive method to guide the search towards the (from the decision maker's perspective) most promising solutions (Miettinen et al. (2008)).

Acknowledgements

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Appendices

A. MILP formulation

For the sake of completeness, we describe the notation used and present the refined mathematical formulation. Since two new sets of constraints were introduced in the model proposed by Martins et al. (2016), the numbering of the constraints differs from the original model. Furthermore, as opposed to Martins et al. (2016), we start by stating the three objective functions and number them from one to three.

Sets

Symbol	Description
T	Time periods in the planning horizon
DD	Donors that deliver food items to food banks
CD	Donors that require collection of food items by food banks
FD	Donors that provide financial donations to food banks
D	All donors, $D = DD \cup CD \cup FD$ (subsets are pairwise disjoint)
OB	Existing food banks at the beginning of the planning horizon
PB	Potential sites for locating new food banks
B	All food banks, $B = OB \cup PB$ and $OB \cap PB = \emptyset$
B_d	Food banks that can receive food products from donor $d \in DD$, $B_d \subseteq B$
SC	Charities served by food banks at the beginning of the planning horizon
HC	Charities on hold, i.e. agencies on the waiting list of the food bank association
C	All charities, $C = SC \cup HC$ and $SC \cap HC = \emptyset$
C_b	Charities whose geographical locations fall outside the service area of food bank $b \in B$, $C_b \subset C$
K	Families of food products
P_k	Individual food items belonging to family $k \in K$, $\cap_{k \in K} P_k = \emptyset$
P	All food products, $P = \cup_{k \in K} P_k$
L	Discrete capacity levels for storage areas / transport resources

Table 16: Index sets

It is assumed that the number of existing food banks does not exceed the number of charities that were served by some food bank prior to the supply chain network redesign project, i.e. $|OB| \leq |SC|$.

Financial data

Symbol	Description
FI^t	Fixed cost of opening a new food bank in period $t \in T$
$VSI^t_{\ell k}$	Cost of installing storage capacity of size $\ell \in L$ for product family $k \in K$ in period $t \in T$ per unit of capacity
$VTI^t_{\ell k}$	Cost of installing transport capacity of size $\ell \in L$ for product family $k \in K$ in period $t \in T$ per unit of capacity
FU^t	Fixed cost of closing an initially existing food bank in period $t \in T$
VU^t_k	Cost of dismantling one unit of storage capacity for product family $k \in K$ due to closing an initially existing food bank in period $t \in T$
FC^t	Fixed cost of serving a charity in period $t \in T$
VS^t_{kb}	Cost of operating one unit of storage capacity for product family $k \in K$ at food bank $b \in B$ in period $t \in T$
VH^t_{kb}	Cost of handling one unit of food products belonging to family $k \in K$ at food bank $b \in B$ in period $t \in T$
O^t	Total budget available in period $t \in T$ for expenditures on facility location and capacity acquisition
$\widetilde{Q}^t_d$	Financial donation of donor $d \in FD$ to purchase food products in period $t \in T$
τ^t_p	Cost of purchasing one unit of food product $p \in P$ in period $t \in T$
φ^t	Cost of disposing one unit of a food product in period $t \in T$
ω^t	Cost of CO_2 emissions (per tonne-d.u.) generated from transporting one unit of a food product in period $t \in T$

Table 17: Financial parameters

We recall that the financial parameters are expressed in monetary units, except parameters τ^t_p, φ^t and ω^t, which are measured in 1,000 €. Tonne is the unit of measurement used for storage and transport capacities as well as for food product quantities.

Additional parameters

Symbol	Description
Q_{pd}^{t}	Quantity of food product $p \in P$ made available by donor $d \in DD \cup CD$ in period $t \in T$
$\overline{M}_{kb}$	Storage capacity for product family $k \in K$ that is available at food bank $b \in OB$ at the beginning of the planning horizon ($\overline{M}_{kb} \geq 1$)
$M_{\ell k}$	Storage capacity of size $\ell \in L$ for product family $k \in K$ that can be installed in a food bank
$\overline{N}_{kb}$	Transport capacity for product family $k \in K$ that is available at food bank $b \in OB$ at the beginning of the planning horizon
$N_{\ell k}$	Transport capacity of size $\ell \in L$ for product family $k \in K$ that can be purchased by a food bank
R_{pc}^{t}	Demand of charity $c \in C$ for food product $p \in P$ in period $t \in T$
X_{pc}^{0}	Quantity of food product $p \in P$ received by charity $c \in SC$ prior to the network redesign project
$\beta_1, \beta_2, \beta_3$	User-defined constants, $\beta_i \in (0, 1]$, $i = 1, 2, 3$
U_{ij}	Distance between origin i and destination j for every $(i, j) \in A$ (in d.u.)
α_i	Non-negative normalising factors ($i = 1, \ldots, 8, i \neq 6$)
α_6^{t}	Non-negative normalising factor that includes the value of the social work generated per unit of storage capacity that is available at a food bank in period $t \in T$

Table 18: Capacity and demand parameters

Variables

Symbol	Description
y_b^t	1 if the *status* of food bank $b \in B$ changes in period $t \in T$, 0 otherwise; if $b \in PB$, $y_b^t = 1$ means that a new food bank is established in site b in period t; if $b \in OB$, $y_b^t = 1$ means that the initially existing food bank b is closed in period t
$w_{\ell kb}^t$	1 if storage capacity of size $\ell \in L$ is installed in food bank $b \in B$ for product family $k \in K$ in period $t \in T$, 0 otherwise
$v_{\ell kb}^t$	1 if transport capacity of size $\ell \in L$ is acquired by food bank $b \in B$ for product family $k \in K$ in period $t \in T$, 0 otherwise
z_{bc}^t	1 if charity $c \in C$ is served by food bank $b \in B$ in period $t \in T$, 0 otherwise

Table 19: Binary decision variables

Symbol	Description
x_{pij}^t	Quantity of food product $p \in P$ moved from origin i to destination j in period $t \in T$, $(i,\ j) \in A$
ξ_d^t	Financial donation from donor $d \in FD$ not spent in period $t \in T \cup \{0\}$ with $\xi_d^0 = 0$ for every $d \in FD$
θ_{kb}^t	Unused transport capacity for product family $k \in K$ in food bank $b \in B$ in period $t \in T$
γ^t	Deviation from the reference budget O^t in period $t \in T$
δ^t	Maximum level of unsatisfied demand among charities served in period $t \in T$
ε^t	Maximum distance between a charity and its assigned food bank in period $t \in T$ (in d.u.)

Table 20: Continuous decision variables

Mathematical formulation

$$
\begin{aligned}
\text{Min}\, z_1 = & \sum_{t\in T}\sum_{b\in B}\sum_{c\in C} FC^t\, z_{bc}^t + \sum_{t\in T}\sum_{b\in OB}\sum_{k\in K} VS_{kb}^t\, \overline{M}_{kb}\left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \\
& \sum_{t\in T}\sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} VS_{kb}^t\, M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} + \\
& \sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\sum_{p\in P_k}\sum_{i\in D\cup B\setminus\{b\}} VH_{kb}^t\, x_{pib}^t + \alpha_1 \sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\theta_{kb}^t \\
& - \alpha_1 \sum_{d\in FD} \xi_d^{|T|}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\text{Min}\, z_2 = & \alpha_2 \sum_{t\in T}\sum_{p\in P}\varphi^t \left[\sum_{d\in DD}\left(Q_{pd}^t - \sum_{b\in B_d} x_{pdb}^t\right) + \sum_{d\in CD}\left(Q_{pd}^t - \sum_{b\in B} x_{pdb}^t\right)\right] + \\
& \alpha_3 \sum_{t\in T}\sum_{b\in B}\sum_{p\in P}\sum_{i\in CD\cup B\setminus\{b\}} \omega^t\, U_{ib}\,(1 + x_{pib}^t)
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
\text{Max}\, z_3 = & \alpha_4 \sum_{t\in T}\sum_{b\in B}\sum_{c\in HC} z_{bc}^t + \alpha_5 \sum_{t\in T}\gamma^t + \\
& \sum_{t\in T}\alpha_6^t \left[\sum_{b\in OB}\sum_{k\in K}\overline{M}_{kb}\left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} M_{lk}\sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}}\right] \\
& - \alpha_7 \sum_{t\in T}\delta^t - \alpha_8 \sum_{t\in T}\varepsilon^t
\end{aligned} \tag{3}
$$

subject to

$$\sum_{b\in B_d} x_{pdb}^t \le Q_{pd}^t \qquad d\in DD,\ p\in P,\ t\in T \tag{4}$$

$$\sum_{b\in B} x_{pdb}^t \le Q_{pd}^t \qquad d\in CD,\ p\in P,\ t\in T \tag{5}$$

$$\sum_{p\in P}\sum_{b\in B}\tau_p^t\, x_{pdb}^t + \xi_d^t = \widetilde{Q}_d^t + \xi_d^{t-1} \qquad d\in FD,\ t\in T \tag{6}$$

$$\sum_{t\in T} y_b^t \le 1 \qquad b\in B \tag{7}$$

$$\sum_{b\in B} y_b^t \le \lceil \beta_1\, |B| \rceil \qquad t\in T \tag{8}$$

$$\sum_{t \in T} \sum_{\ell \in L} w_{\ell k b}^{t} \leq \sum_{t \in T} y_b^t \qquad b \in PB,\ k \in K \tag{9}$$

$$\sum_{t \in T} \sum_{\ell \in L} w_{\ell k b}^{t} \leq 1 - \sum_{t \in T} y_b^t \qquad b \in OB,\ k \in K \tag{10}$$

$$\sum_{\ell \in L} w_{\ell k b}^{t} \leq \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{11}$$

$$\sum_{\ell \in L} \sum_{k \in K} w_{\ell k b}^{t} \geq y_b^t \qquad b \in PB,\ t \in T \tag{12}$$

$$\sum_{\ell \in L} v_{\ell k b}^{t} \leq |L| \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{13}$$

$$\sum_{\ell \in L} v_{\ell k b}^{t} \leq |L| \left[\overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \right] \qquad b \in OB,\ k \in K,\ t \in T \tag{14}$$

$$\begin{aligned} &\sum_{b \in PB} FI^t \, y_b^t + \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VSI_{\ell k}^t \, M_{\ell k} \, w_{\ell k b}^t + \\ &\quad \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VTI_{\ell k}^t \, N_{\ell k} \, v_{\ell k b}^t + \\ &\quad \sum_{b \in OB} \left(FU^t + \sum_{k \in K} VU_k^t \, \overline{M}_{kb} \right) y_b^t + \gamma^t = O^t \qquad t \in T \end{aligned} \tag{15}$$

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{16}$$

$$\begin{aligned} &\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \\ &\quad \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \qquad b \in OB,\ k \in K,\ t \in T \end{aligned} \tag{17}$$

$$\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x_{pib}^t + \theta_{kb}^t = \sum_{\ell \in L} N_{\ell k} \sum_{\tilde{t}=1}^{t} v_{\ell k b}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{18}$$

$$\begin{aligned} &\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x_{pib}^t + \theta_{kb}^t = \overline{N}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \\ &\quad \sum_{\ell \in L} N_{\ell k} \sum_{\tilde{t}=1}^{t} v_{\ell k b}^{\tilde{t}} \qquad b \in OB,\ k \in K,\ t \in T \end{aligned} \tag{19}$$

$$\sum_{b \in B} z_{bc}^t = 1 \qquad c \in SC,\ t \in T \tag{20}$$

$$\sum_{b \in B} z_{bc}^{t} \leq 1 \qquad c \in HC,\ t \in T \tag{21}$$

$$\sum_{b \in B} z_{bc}^{t+1} \geq \sum_{b \in B} z_{bc}^{t} \qquad c \in HC,\ t = 1, \ldots, |T|-1 \tag{22}$$

$$z_{bc}^{t-1} - z_{bc}^{t} \leq \sum_{\overline{b} \in B} y_{\overline{b}}^{t} \qquad b \in B,\ c \in C,\ t = 2, \ldots, |T| \tag{23}$$

$$\sum_{t \in T} \sum_{c \in C_b} z_{bc}^{t} \leq 0 \qquad b \in B \tag{24}$$

$$\sum_{b \in B} x_{pbc}^{t} \geq \beta_2 X_{pc}^{0} \qquad c \in SC,\ p \in P,\ t \in T \tag{25}$$

$$\sum_{b \in B} x_{pbc}^{t} \geq \beta_3 R_{pc}^{t} \sum_{b \in B} z_{bc}^{t} \qquad c \in HC,\ p \in P,\ t \in T \tag{26}$$

$$x_{pbc}^{t} \leq R_{pc}^{t} z_{bc}^{t} \qquad b \in B,\ c \in C,\ p \in P,\ t \in T \tag{27}$$

$$\sum_{p \in P} \sum_{b \in B} \frac{R_{pc}^{t} z_{bc}^{t} - x_{pbc}^{t}}{R_{pc}^{t}} \leq \delta^{t} \qquad c \in C,\ t \in T \tag{28}$$

$$U_{bc} z_{bc}^{t} \leq \varepsilon^{t} \qquad b \in B,\ c \in C,\ t \in T \tag{29}$$

$$z_{bc}^{t} \leq \sum_{\tilde{t}=1}^{t} y_{b}^{\tilde{t}} \qquad b \in PB, c \in C,\ t \in T \tag{30}$$

$$z_{bc}^{t} \leq 1 - \sum_{\tilde{t}=1}^{t} y_{b}^{\tilde{t}} \qquad b \in OB, c \in C,\ t \in T \tag{31}$$

$$\sum_{c \in C} z_{bc}^{t} \geq \sum_{\tilde{t}=1}^{t} y_{b}^{\tilde{t}} \qquad b \in PB,\ t \in T \tag{32}$$

$$\sum_{c \in C} z_{bc}^{t} \geq 1 - \sum_{\tilde{t}=1}^{t} y_{b}^{\tilde{t}} \qquad b \in OB,\ t \in T \tag{33}$$

$$\sum_{i \in D \cup B \setminus \{b\}} x_{pib}^{t} = \sum_{j \in C \cup B \setminus \{b\}} x_{pbj}^{t} \qquad b \in B,\ p \in P,\ t \in T \tag{34}$$

$$y_{b}^{t},\ z_{bc}^{t} \in \{0, 1\} \qquad b \in B,\ c \in C,\ t \in T \tag{35}$$

$$w_{\ell kb}^{t},\ v_{\ell kb}^{t} \in \{0, 1\} \qquad b \in B,\ \ell \in L,\ k \in K,\ t \in T \tag{36}$$

$$x_{pij}^{t} \geq 0 \qquad p \in P,\ (i, j) \in A,\ t \in T \tag{37}$$

$$\theta^t_{kb} \geq 0 \qquad b \in B,\ k \in K,\ t \in T \qquad (38)$$

$$\xi^t_d \geq 0 \qquad d \in FD,\ t \in T \cup \{0\} \qquad (39)$$

$$\delta^t,\ \varepsilon^t \geq 0 \qquad t \in T \qquad (40)$$

$$\gamma^t \text{ free} \qquad t \in T \qquad (41)$$

B. Detailed results

The following table summarizes the main characteristics of the lexicographic solutions obtained for Instance 15.

	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective function values						
economic (m.u.)	6,094.4	6,094.4	7,257.2	8,825.5	8,183.4	8,208.1
environmental (kEUR)	505.6	529.9	142.1	142.1	390.1	370.4
social	-82.6	-75.6	63.9	181.2	275.7	275.7
Food banks						
# banks closed	1	1	2	-	-	-
# new banks	-	-	1	1	-	-
# operating banks	3	3	3	5	4	4
Total storage capacity added (t)	1,381.7	1,381.7	3,774.4	3,949.6	1,415.4	1,415.4
Total transp. capacity added (t)	-	-	505.5	505.5	-	-
Avg. storage capacity utilisation (%)						
dry products	18.2	18.2	21.1	20.6	25.6	25.4
fresh products	43.7	43.7	39.1	36.2	57.2	57.8
frozen products	29.2	29.2	38.4	39.8	41.9	42.2
Avg. transp. capacity utilisation (%)						
dry products	19.2	19.4	12.3	9.3	17.2	16.4
fresh products	-	-	-	-	-	-
frozen products	-	-	-	-	2.2	2.8
Flow between food banks (t)	-	-	-	-	9.9	12.7
Charities						
total # new served (HC)	-	-	3	3	3	3
Avg. satisfied demand (%)						
of charities SC	70.5	70.5	77.3	81.9	86.2	86.3
of new charities HC	-	-	76.6	78.6	86.1	86.1
of all charities C	59.7	59.7	73.5	81.4	86.2	86.3
min. # assigned to a bank	2	1	4	1	1	1

	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
max. # assigned to a bank	8	8	10	7	9	9
# changes in assignments						
banks-charities	-	-	1	-	-	-
# assignments to						
food bank 1	8	8	9	7	9	9
food bank 2	-	-	-	1	2	2
food bank 3	2	1	-	1	1	1
food bank 4	6	7	5	5	7	7
food bank 5	-	-	4	5	-	-
Max. distance to an assigned						
bank (d.u.)	232.1	217.9	212.8	182.5	182.5	182.5
Donations						
total food donations (kEUR)	10,122.2	10,122.2	12,858.2	14,022.5	14,775.4	14,790.1
total food donations (t)	12,337.4	12,337.4	15,196.7	16,824.6	17,824.2	17,835.8
from donors DD (%)	72.7	72.5	85.4	77.1	72.2	72.7
from donors CD (%)	27.0	27.3	13.5	12.2	18.9	18.0
from donor FD (%)	0.3	0.2	1.2	10.7	9.0	9.2
unused financial donations (kEUR)	1,075.4	1,140.6	1,164.4	0.0	0.0	0.0
unused financial donations (%)	85.4	90.6	92.5	0.0	0.0	0.0
Environmental indicators						
total food waste (kEUR)	258.0	257.1	84.1	84.1	7.9	10.6
total food waste (t)	4,041.5	4,027.0	1,316.4	1,316.4	112.3	150.4
total food waste (%)	24.7	24.7	8.1	8.1	0.7	0.9
at donors DD (%)	30.9	31.0	-	-	0.9	-
at donors CD (%)	1.0	-	39.1	39.1	-	4.5
CO_2 emissions (kEUR)	753.1	802.8	200.2	200.2	772.3	730.2
total CO_2 (t-d.u.)	869,254.3	925,322.2	230,295.9	230,295.9	890,358.0	846,229.0
Social indicators						
total value of social work						
created (kEUR)	1,951.6	1,951.6	2,186.33	2,562.5	2,056.8	2,056.8
total investment capital required						
(% of total reference budget)	22.0	22.0	67.3	62.6	18.1	18.1

Table 21: Characteristics of lexicographic solutions (Instance 15)

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Qbing ist eine Forschungsgruppe an der Hochschule für Technik und Wirtschaft des Saarlandes, die spezialisiert ist auf interdisziplinäre Projekte in den Bereichen Produktion, Logistik und Technologie. Ein Team aus derzeit acht Ingenieuren und Logistikexperten arbeitet unter der wissenschaftlichen Leitung von Prof. Dr. Steffen Hütter sowohl in öffentlich geförderten Projekten als auch zusammen mit Industriepartnern an aktuellen Fragestellungen zur Optimierung von logistischen Prozessabläufen in Handel und Industrie unter Einbeziehung modernster Sensortechnologie und Telemetrie. Qbing hat auch und gerade auf dem Gebiet der angewandten Forschung Erfahrung in der Zusammenarbeit mit kleinen und mittelständischen Unternehmen.

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