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Redesigning a food bank supply chain network in a triple bottom line context

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ABSTRACT

We address the problem of redesigning a multi-echelon food bank supply chain network for the collection of food donations and their distribution to charitable agencies. Strategic decisions comprise opening new food banks and selecting their storage and transport capacities from a set of discrete sizes over a multi-period planning horizon. In addition, existing food banks may be closed or have their capacities expanded. Logistics decisions involve the number of charitable agencies to be supplied, their allocation to food banks, and the flow of food products across the network. We propose a mixed-integer linear programming model that accounts for all dimensions of sustainability – economic, environmental and social – through three objective functions. A computational study is conducted for problem instances capturing the characteristics of the current network operated by the Portuguese Federation of Food Banks (FPBA) in the south of Portugal. To investigate the trade-offs that occur under the three conflicting objectives, a subset of non-dominated solutions is identified through lexicographic ordering. Our study reveals that the largest trade-offs occur between the economic and the other two objectives, and that attributing the highest priority to the environmental objective results in the most balanced solutions. Moreover, multiobjective strategies that can improve the sustainability performance of the FPBA are identified. In particular, we have concluded that there is margin for improving the current performance, especially if the social dimension continues to be favoured by the FPBA.

1. Introduction

In 2016, the proportion of people at risk of poverty or social exclusion in the European Union (EU) was estimated at 23.4%, affecting around 117.5 million people (Eurostat, 2017). Paradoxically, 20–30% of all food produced in the EU is wasted annually across the food supply chain from the farm to the household, with associated costs estimated at 143 billion euros in 2012 (Stenmarck et al., 2016). Over the last few years, the EU has promoted various actions to reduce food losses and food waste across the food supply chain (European Commission (European Commission.a, 2017). In particular, the member states are committed to achieve a 30% food waste reduction by 2025 (European Parliament (European Parliament, 2018). The aforementioned figures highlight that a shortage in food supply is not at the root of the problem of food insecurity. The real challenge lies in distributing the available food equitably among those people in need of food assistance.

Many humanitarian aid organisations, including food banks, act as intermediaries between food resources and people in need (Orgut et al., 2016a, Power and Albala, 2015). Typically, these organisations receive edible food from corporations and individuals, process the donated food products at storage facilities and distribute them to the end users, either directly or indirectly via non-profit community and governmental agencies. For social economy actors, such as food banks, return on investment and other economic parameters are not of primary concern. Instead, their activities are mostly centered around social and environmental performance. In this respect, food banks play a significant role in promoting the sustainability of the food supply chain.

Founded in 1999, the Portuguese Federation of Food Banks (the Portuguese acronym is FPBA) is a non-governmental organisation that coordinates a network of 21 food banks. The mission of the FPBA is to reduce food waste through the recovery of surplus and about-to-waste food items and the distribution of this food to the needy population (FPBA, 2018). It is estimated that around 1 million tonnes are lost across the food supply chain in Portugal every year, representing 17% of the total food production (Baptista et al., 2012). Rather than providing aid directly to those in need, the Portuguese food banks dole out

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donated food to a variety of charitable agencies such as family associations and nursing homes, for local distribution. In 2016, the members of the FPBA served 2505 charitable agencies, which, in turn, supported more than 400,000 people (FPBA, 2018).

Food banks operate with limited resources which depend primarily on donations and volunteer work. It is therefore critical for the FPBA to design and manage its supply chain network in an efficient and effective way in order to secure the largest possible quantity of food donations and, consequently, reach as many needy people as possible (González-Torre et al. 2017). The current configuration of the network of food banks is not the outcome of a strategic planning process, but rather emerged through operational decisions and occasionally identified donation opportunities over the last 20 years. In this study, we investigate the benefits that are likely to be achieved from redesigning the existing network. Not only cost savings and improved operational performance are expected, but also environmental and social gains are anticipated.

The contribution of this paper is fourfold. (1) Focus is given for the first time to a strategic planning problem arising in the context of food aid distribution. (2) We propose a novel multi-objective, mixed-integer linear programming (MILP) model that incorporates the three dimensions of sustainability – economic, environmental and social – into the decision-making process. In particular, we develop new metrics to assess the social impact of redesigning the food bank supply chain network. These include, among others, the value of the social work created by the operation of food banks. As our review of the literature will show, the social dimension of sustainability has attracted limited attention in supply chain network design (SCND), mainly due to difficulties associated with quantifying objectives of social nature. Our work makes an important contribution in this direction. Moreover, the new MILP model also encompasses a number of features of practical interest that significantly enlarge its scope as compared with other SCND models. (3) We perform a computational study on problem instances based on real data provided by the FPBA for the south of Portugal. To this end, a subset of non-dominated solutions are identified using lexicographic ordering. (4) We evaluate the solutions obtained using key performance indicators relative to network redesign decisions, environmental outcome and social impact, among others. By comparing our results with the strategy currently adopted by the FPBA to manage its food bank network, we provide additional insights that can help this organisation identify measures to improve the level of sustainability of its supply chain.

The remainder of the paper is organised as follows. Section 2 provides a review of the literature related to sustainability in (food) supply chain management and, in particular, in SCND. In Section 3, a formal statement of the food bank supply chain network redesign problem is given, a mathematical formulation is proposed and the solution methodology is described. Section 4 reports on the numerical experiments carried out, the results obtained and the managerial insights gained. Finally, in Section 5, conclusions are presented and directions for future research are identified.

2. Literature review

The simultaneous consideration of economic, environmental and social issues in corporate decision-making processes is often termed triple bottom line. The recent surveys by Brandenburg et al. (2014), Hassini et al. (2012) and Rajeev et al. (2017) indicate that the three dimensions of sustainability have gained increasing attention across many research areas over the last years, including the field of supply chain management (SCM). The food supply chain has been subject to sustainability initiatives across all levels, from the agricultural sector to the distribution industry (see e.g. Beske et al. (2014), Fredriksson and Liljestrand (2015), Soto-Silva et al. (2016), Soysal et al. (2012)). However, holistic approaches for sustainable SCM are still emerging in the Operational Research literature. In this section, we first address this aspect in the context of SCND, both in greenfield and network redesign settings. Then, we review relevant contributions on the integration of location decisions into food aid distribution models. At the end of the section, we highlight a few features in network (re)design that are present in our problem but have not received sufficient attention in the literature.

SCND is the strategic planning process for optimising the configuration of a supply chain network. It involves determining the optimal number and location of facilities (e.g. plants, warehouses), allocating capacity and technology requirements to facilities, and deciding on the flow of products across the supply chain so that customer demands are satisfied. Most SCND studies pursue financial objectives – either cost or profit oriented (Melo et al., 2009). Environmental metrics have been gradually integrated into SCND models in the last years (Eskandarpour et al., 2015). The former range from greenhouse gas emissions to energy consumption.

In contrast to economic and environmental aspects, the social dimension is under-represented in SCND. Eskandarpour et al. (2015) argue that it is comparatively more difficult to quantify social factors and embed them in a mathematical framework. Arampantzi and Minis (2017) are among the few authors that integrate the three dimensions of sustainable development into a comprehensive MILP model for redesigning a network comprising suppliers, plants, distribution centres (DCs), and customers. Strategic decisions include opening new facilities and expanding the capacity of existing facilities over multiple time periods. In addition to economic and environmental performance, social responsibility is expressed by a number of metrics that account for employment opportunities, social community development and labour conditions across the supply chain. Social indicators are also present in the MILP model developed by Pishvae et al. (2012) to design a network involving plants, DCs and customers. The number of job positions that are created by opening new facilities and installing specific manufacturing technologies are maximised, whereas the potential loss of working days caused by possible damages from operating new facilities at given locations are minimised. These social metrics are also included in the MILP model proposed by Devika et al. (2014) for designing a multi-echelon closed-loop network. Santibañez-Aguilar et al. (2014) developed a MILP model to design a biofuel supply chain under a triple bottom line approach. The latter is represented by net profit, environmental impact and the number of jobs created by all the activities of the supply chain. Varsei and Polyakovskiy (2017) solve a case study of a wine company that needs to redesign its distribution network. Social performance is measured by assigning scores to potential locations for new bottling plants, based on the unemployment rate and the gross domestic product in their geographical areas. Economic and environmental objectives include minimising the total supply chain cost and the CO_2 emissions generated by transport activities, respectively. In the present work, we develop tailored metrics to measure the social impact of redesigning the network of food banks, and complement them with additional economic and environmental metrics that are in accordance with selected standards developed by the Global Reporting Initiative (Global Reporting Initiative, 2018).

In the context of food aid distribution, a few works have addressed location planning. Davis et al. (2014) identify the optimal locations for food delivery points and assign the recipients of the food relief to the new sites, from which they collect food items rather than travelling to food banks. Solak et al. (2014) focus on a variant of the location-routing problem for the distribution of donated food. The objective is to minimise a weighted average of the routing costs and the travel costs of the charitable agencies to collect food items from the designated facilities. The latter costs measure the inconvenience caused to the charities and can be seen as a surrogate for the environmental and social impacts of the location and routing decisions. Recently, Rancourt et al. (2015) addressed the problem of locating depots for food aid distribution in a rural region of Kenya. The objective is to minimise the total welfare cost which includes, among others, the cost incurred to communities for travelling to a depot to collect food items.

The multi-period, multi-echelon SCND problem that we study includes some practical features that have not received much attention in the literature. While most SCND models impose full demand satisfaction, in our case the volume of food donations is insufficient to meet all demand requirements. Therefore, some charitable agencies may receive partial food assistance or no assistance at all. Another distinct feature of our problem is the possibility of food banks exchanging products. Melo et al. (2012) are among the few authors who modelled product flows between facilities belonging to the same echelon in a facility relocation problem.

Even though SCND has attracted considerable attention in the literature (Alumur et al., 2015, Melo et al., 2009), focus has primarily been given to the industrial context. In contrast, the non-profit counterpart has received far less attention (Charles et al., 2016, Tofighi et al., 2008). Humanitarian aid supply chains, including those operated by food banks, share some features with their industrial counterpart, but at the same time they also have specific attributes. To the best of our knowledge, mathematical models directed to the strategic design of food bank networks have not been proposed in the literature so far. This is possibly explained by the social purpose that this type of networks serves and the distinguishing characteristics of the numerous (for-profit and non-profit) organisations that interact with food banks. Contributions in the literature have focused so far on tactical and operational problems of food bank supply chains (see e.g. Brock and Davis (2015), Giuseppe et al. (2014), Martins et al. (2011), Mohan et al. (2013), Orgut et al. (2016b)), while the strategic planning level has been neglected. This paper attempts to fill this gap. Our main contribution is to model a food bank network redesign problem motivated by a real case and to integrate a triple bottom line framework into the decision-making process.

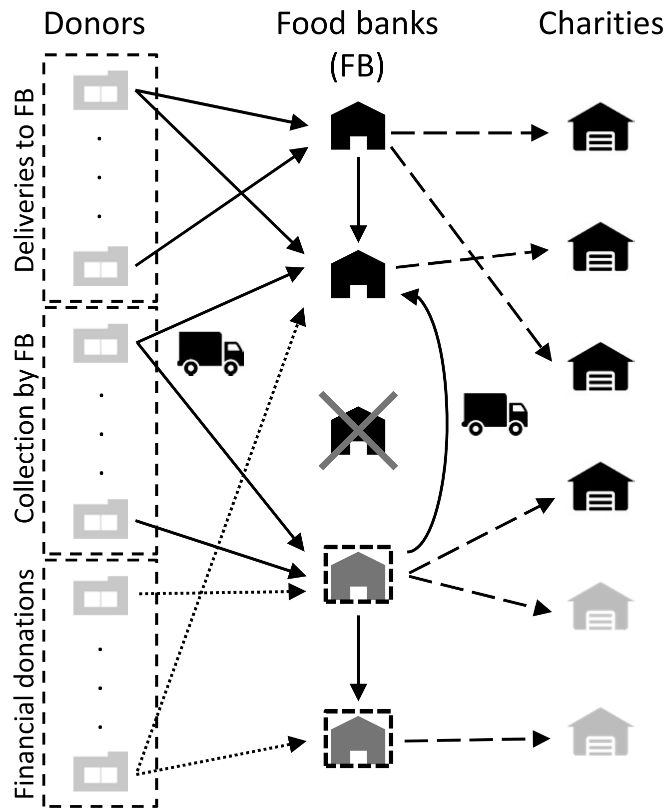

Fig. 1. Schematic configuration of a food bank supply chain network.

3. Food bank supply chain network redesign model

In this section, we describe the food bank supply chain in detail and present a MILP model for the multi-period, multi-echelon, multi-product network redesign problem inspired from the FPBA. The proposed methodological approach is also discussed.

3.1. Problem description

The supply chain network includes three different kinds of stakeholders: donors, food banks and charitable agencies (see Fig. 1. Food products are secured from a wide range of sources, such as food manufacturers, wholesalers, supermarkets, grocery chains, and consumers. Typically, donated food products are not sellable but still edible even if they are approaching their expiry dates. While most donations are delivered to local food banks, some donors require the food items to be collected. In addition to food donations, there are also individuals and businesses that donate money. Financial donations, which are illustrated by the dotted arrows in Fig. 1, are mostly used by food banks to make food purchases, often at discounted prices, to supplement material donations.

Each food bank operates a warehouse which serves as a single collection and distribution point for food donations. The warehouses vary in size, layout, storage capacity, and equipment. Storage space can be divided in up to three major areas, one for dry products (e.g. canned goods), one for refrigerated items (e.g. vegetables) and a third area for frozen products (e.g. meat and fish). Some food banks store a single family of products, typically dry products. Furthermore, each food bank either maintains its own fleet of vehicles for food collections or rents transport capacity when needed. Vehicles may also be used to transfer food items from one food bank to another. This practice is meaningful when a food bank receives a large quantity of a particular food item that exceeds the needs of the charities that it serves, and at the same time, another food bank experiences a shortage of the same product.

Each food bank redistributes the donated products free of charge to a distinct set of non-profit community and governmental agencies, such as hostels for the homeless, parish social centres, elderly care centres, and nursing homes. These, in turn, either distribute the food items to individuals and families experiencing food insecurity, or use the donations to prepare and serve meals. Charitable agencies, henceforth called charities, must travel and collect food products at a designated food bank on specific days (this feature is depicted by the arrows with dashed lines in Fig. 1. Since they must support their own travel expenses, these agencies are usually located within a certain radius of the food bank. Due to an imbalance between donated food and demand, the FPBA is unable to serve all charities. As a rule, an agency applying for food assistance for the first time joins the group of charities waiting to be served.

The FPBA strives to increase the number of supported charities and the quantity of redistributed food products. Redesigning the existing food bank network is an important step for achieving these goals. To this end, we consider a finite multi-period planning horizon, over which gradual changes in the network configuration and in the capacities of food banks are planned, taking into account predictable variations in various parameters (e.g. food donations, demand levels, capital available for network redesign). Network redesign decisions include closing existing food banks (this feature is highlighted in Fig. 1 by an x mark) and opening new food banks at potential sites (the facilities in the dashed boxes in Fig. 1). In addition, capacity planning involves the purchase and/or expansion of storage space and transport capacity. In both cases, capacity acquisition takes the form of selecting a capacity level from a set of available discrete sizes. Additional features of our problem and assumptions are described next.

- Each donor that delivers products does so to a pre-defined set of food banks.
- If an existing food bank has its capacity expanded then it must remain in operation until the end of the planning horizon.
- If a new food bank is opened in a candidate site in a given time

period then storage capacity must also be installed in the same period for at least one product family.

- Individual food products are grouped into families according to their refrigeration needs.
- Storage capacity for different product families may be acquired for the same food bank, but at the most only one additional storage area per product family can be installed in the same facility over the planning horizon.
- It is only meaningful to invest in transport capacity for a given product family in a food bank if that family is stored in that facility. Moreover, different transport capacity levels may be purchased by a food bank for the same product family in a time period.
- Location and capacity acquisition decisions are covered by a given budget in each time period. Due to the sizeable investment associated with these decisions, temporarily closing and reopening of food banks is not permitted. Furthermore, a limit is imposed on the number of facilities that can be opened and closed per period.
- All charities supported by the food bank association prior to the network redesign project must continue to be served. Additionally, charities awaiting support may eventually receive food assistance. In both cases, demand for individual food items may not be fully satisfied, but a certain minimum level of assistance must be guaranteed to all charities served by a food bank. In each time period, a charity may be assigned to a single food bank and the distance travelled to collect food items cannot exceed a pre-specified route length limit.

3.2. Model parameters

The notation used hereafter is introduced. All financial parameters are expressed in monetary units (m.u.), except parameters τ_p^t, φ^t and ω^t, which are measured in K€. Tonne is the unit of measurement used for storage and transport capacities as well as for food product quantities. The distance between two locations is measured by a distance unit (d.u.) that can be converted into kilometres (this issue will be detailed in Section 4.1).

Sets:	
T	Time periods in the planning horizon
DD	Donors that deliver food items to food banks
CD	Donors that require food items to be collected by food banks
FD	Donors that provide financial donations to food banks
OB	Existing food banks at the beginning of the planning horizon
PB	Potential sites for locating new food banks
SC	Charities served by food banks at the beginning of the planning horizon
HC	Charities on hold, i.e. agencies awaiting food assistance
K	Families of food products
P_k	Individual food items belonging to family $k \in K$, $\cap_{k\in K} P_k = \emptyset$
L	Discrete capacity levels for storage areas/ transport resources

Let $D = DD \cup CD \cup FD$ be the set of all donors. The set of all food banks is represented by $B = OB \cup PB$, and $B_d \subseteq B$ is the subset of food banks that can receive food products from donor $d \in DD$. The set of all charities is denoted by $C = SC \cup HC$, and $C_b \subset C$ is the subset of charities whose geographical locations fall outside the service area of food bank $b \in B$. The set of all food products is represented by $P = \cup_{k\in K} P_k$. For notational convenience, we also introduce the set A of all origin-destination pairs in the network depicted in Fig. 1: $A = \{(d,\ b)\colon d \in DD,\ b \in B_d\} \cup \{(d,\ b)\colon d \in CD \cup FD,\ b \in B\}.$

$$\cup \{(b,\ b')\colon b, b' \in B, b \neq b'\} \cup \{(b,\ c)\colon b \in B,\ c \in C\}$$

Financial parameters:	
FI^t	Fixed cost of opening a new food bank in period $t \in T$
$VSI_{\ell k}^t$	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
$VTI_{\ell k}^t$	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_k^t	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_{kb}^t	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_{kb}^t	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
$\tilde{Q}_d^t$	Financial donation of donor $d \in FD$ in period $t \in T$ to purchase food products
τ_p^t	Cost of purchasing one unit of food product $p \in P$ in period $t \in T$
φ^t	Cost of disposing of 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 tonne of a food product in period $t \in T$

Parameters FI^t and FU^t represent, respectively, fixed administrative and legal costs incurred by the setup (e.g. expenditures associated with adapting or refurbishing an existing building, purchase of equipment) or shutdown (e.g. indemnity payments due to termination of employment contracts, expenditures for equipment transfers) of a food bank in time period t. The costs of installing storage capacity ($VSI_{\ell k}^t$) and transport capacity ($VTI_{\ell k}^t$) at both new and existing food bank locations reflect economies of scale, thus favouring large capacity levels. Moreover, since each product family requires specific storage and transport conditions, the capacity acquisition costs also differ across product families. Dismantling costs (VU_k^t) are associated with closing a food bank and depend on the type of existing storage areas. Costs related to removing transport capacity due to facility closure are assumed to be negligible. The operation of a food bank incurs fixed and variable costs. The former include administrative and managerial overhead expenses (FC^t) for each charity served. Variable costs depend on the available capacity and on the amount of products handled by each food bank. Parameter VS_{kb}^t reflects the cost of maintaining storage areas (e.g. equipment, energy consumption), and depends on the capacity available for individual product families. Handling costs (VH_{kb}^t) are associated with processing incoming donations and preparing food products for redistribution. In both cases, they vary from location to location due to different regional cost structures.

Capacity and demand parameters:	
Q_{pd}^t	Quantity of food product $p \in P$ made available by donor $d \in DD \cup CD$ in $t \in T$
$\bar{M}_{kb}$	Storage capacity for product family $k \in K$ that is available at food bank $b \in OB$ at the beginning of the planning horizon ($\bar{M}_{kb} \geq 1$)
$M_{\ell k}$	Storage capacity of size $\ell \in L$ for product family $k \in K$ that can be installed in a food bank
$\bar{N}_{kb}$	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
U_{ij}	Distance between origin i and destination j for every $(i, j) \in A$ (in d.u.)
β_i	User-defined constants, $\beta_i \in (0,1]$, $i = 1,2,3$
α_i	Non-negative factors ($i = 1,\ldots,8$, $i \neq 6$)
α_6^t	Non-negative factor that includes the value of the social work generated per unit of storage capacity available at a food bank in period $t \in T$
μ	Average weight of an empty vehicle for transporting food products

Parameter β_1 is used to impose a limit on the maximum number of food bank locations that can be opened or closed per period (cf. constraints (5)). The minimum level of food assistance provided to a charity supported by a food bank is specified by β_2 for $c \in SC$, and by β_3 for $c \in HC$ (cf. constraints (22) and (23)). Parameter α_1 is used in the economic objective function as a penalty factor for unused resources. Parameters α_2 and α_3 are weight factors representing the relative importance of the components in the environmental objective function. Parameters α_i (i = 4,5,7,8) and α_6^t are used to weigh and normalise the individual terms in the social objective function. Finally, parameter μ is required to assess the environmental impact of transport used to collect food items from specific donors and other food banks.

3.3. Decision and auxiliary variables

All decisions are implemented at the beginning of each time period. Strategic decisions related to facility location and capacity acquisition are represented by binary variables. Moreover, binary single-assignment variables are also defined. The flow of food products across the network is modelled by continuous variables.

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
x_{pij}^t	Quantity of food product $p \in P$ moved from origin i to destination j in period $t \in T$, $(i, j) \in A$

In addition, the following auxiliary variables are defined:

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 over charities served in period $t \in T$
ε^t	Maximum distance between a charity and its assigned food bank in period $t \in T$

3.4. Network redesign constraints

We now describe in detail the constraints in our MILP model.

3.4.1. Donor-related constraints

$$\sum_{b \in B_d} x_{pdb}^t \leq Q_{pd}^t \qquad d \in DD,\ p \in P,\ t \in T \tag{1}$$

$$\sum_{b \in B} x_{pdb}^t \leq Q_{pd}^t \qquad d \in CD,\ p \in P,\ t \in T \tag{2}$$

$$\sum_{p \in P} \sum_{b \in B} \tau_p^t\, x_{pdb}^t + \xi_d^t = \tilde{Q}_d^t + \xi_d^{t-1} \qquad d \in FD,\ t \in T \tag{3}$$

Constraints (1) and (2) ensure that the quantity of each food item supplied by a donor to food banks does not exceed the amount available in each time period. Constraints (3) play a similar role with respect to financial donations for making food purchases. Financial donations that are not spent in a given time period can be used in later periods.

3.4.2. Facility location and capacity acquisition constraints

$$\sum_{t \in T} y_b^t \leq 1 \qquad b \in B \tag{4}$$

$$\sum_{b \in B} y_b^t \leq \lceil \beta_1 |B| \rceil \qquad t \in T \tag{5}$$

$$\sum_{t \in T} \sum_{\ell \in L} w_{\ell kb}^t \leq \sum_{t \in T} y_b^t \qquad b \in PB,\ k \in K \tag{6}$$

$$\sum_{t \in T} \sum_{\ell \in L} w_{\ell kb}^t \leq 1 - \sum_{t \in T} y_b^t \qquad b \in OB,\ k \in K \tag{7}$$

$$\sum_{\ell \in L} w_{\ell kb}^t \leq \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{8}$$

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

$$\sum_{\ell \in L} v_{\ell kb}^t \leq |L| \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{10}$$

$$\sum_{\ell \in L} v_{\ell kb}^t \leq |L| \left[\bar{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} \right] \qquad b \in OB,\ k \in K,\ t \in T \tag{11}$$

$$\sum_{b \in PB} FI^t y_b^t + \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VSI_{\ell k}^t M_{\ell k} w_{\ell kb}^t + \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VTI_{\ell k}^t N_{\ell k} v_{\ell kb}^t + \sum_{b \in OB} \left(FU^t + \sum_{k \in K} VU_k^t \bar{M}_{kb}\right) y_b^t + \gamma^t = O^t \qquad t \in T \tag{12}$$

Constraints (4) enforce the *status* of a food bank to change at the most once over the time horizon. Hence, if a new facility is established at a candidate location it cannot be closed afterwards. Analogously, if an initially existing food bank is closed then it cannot be reopened. Inequalities (5) limit the total number of status changes at food bank locations in each time period. Constraints (6) and (7) state that the installation of storage capacity for each product family can occur at the most once over the planning horizon. Furthermore, constraints (7) also guarantee that an existing food bank can only have its storage capacity expanded unless it is operated until the end of the time horizon. In the case of new locations, constraints (8) are further required to ensure that storage capacity attributed to a product family can only be installed unless a new food bank is already operating in that location. Inequalities (9) stipulate that storage capacity must be installed for at least one product family in the same time period in which a new food bank is opened. Constraints (10) and (11) state that the acquisition of transport capacity by a food bank for a product family is only possible if that facility holds storage capacity for the same family. Notice that in each time period it is possible to purchase vehicles having different sizes to transport food products of the same family. Budget constraints are imposed by equalities (12). Investment spending is incurred for opening new food banks at potential locations, installing storage areas (at both new and existing locations), purchasing new transport vehicles, and closing initially existing food banks as well as dismantling their storage capacities. We note that the slack variables γ^t are unrestricted in sign (cf. (38)), which enables us to identify those time periods with 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. Naturally, γ^t will be maximised over the planning horizon in one of the objective functions (cf. (41)).

3.4.3. Capacity utilisation constraints

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{13}$$

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \bar{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} \qquad b \in OB,\ k \in K,\ t \in T \tag{14}$$

$$\sum_{p\in P_k}\sum_{i\in CD\cup B\setminus\{b\}} x_{pib}^t + \theta_{kb}^t = \sum_{\ell\in L} N_{\ell k}\sum_{\bar{t}=1}^{t} v_{\ell kb}^{\bar{t}} \qquad b\in PB,\ k\in K,\ t\in T \tag{15}$$

$$\sum_{p\in P_k}\sum_{i\in CD\cup B\setminus\{b\}} x_{pib}^t + \theta_{kb}^t = \bar{N}_{kb}\left(1-\sum_{\bar{t}=1}^{t} y_b^{\bar{t}}\right) + \sum_{\ell\in L} N_{\ell k}\sum_{\bar{t}=1}^{t} v_{\ell kb}^{\bar{t}} \qquad b\in OB,\ k\in K,\ t\in T \tag{16}$$

Constraints (13) and (14) guarantee that the total quantity of products of a given family, which are received from donors and other food banks, does not exceed the storage capacity available at each operating facility. Equalities (15) and (16) play a similar role with respect to transport capacity for collecting food items from donors $d \in CD$ and other food banks. The main difference is that slack variables θ_{kb}^t are included in the latter constraints to represent the amount of unused transport capacity. These variables are used in the economic objective function (39) to enforce the acquisition of transport resources only when they are needed and not earlier.

3.4.4. Charity-related constraints

$$\sum_{b\in B} z_{bc}^t = 1 \quad c\in SC,\ t\in T \tag{17}$$

$$\sum_{b\in B} z_{bc}^t \le 1 \qquad c\in HC,\ t\in T \tag{18}$$

$$\sum_{b\in B} z_{bc}^{t+1} \ge \sum_{b\in B} z_{bc}^t \qquad c\in HC,\ t=1,\ldots,|T|-1 \tag{19}$$

$$z_{bc}^{t-1} - z_{bc}^t \le \sum_{\bar{b}\in B} y_{\bar{b}}^t \qquad b\in B,\ c\in C,\ t=2,\ldots,|T| \tag{20}$$

$$\sum_{t\in T}\sum_{c\in C_b} z_{bc}^t \le 0 \qquad b\in B \tag{21}$$

$$\sum_{b\in B} x_{pbc}^t \ge \beta_2 X_{pc}^0 \qquad c\in SC,\ p\in P,\ t\in T \tag{22}$$

$$\sum_{b\in B} x_{pbc}^t \ge \beta_3 R_{pc}^t \sum_{b\in B} z_{bc}^t \qquad c\in HC,\ p\in P,\ t\in T \tag{23}$$

$$x_{pbc}^t \le R_{pc}^t z_{bc}^t \qquad b\in B,\ c\in C,\ p\in P,\ t\in T \tag{24}$$

$$\sum_{p\in P}\sum_{b\in B}\frac{R_{pc}^t z_{bc}^t - x_{pbc}^t}{R_{pc}^t} \le \delta^t \qquad c\in C,\ t\in T \tag{25}$$

$$U_{bc} z_{bc}^t \le \varepsilon^t \qquad b\in B,\ c\in C,\ t\in T \tag{26}$$

Each charity that received food assistance prior to the network redesign project must continue to be supported until the end of the planning horizon as enforced by equalities (17). Every charitable agency awaiting food assistance may be served according to constraints (18). If support is provided to such an agency in a given time period then constraints (19) ensure that the agency will continue to receive food items until the end of the planning horizon. Observe that in each period, a charity cannot be assigned to more than one food bank although the designated food bank may vary from period to period. However, for organisational reasons, the re-assignment of charities to food banks is limited by constraints (20) to those periods in which the network configuration changes, i.e. when at least one new food bank is opened and/or an existing facility is closed. Moreover, charities cannot be assigned to food banks that are outside their desired service area according to constraints (21). Constraints (22) guarantee that initially served charities receive at least a given percentage of their initial supply of each food product. For charities on hold, constraints (23) enforce a minimum level of demand coverage should they get food assistance. Inequalities (24) state that the quantity of each food product supplied to a charity cannot exceed its demand. Constraints (25) enforce the level of unsatisfied demand of a served charity to be limited by a threshold δ^t in each time period. Constraints (26) state that the distance between a served charity and its designated food bank does not exceed a threshold value. The thresholds on the right-hand side of constraints (25) and (26) are relevant for the evaluation of the social impact of food redistribution (cf. (41)).

3.4.5. Other constraints

$$z_{bc}^t \le \sum_{\bar{t}=1}^{t} y_b^{\bar{t}} \qquad b\in PB,\ c\in C,\ t\in T \tag{27}$$

$$z_{bc}^t \le 1 - \sum_{\bar{t}=1}^{t} y_b^{\bar{t}} \qquad b\in OB,\ c\in C,\ t\in T \tag{28}$$

$$\sum_{c\in C} z_{bc}^t \ge \sum_{\bar{t}=1}^{t} y_b^{\bar{t}} \qquad b\in PB,\ t\in T \tag{29}$$

$$\sum_{c\in C} z_{bc}^t \ge 1 - \sum_{\bar{t}=1}^{t} y_b^{\bar{t}} \qquad b\in OB,\ t\in T \tag{30}$$

$$\sum_{i\in D\cup B\setminus\{b\}} x_{pib}^t = \sum_{j\in C\cup B\setminus\{b\}} x_{pbj}^t \qquad b\in B,\ p\in P,\ t\in T \tag{31}$$

$$y_b^t,\ z_{bc}^t \in \{0,1\} \qquad b\in B,\ c\in C,\ t\in T \tag{32}$$

$$w_{\ell kb}^t,\ v_{\ell kb}^t \in \{0,1\} \qquad b\in B,\ \ell\in L,\ k\in K,\ t\in T \tag{33}$$

$$x_{pij}^t \ge 0 \qquad p\in P,\ (i,j)\in A,\ t\in T \tag{34}$$

$$\theta_{kb}^t \ge 0 \qquad b\in B,\ k\in K,\ t\in T \tag{35}$$

$$\xi_d^t \ge 0 \qquad d\in FD,\ t\in T\cup\{0\} \tag{36}$$

$$\delta^t,\ \varepsilon^t \ge 0 \qquad t\in T \tag{37}$$

$$\gamma^t \text{ free} \qquad t\in T \tag{38}$$

Constraints (27) and (28) ensure that charities can only be supplied by operating food banks. Conversely, constraints (29) and (30) require each operating food bank to serve at least one charity in each time period. Equalities (31) guarantee the conservation of product flow at each food bank location in every time period. Finally, constraints (32) through (38) define the domains of all variables.

3.5. Objective functions

We now describe how we integrate the three dimensions of sustainability into our model. The metrics chosen to quantify the performance of the food bank supply chain are in accordance with selected standards developed by the Global Reporting Initiative (Global Reporting Initiative, 2018). In addition, tailored metrics developed by the authors for this study are also included.

3.5.1. Economic objective

The economic objective function (39) aims at identifying the network configuration with the least total cost. It includes the total fixed cost for supporting charities (the first component), the total cost for operating storage areas and handling products at food banks (the next three components), and the total cost associated with unused transport capacity. The latter cost is determined by multiplying the unused capacity by a penalty factor α_1 that accounts for economical inefficiencies. The last component in the economic objective function represents the total revenue obtained at the end of the planning horizon due to not totally spending the available financial donations. This is in line with the focus given by food banks to the collection and distribution of food donations rather than to the purchase of food products.

$$\text{Min } z_1 = \sum_{t\in T}\sum_{b\in B}\sum_{c\in C} FC^t z^t_{bc} + \sum_{t\in T}\sum_{b\in OB}\sum_{k\in K} VS^t_{kb}\,\bar{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) + \sum_{t\in T}\sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} VS^t_{kb}\,M_{\ell k}\sum_{\tilde{t}=1}^{t} w^{\tilde{t}}_{\ell kb} + \sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\sum_{p\in P_k}\sum_{i\in D\cup B\setminus\{b\}} VH^t_{kb}\,x^t_{pib} + \alpha_1\sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\Theta^t_{kb} - \alpha_1\sum_{d\in FD}\xi^{|T|}_d \tag{39}$$

3.5.2. Environmental objective

The environmental objective function (40) minimises the total value of food waste and of CO_2 emitted by transport activities. Due to the perishability of food products, unused donated food must be disposed of at a cost. CO_2 emissions are associated with the trips undertaken by food bank vehicles to collect food items from specific donors or from other food banks. 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 (40). Parameters α_2 and α_3 in (40) are pre-specified positive scaling factors.

$$\text{Min } z_2 = \alpha_2\sum_{t\in T}\sum_{p\in P}\varphi^t\left[\sum_{d\in DD}\left(Q^t_{pd}-\sum_{b\in B_d}x^t_{pdb}\right)+\sum_{d\in CD}\left(Q^t_{pd}-\sum_{b\in B}x^t_{pdb}\right)\right] + \alpha_3\sum_{t\in T}\sum_{b\in B}\sum_{p\in P}\sum_{i\in CD\cup B\setminus\{b\}}\omega^t\,U_{ib}(2\mu + x^t_{pib}) \tag{40}$$

3.5.3. Social objective

The social objective function (41) contributes to providing access to donated food in an equitable manner and to valuing the social role played by food banks.

$$\text{Max } z_3 = \alpha_4\sum_{t\in T}\sum_{b\in B}\sum_{c\in HC} z^t_{bc} + \alpha_5\sum_{t\in T}\gamma^t + \sum_{t\in T}\alpha^t_6\left[\sum_{b\in OB}\sum_{k\in K}\bar{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t}y^{\tilde{t}}_b\right)+\sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K}M_{lk}\sum_{\tilde{t}=1}^{t}w^{\tilde{t}}_{\ell kb}\right] - \alpha_7\sum_{t\in T}\delta^t - \alpha_8\sum_{t\in T}\varepsilon^t \tag{41}$$

The first component accounts for the total number of charities that were initially awaiting support and that start to receive food assistance. The second component measures the total deviation from the reference budget for network redesign (recall constraints (12)). 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 emphasise this aspect by incorporating the variables γ^t into the objective function (41). The third component 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^t_6 incorporates the monetary value of volunteer work 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 activities of food banks. The last two components in (41) penalise the highest level of unsatisfied demand and the excessive travel of charities to collect food products from their designated food banks. The decision to close down an existing food bank negatively impacts the value of the social objective through the second, third and fifth components. Note that since the individual social components have different units of measurement, they are multiplied by normalising factors. 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.

Finally, we note that the problem that we study is NP-hard, since it includes the uncapacitated multi-period facility location problem as a particular case (Jacobsen et al., 1990).

3.6. Solution methodology

This study is the first to apply a multi-objective optimisation methodology to address key strategic decisions faced by an institution like the FPBA. The food bank supply chain redesign problem is challenging due to complex, intertwined decisions that need to be made. Therefore, solutions obtained to the problem have to be subjected to a detailed analysis, and the trade-offs that occur by considering economic, environmental and social objectives simultaneously need to be identified. This analysis is not viable when a large number of Pareto solutions are available. Hence, we have selected lexicographic ordering to provide the decision maker with a concise set of Pareto optimal solutions. Lexicographic solutions are the reference key points that frame the range of every efficient solution available. Limiting the number of alternative optimal (re)designs for the food bank network to the number of lexicographic solutions allows for informed decisions, and supports the strategic (re)positioning of the supply chain. The lexicographic method identifies six Pareto optimal solutions by solving 15 single objective MILP problems, which result from considering all possible combinations for ranking the three objective functions as shown in Table 1.

4. Computational study

This section is devoted to a computational study based on real data provided by the FPBA. Rather than studying the particular case of the FPBA, we have opted 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 enable the generalisation of the insights derived from the results obtained to other food aid supply chains with similar settings. We first summarise the data collection and processing steps that were used to generate the instances, followed by an analysis of the numerical results.

4.1. Construction of problem instances

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, located in Lisbon, were also closely examined. This information allowed us to generate instances based on a real case. Input parameters were obtained by randomly selecting values within ranges delimited by average values provided by the FPBA. Supply and demand parameters of each instance

Table 1
Priority ranking of the objectives.

Lexicographic solution (LS)		Objectives		
Type	Notation	Economic	Environmental	Social
Economic-centric	LS1	1	2	3
	LS2	1	3	2
Environmental-centric	LS3	2	1	3
	LS4	3	1	2
Social-centric	LS5	2	3	1
	LS6	3	2	1

were semi-randomly generated by considering that in the period 2010–2015 the estimated volume of food products redistributed by the FPBA in the area covered by our study varied between 3750 and 4500 tonnes. Storage capacity parameters required the profiling and classification of the FPBA facilities according to the volume of items processed. For every product family, the smallest and largest storage capacities in operating food banks determined the range of admissible values for the related parameters of the instances generated. Official sources were also used when appropriate, e.g. to set the CO_2 emission cost and the food disposal cost. The interested reader is referred to Martins et al. (2017) for further details.

Our study is devoted to the redesign of the network of food banks located in the southern region of Portugal over a five-period planning horizon ($|T| = 5$). Currently, four food banks with different sizes (a large, a medium and two small-sized facilities) are operated in this region, and their service area accounts for one-third of the total area covered by the FPBA in mainland Portugal. Fig. 2 shows the locations of the existing facilities ($|OB| = 4$) and of a potential site for a new food bank ($|PB| = 1$), with the latter selected in an area with a relatively high proportion of population in need. Currently, agencies in this area have to travel longer to collect food products. Considering that one unit in the rectangle in Fig. 2 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 south of Portugal, even though the actual locations of the FPBA facilities do not exactly match those depicted in Fig. 2. This will allow us to draw conclusions that are not only relevant to the FPBA but can also be generalised to other food aid supply chain networks. Hence, our study represents an important first step before addressing the entire network of the FPBA at a later stage.

Regarding the maximum number of allowed status changes at food bank locations (i.e. opening/closing facilities) per period, we have selected the most flexible scenario by setting $\beta_1 = 1$. Notice that in this case constraints (5) are redundant.

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 was accomplished by taking a scale of 1:20 which resulted in 10 donors and 19 charities. 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 ($|FD| = 1$). Regarding the charities, we have taken $|SC| = 16$ and $|HC| = 3$. This choice yields a ratio of 1.6 between the number of served charities (16) and the number of donors (10), which reflects the real situation. For every charity $c \in SC$, a minimum level of demand satisfaction of 70% was imposed ($\beta_2 = 0.7$). For charities awaiting food assistance, we have set $\beta_3 = 0.5$, thus requiring at least half of the demand of an agency $c \in HC$ to be satisfied.

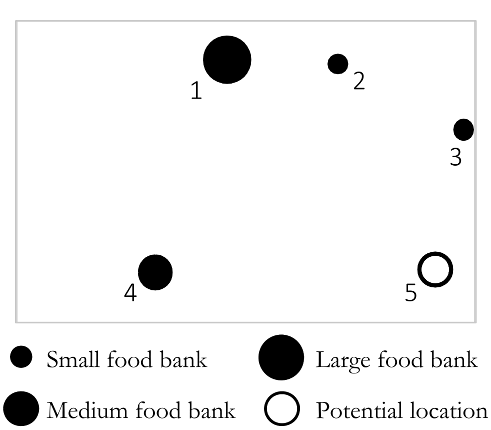

Fig. 2. Locations of all food banks.

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 $(i, j) \in A$. A maximum distance of 250 d. u. was imposed between each charity and its designated food bank. This limit was also considered for defining the set B_d. Our instances have five products ($|P| = 5$), 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. These products are distributed over three families ($|K| = 3$) - dry, fresh and frozen products - as follows: $P_1 = \{1,2\}$, $P_2 = \{3,4\}$, $P_3 = \{5\}$. 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 ($|L| = 3$).

In total, 20 instances were generated. All instances share the location of the food banks, the storage and transport capacities available for purchase at each facility ($M_{\ell k}$ and $N_{\ell k}$) and all financial parameters, except the financial donations ($\tilde{Q}_d^t$). All remaining parameters, namely the location of donors and charities, the quantities of products available for donation (Q_{pd}^t), the value of financial donations, the demand of charities (R_{pc}^t), and the initial capacities of food banks ($\bar{M}_{kb}$ and $\bar{N}_{kb}$) differ from instance to instance. Cost parameters rise at a rate of 2% per period with the only exception of the CO_2 and disposal costs. The latter were subject to a growth rate of 5% to convey the commitment of the FPBA to environmental goals. All our instances reflect a neutral attitude of the decision maker. This is accomplished by assuming that the two components in the environmental objective are equally important (i.e. $\alpha_2 = \alpha_3 = 0.5$), and by giving equal preference to the five components in the social objective. Each test instance has 5067 constraints and 5420 variables, of which 950 are binary variables.

4.2. 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 (8192 + 4096) MB DDR3L) and running Windows 7 (64-bit). On average, 1767.2 s (approx. 29 min) were needed to identify all lexicographic solutions associated with an instance. Interestingly, the largest amount of CPU time was invested in obtaining the social-centric (46.3%) and the environmental-centric lexicographic solutions (43.5%). The identification of the economic-centric solutions required only about 10.2% of the overall computational effort.

4.2.1. Evaluation of lexicographic solutions

Table 2 summarises 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 percent standard deviations from the ideal vector. For each type of lexicographic solution and each instance, we have measured the deviation of the objective function value of a particular criterion to the average ideal value of that criterion (the latter being one of the three values in boldface shown in the table). It can be seen that the standard deviations are particularly large for the environmental objective.

For the economic-centric solutions (LS1, 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

Table 2
Objective function values of lexicographic solutions.

Lexicographic	Objective value (avg)			Standard deviation (avg %)		
solution	Economic	Environmental	Social	Economic	Environmental	Social
LS1	**6690.34**	463.53	−91.73	14	89	18
LS2	**6690.34**	477.20	−89.46	14	92	18
LS3	8688.94	**166.82**	2.26	20	29	20
LS4	9801.13	**166.82**	156.38	21	29	27
LS5	9378.17	348.50	**241.49**	15	96	10
LS6	9418.56	340.54	**241.49**	15	97	10

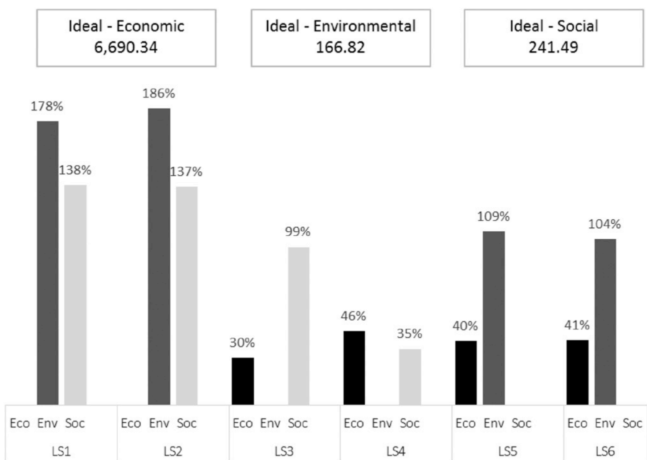

Fig. 3. Deviation of the lexicographic solutions from the average ideal vector.

components (see Section 4.2.2 for further details). In contrast, the social-centric solutions (LS5, LS6) achieve the highest social value, as expected.

The trade-offs between the three criteria are shown in Fig. 3. The largest differences from the ideal vector occur in the environmental and social objectives when the economic criterion is the most important. 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 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 implemented.

Fig. 4 illustrates the typical structure of the food bank supply chain network associated with LS4 for a representative instance. All facility location and capacity acquisition decisions are implemented in the first period and involve significant investment spending. The large and medium-sized food banks are maintained, and a new food bank is opened with storage capacity for all product families and transport capacity to collect donations of dry products.

The two small facilities are also kept and their storage capacities are expanded through the purchase 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. All charities on the waiting list are supported over the whole planning horizon. Since food assistance is provided to all 19 charities and the average level of satisfied demand is relatively high (about 81.4%), only 8.1% of the donated products are disposed of. To keep the level of CO_2 emissions low, food products are not moved between food banks and in-kind donations from donors *DD* are preferred to food collections from donors *CD*. Regarding the financial donations, these are completely used up. Finally, LS4 exhibits the largest social work value among all lexicographic solutions. Further details of individual features of LS4 can be found in Martins et al. (2017).

4.2.2. Managerial insights

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

%Cost:	Ratio to largest economic objective function value.
%Storage:	Ratio to largest unused storage capacity at an operating food bank.
%Waste:	Ratio to largest level of unused in-kind food donations.
%CO2:	Ratio to largest total cost for CO_2 emissions.
%Demand:	Ratio to largest level of unsatisfied demand over all charities (*SC* and *HC*).
%Distance:	Ratio to largest distance between a charity and its designated food bank.
%Investment:	Ratio to largest investment capital required w.r.t the total reference budget ($\sum_{t\in t} O^t$).
%Work:	1 - ratio to largest value of the social work created by the food aid supply chain.

These KPIs are depicted in Fig. 5 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 2, 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 Fig. 5 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 2818.33. For LS1, the average social work value obtained is equal to 2077.55, 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 previous analysis of the trade-offs that arise in the economic-centric solutions LS1 and LS2 is emphasised by the two upper radar charts in Fig. 5, 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, have a better social performance than LS3, whereas the latter solutions achieve superior results with respect to total cost and storage capacity 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 Fig. 5 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

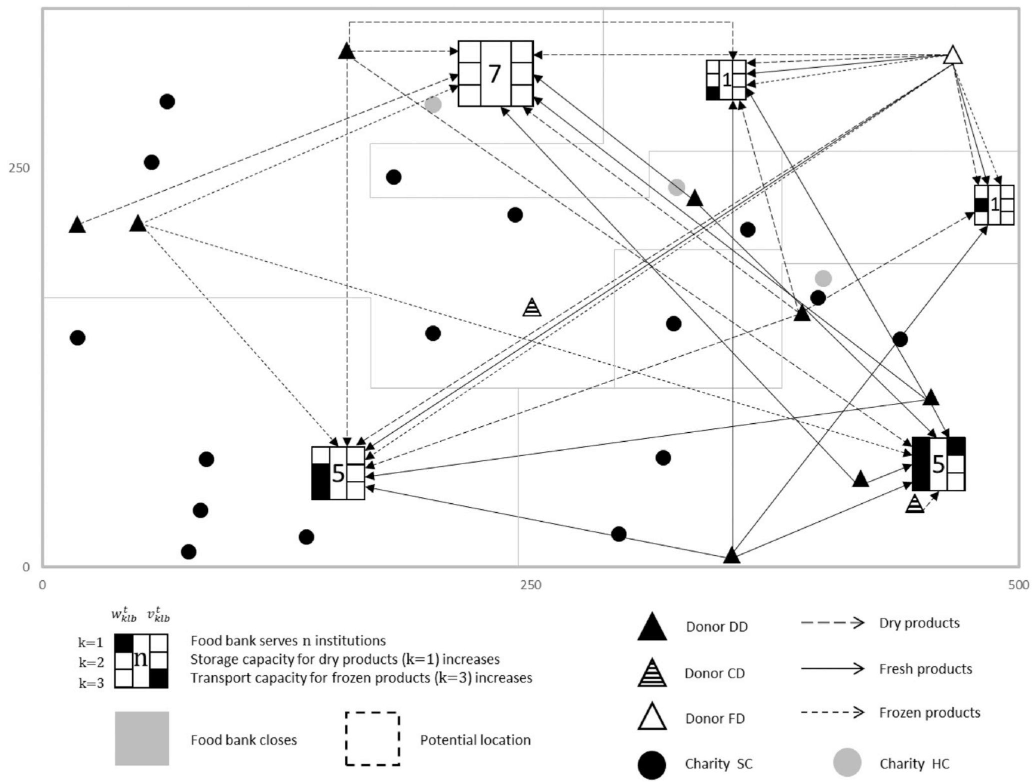

Fig. 4. Supply chain configuration of LS4 (instance 15).

designated food bank, and the least effort to raise investment capital. However, these positive features are overruled by a reduced economic performance and a high CO_2 cost.

Additional information on the lexicographic solutions is summarised in Table 5 (averages over 20 test instances) in appendix. The economic-centric solutions LS1 and LS2 are characterised 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 demonstrated 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 are all charities on the waiting list served but also the quantity of food items received by all charities is 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, vehicles are engaged in more trips for food collection and for deliveries between food banks. 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 only surpassed by LS4.

Regarding the environmental-centric solutions, 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 collections from other food banks and not picking up all food items 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 in 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.

Finally, a feature common 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 3 summarises the main findings of our

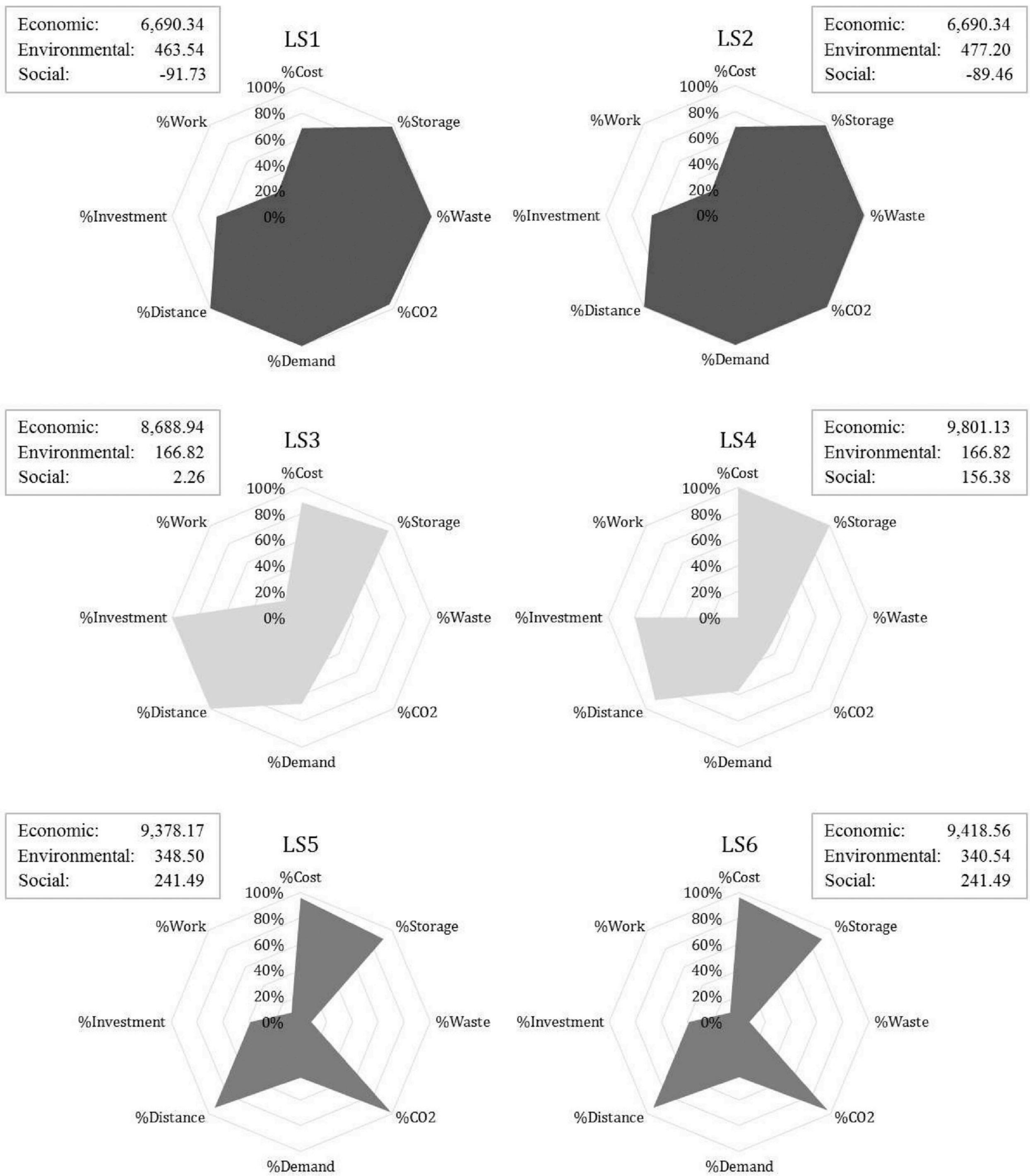

Fig. 5. Comparison of selected KPIs for the lexicographic solutions.

Table 3
Main features of lexicographic solutions.

Feature	Economic-centric solutions	Environmental-centric solutions	Social-centric solutions
Changes in network structure	medium	high	low
Level of food assistance	low	medium	high
Use of financial donations	low	medium	high
Level of food waste	high	medium	low
CO_2 emission cost	high	low	high
Investment effort	medium	high	low
Social work value creation	low	high	high

Table 4
Comparison of lexicographic solutions with existing network configuration.

Estimated objective function values	Existing network	Lexicographic solutions					
		LS1	LS2	LS3	LS4	LS5	LS6
Economic (m.u.)	7786.40	−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%

analysis.

4.2.3. Comparison with existing network configuration

To be able to compare the results presented in the previous section with the features of the existing food aid supply chain, we have assumed that the current situation (period 0) remains unchanged. Accordingly, the four existing food banks are operated with their initial capacities over all five time periods, and the acquisition of additional (storage and transport) capacity is not considered. Moreover, those charities currently served by food banks continue to receive food assistance, and their requirements X_{pc}^0 for each product $p \in P$ ($c \in SC$) are fully satisfied in all periods. Charities on hold are not supported. In order to be consistent with the profile of the FPBA, 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, 3935.52 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 $\sum_{p \in P} \sum_{c \in SC} X_{pc}^0$ over the 20 instances. Furthermore, all other input data were obtained by taking the corresponding averages over the test instances. Table 4 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.

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 remain unchanged. The values shown in Table 4 also indicate that a policy which 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, is not of 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.

5. Conclusions

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 define the problem, we developed a multi-objective MILP 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 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 in southern 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. 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. 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 most promising solutions (from the decision maker's perspective). Future research could also focus on designing a custom made solution approach for the problem introduced in this paper, especially when large instances need to be solved within a reasonable time limit.

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Appendix

The following table summarises the main characteristics of the lexicographic solutions obtained.

Table 5
Characteristics of the lexicographic solutions (averages over 20 test instances).

	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)	1574.5	1574.5	3153.0	3002.7	1511.4	1511.4
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
# 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
Food donations						
total quantity (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
Economic indicators						
total cost (m.u.)	6690.3	6690.3	8688.9	9801.1	9378.2	9418.6
food donations (kEUR)	11,019.7	11,019.7	13,676.1	14,382.5	15,373.3	15,411.2
unused financial donations (kEUR)	1063.0	1069.4	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)	4358.0	4330.3	1613.0	1612.9	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)	2077.5	2077.5	2305.3	2818.3	2538.4	2538.4
total investment capital required (% of total reference budget)	42.7	42.0	65.0	51.7	25.1	25.1

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