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Redesigning a food bank supply chain network, Part I: Background and mathematical formulation

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Abstract

Motivated by the increasing global interest in reducing food waste, we address the problem of redesigning a multi-echelon supply chain network for the collection of donated food products and their distribution to non-profit organisations that provide food assistance to the needy population. For the social enterprise managing the network, important strategic decisions comprise opening new food bank warehouses and selecting their storage and transport capacities from a set of discrete sizes over a multi-period planning horizon. Facility decisions also affect existing food banks that may be closed or have its capacity expanded. Logistics decisions involve the number of organisations to be supplied, their allocation to operating food banks and the flow of multiple food products throughout the network. Decisions must be made taking into account that food donations are insufficient and a limited investment budget is available. The paper is organised in two parts. In Part I, we propose a novel mixed-integer linear programming model that captures various practical features of a food aid supply chain. In particular, sustainability is explicitly accounted for within the decision-making process by integrating economic, environmental and social objectives. In Part II, a computational study is conducted to investigate the trade-offs achieved by considering the three conflicting objective functions. Numerical results are presented for real-case based instances shaped by the food bank network coordinated by the Portuguese Federation of Food Banks.

Keywords: Supply chain, sustainability, tri-objective problem, MILP model

1. Introduction

In 2014, the proportion of people at risk of poverty or social exclusion in the European Union (EU) was estimated at 24.4%, affecting around 122 million people (Eurostat, 2015). Moreover, 9.5% of the EU population was unable to afford a quality meal (i.e. a meal with meat, chicken,

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fish or a vegetarian equivalent meal) every second day (Eurostat, 2016). 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 throughout the food supply chain (European Commission, 2016b). In particular, the member states are committed to achieve a 30% food waste reduction by 2025 (European Commission, 2016a). 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.

A wide variety of humanitarian aid organisations, including food banks, act as intermediaries between food resources and people in need (Orgut et al., 2016; Power, 2015). Typically, they obtain edible food from donor organisations and individuals, process the donated food products at storage facilities and distribute them to the end users, either directly or indirectly via charitable and other third sector institutions. For social economy actors, such as food banks, return on investment and other economic objectives are not of primary concern. Instead, environmental and social objectives determine their activities. Therefore, food banks play a significant role in promoting the sustainability of the food supply chain.

The concept of food banks has its origins in the late 1960s in the USA. Over the past three decades, this concept has expanded to many countries around the world, often prompted by economic downturns and government cuts to social benefit programmes (Power, 2015). In Europe, the European Federation of Food Banks represents an extensive network of food banks in 23 countries, including Portugal (FEBA, 2016). Founded in 1999, the Portuguese Federation of Food Banks (the acronym in Portuguese is FPBA) coordinates a network of 21 food banks, 18 of them located in mainland Portugal and the remaining three in the Azores and Madeira islands. 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, 2016). It is estimated that around 1 million tons are lost across the food supply chain in Portugal every year, corresponding to 17% of the total food production (Baptista et al., 2012). The Portuguese parliament has declared 2016 as the "Year against Food Waste" to raise awareness about the importance of this issue and move stakeholders across the food supply chain towards taking specific actions.

Rather than providing aid directly to those in need, the Portuguese food banks dole out donated food to various non-profit organisations such as family associations, parish social centres and nursing homes, for local distribution. The financial crisis in 2007-2008 and the subsequent implementation of austerity measures have contributed to the country's rising number of people seeking food assistance. In 2015, the members of FPBA served 2,654 organisations, which, in turn, supported more than 400,000 people (FPBA, 2016). This represents an increase of approximately 74% from 2008.

Food banks operate with limited resources which depend primarily on donations and on the work of volunteers. It is therefore critical for the FPBA to design and manage its supply chain network in an efficient and effective way in order to be able to receive the largest possible quantity of food donations and, consequently, reach as many needy people as possible. From a sustainability perspective, the identification of the best geographical locations and capacities for food banks may not only have positive environmental and social impacts but may also lead to cost savings and improved operational performance.

Our study addresses a supply chain network redesign problem motivated by a real situation encountered at the FPBA. The current configuration of the distribution network of food banks is not the outcome of a strategic planning process, but it rather emerged through operational decisions and occasionally identified donation opportunities. Each food bank operates a centralised warehouse which serves as a single collection and distribution point for food donations. Storage space was mostly donated by private organisations and municipalities. The geographical location of the warehouses and/or the available capacities may not be the most ideal choice. Therefore, the main contribution of this study is to investigate the benefits that are likely to be achieved from redesigning the existing distribution network of a food bank supply chain. From an economic perspective, redesigning a supply chain network can result in a 5–15% reduction of the overall logistics costs, with 10% being often realised in an industrial context (Ballou, 2001; Harrison, 2004). A similar or even higher cost reduction potential is expected to be achieved for the FPBA. Environmental and social gains are also anticipated. Our conjecture relies on the fact that the network configuration has evolved over the years without following a specific strategic plan. We develop a multi-objective mixed-integer linear programming (MILP) model that incorporates the three dimensions of sustainability, i.e. economic, environmental and social goals, into the decision-making process. The model captures the dynamics of the food bank supply chain by addressing strategic facility location, capacity acquisition and distribution decisions over a multi-period finite planning horizon.

Our study is divided into two papers, hereby called Part I and Part II. Part I is organised as follows. Section 2 provides a review of the literature related to sustainability in (food) supply chain management and, in particular, in supply chain network design for non-profit organisations. Section 3 describes the main stakeholders in the network of the FPBA and explains the activities in which they are involved. In Section 4, we propose a mathematical model to redesign a food bank collection and distribution network, and relate the novel model to the literature on supply chain network design. In Part II, computational experiments for real case-based instances using a state-of-the-art MILP solver will be presented and directions for future research will be identified.

2. Literature review

The simultaneous consideration of economic, environmental and social issues in corporate decision-making processes is often termed *triple bottom line* (TBL), an expression originally coined by Elkington (1997). 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) as evidenced by the recent surveys by Hassini et al. (2012) and Brandenburg et al. (2014). The food supply chain has also been subject to sustainability initiatives across all levels, from the agricultural sector to the distribution industry (Beske et al., 2014; Fredriksson and Liljestrand, 2015; Soto-Silva et al., 2016). However, holistic approaches for sustainable SCM are still emerging in the academic literature dedicated to Operational Research.

Supply chain network design (SCND) is the strategic planning process for optimising the configuration of a supply chain. Typically, SCND involves determining the optimal number and location of facilities (e.g. manufacturing plants and warehouses), allocating capacity and technology requirements to facilities, and deciding on the flow of products throughout the supply chain such that customer demands are satisfied. Although research on SCND has primarily concentrated on economic factors through maximising profit or minimising cost objectives (Melo et al., 2009), the incorporation of the environmental dimension is gradually being considered at the strategic level. Eskandarpour et al. (2015) listed various metrics that have been used to assess environmental factors in the context of SCND. They range from greenhouse gas emissions (e.g. from transportation-related activities) to energy consumption (e.g. due to the type of facilities in place and the technology choices made). Govindan et al. (2014) have incorporated such metrics into a MILP model to design a multi-echelon supply chain network for perishable food products. In addition to location and capacity acquisition decisions for new manufacturing facilities and distribution centres, the model also includes the determination of vehicle routes for shipping food items across the network.

In contrast to economic and environmental issues, the third dimension of sustainability - social equity or social justice - is under-represented. Eskandarpour et al. (2015) argue that it is comparatively more difficult to quantify social factors and embed them in a mathematical framework. This view applies not only to SCND but also to analytical models in SCM in general (Beske et al., 2014; Brandenburg et al., 2014). In the context of locating manufacturing facilities, Chen et al. (2014) have also noted that the social dimension is often neglected. Devika et al. (2014) are among the few authors that have taken into account economic, environmental and social aspects to design a multi-echelon closed-loop network. The proposed MILP model incorporates location and technology acquisition decisions for various types of facilities, including production plants and collection, remanufacturing and recycling points. Total costs and environmental impacts are minimised, whereas social benefits are maximised. The latter objective is measured through the number of job opportunities that are created by establishing new facilities. In addition, work safety is also considered by way of the potential loss of working days caused by possible damages from establishing and operating new facilities at given locations. Three metaheuristics are developed to identify Pareto-optimal solutions.

A food bank supply chain network shares several characteristics with its industrial counterpart. In fact, multiple relevant location and transportation problems encountered in the context of food distribution are defined on networks and share a common structure with classical supply chain planning problems. However, analytical models specifically directed to managing the logistics networks of food banks are relatively scarce. This is possibly explained by the social purpose this type of networks serve and the specific characteristics of the numerous (commercial and non-profit) organisations that interact with food banks. These issues are not present in supply chains in the industrial sector. Contributions in the literature have focused so far on tactical and operational problems of food bank supply chain networks, while the strategic planning level has been neglected. Next, a review of recent work is provided.

The design of delivery routes for a fleet of capacitated vehicles is at the core of the vehicle routing problem (VRP). Balcik et al. (2014) address this problem for the collection of food products from donors and the distribution of the donated food to non-profit organisations. Since supply is often less than demand, the objective is to maximise total equity (i.e. the fair distribution of donated food among the recipients served by a vehicle). 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. In a second phase, the authors study a periodic VRP with backhauls to obtain weekly transportation schedules for the collection and distribution of donated food. Solak et al. (2014) also focus on a variant of the location-routing problem for the distribution of donated food. The objective is to minimise the weighted average of the vehicles' routing costs and the travel costs of the beneficiary institutions to pick up food from the assigned locations. The latter costs measure the inconvenience caused to the partner agencies and can be seen as a surrogate for the environmental and social impacts of the location and routing decisions.

Scheduling routes for food collection and delivery relies on estimates for the availability of different food types from the donor organisations and the actual needs at the receiving institutions. Brock and Davis (2015) propose four methods to forecast collection amounts. Giuseppe et al. (2014) develop a non-linear mathematical model to determine the optimal time point for retailers to withdraw food products from the shelves, and the quantities to donate to food banks and to sell to the livestock market. Mohan et al. (2013) report on an econometric model to estimate demand for donated food. In addition, various measures to improve the warehouse operations of a non-profit organisation were devised and validated using a discrete simulation model. Efficiency gains could be achieved through reducing warehouse operational costs and increasing the quantity of food reaching the people in need. Finally, at the tactical planning level, Martins et al. (2011) describe a linear programming model to assign food products stored by a Portuguese food bank to non-profit institutions taking into account the specific dietary requirements of each institution.

Even though SCND has attracted considerable attention in the literature (Melo et al., 2009; Alumur et al., 2015), focus has primarily been given to the industrial context. In contrast, the non-commercial counterpart, as it is the case of humanitarian aid supply chains, has received far less attention. Such supply chains, including those operated by food banks, share some features with their industrial counterpart but at the same time they also have specific characteristics. As shown by the previous description of the relevant literature, SCND has not been addressed so far in the context of food banks. To the best of our knowledge, our study constitutes the first attempt to model a network redesign problem motivated by a real case and to incorporate a triple bottom line approach into the decision-making process.

3. Characteristics of the food bank supply chain

In this section, we examine some of the problem characteristics in more detail. In particular, we present the main stakeholders of the food aid supply chain based on the operation of the FPBA, and describe their role across the supply chain.

3.1. Donors

The members of the FPBA secure food products from different kinds of donors. They comprise, among others, farmers, food manufacturers, wholesalers, retailers, such as supermarkets and grocery chains, and consumers. Typically, donated food products are not sellable but still edible even if they are approaching their "expiration", "sell by" or "best by" date. Donated food may come, for example, from farmers with surplus agricultural produce or whose products may not be visually appealing, from retailers who over-ordered and from distributors who experienced damages during transportation (e.g. damaged packaging). In addition, excess agricultural products are also received from the EU Fund for European Aid to the most Deprived (FEAD). The majority of high-volume donations are delivered by the donor organisations to local food banks. Some donors require the food items to be collected and in this case, food bank vehicles are used for this purpose. For example, in large cities such as Lisbon and Oporto, food bank vehicles collect vegetables and fruit from a central wholesale market on a daily basis. Food donation is part of the corporate social responsibility of many businesses. Moreover, economic benefits, such as tax deductions and reduction of storage and disposal costs, also encourage food donations. Consumers also serve as a source of supply, chiefly during annual collection campaigns organised by the FPBA. On special collection days, food is donated at a series of collection points mostly in supermarkets and then transported to the nearest regional food bank by volunteers.

In addition to food donations, there are also individuals and businesses that donate money. Financial donations are mostly used by food banks to make food purchases, often at discounted prices, to supplement material donations.

3.2. Food bank warehouses

FPBA coordinates a network of 21 food banks. Figure 1 depicts the locations of food banks across the 18 administrative districts in mainland Portugal. Each food bank operates a warehouse which serves as a single collection and distribution point for food donations. The largest warehouses are located in Lisbon, Setúbal and Oporto.

Incoming food donations are inspected for quality, sorted, stored and eventually prepared for delivery to non-profit institutions. Food bank warehouses vary on their sizes, infrastructures and storage capacities and capabilities. Storage space may be divided in up to three major areas, one for dry products (e.g. canned goods), one for refrigerated items (e.g. dairy products) and a third one for frozen products (e.g. meat and fish). Warehouse layouts differ among locations. Some food banks store a single type of products, typically dry products. Furthermore, each warehouse maintains its own fleet of vehicles for food collections or otherwise, rents transport capacity when needed. Vehicles differ in size and equipment (e.g. refrigerated versus non-refrigerated vehicles).

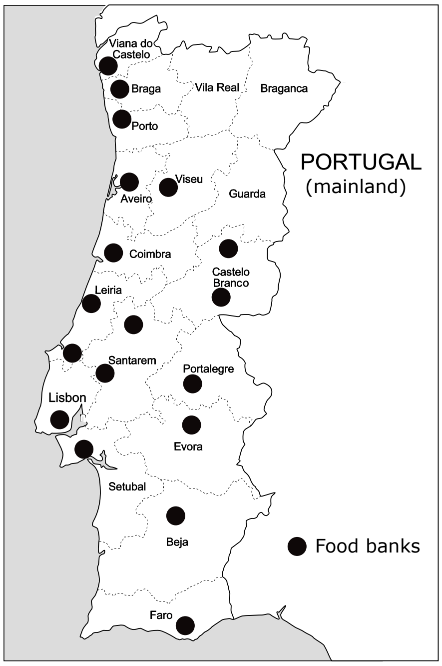

Figure 1: Locations of Portuguese food banks

The amount of food donations has increased over the last years (FPBA, 2016) and this poses warehouse capacity problems. Warehouse capacity management can be addressed in various ways, including establishing new warehouses, expanding the available capacity or even closing existing facilities. These options will be considered in the mathematical model to be presented in Section 4. Furthermore, food bank warehouses are not evenly distributed across the country as shown in Figure 1. In particular, in some districts (e.g. Vila Real, Bragança, Guarda), the population in need of food assistance is farther away from the nearest warehouse than desired. Therefore, to provide access to donated food in an equitable manner it is necessary to redesign the existing network, e.g. through opening new warehouses.

Sometimes, the quantity of a particular food product that is donated to a food bank warehouse largely exceeds the needs of the non-profit institutions served by that local branch. In such occasions, it would be advantageous to distribute the excess quantity to a food bank facing a shortage of the same product. However, this is not a well-established practice, mostly due to the additional organisational effort that is required (e.g. to identify other members of the FPBA needing the same product) and the lack of transport resources. In fact, it could be beneficial to increase the number of inter-warehouse shipments. This aspect, which has not received much attention in the literature dedicated to SCND (Alumur et al., 2015; Melo et al., 2009), will be addressed by our mathematical model.

3.3. Beneficiary institutions

Each food bank redistributes the donated products free of charge to a distinct set of non-profit local organisations such as hostels for the homeless, parish social centres, elderly care centres and nursing homes. These, in turn, either distribute the items that they receive to individuals and families experiencing food insecurity, or use the food products to prepare and serve meals. Food banks try to supply food items that best meet the particular nutritional needs of each recipient (Martins et al., 2011). For example, food parcels delivered to an elderly care centre differ from parcels prepared for a day nursery.

Beneficiary institutions must travel and collect their food products at their assigned warehouse on specific days. Since they must support their own transport expenses, these organisations are usually located within a certain radius of the food bank warehouse. Due to an imbalance between donated food and demand, the FPBA is unable to serve all organisations. When an organisation applies for food assistance it is first put onto a waiting list. In recent years, it has been possible to gradually increase the number of supported organisations due to the growing amount of donations. The FPBA ensures that food donations are redistributed among the served institutions in an equitable manner.

3.4. Economic, environmental and social issues

The role played by food banks in the food supply chain clearly highlights the different nature of the objectives pursued by their activities compared to for-profit businesses.

Similar to commercial organisations, food banks are also concerned with improving the efficiency of their operations through managing the available resources at the lowest total cost. This entails minimising the costs associated with operating the storage capacity at warehouses and the transport capacity for collection of food items from donors and for distribution of donated food to other warehouses. Additional costs are incurred by activities related to the inspection and processing of incoming donations as well as preparation of food parcels at food bank warehouses. Administrative costs are also incurred, namely to support beneficiary institutions.

Regarding environmental objectives, food banks are particularly conscious of their responsibility in food waste minimisation. This objective translates into receiving as many food items as possible. Disposal costs are avoided when all donated food products are redistributed to beneficiary organisations. Additionally, raw materials and other resources used in food production are not wasted. On the other hand, collection of donated food items by food bank vehicles generate CO_2 emissions that are undesired.

Providing access to donated food in an equitable manner is a primary social objective guiding food distribution decisions. There are various ways of measuring equity that reflect different perspectives of fairness (Orgut et al., 2016). Regarding the FPBA, focus is given to reaching the maximum number of beneficiary institutions and to supplying them with the available food products in the most balanced way possible taking into account the needs of the population supported by each institution.

Naturally, cost-efficiency, environmental sustainability and social equity are conflicting objectives. We incorporate them into a novel multi-objective MILP formulation that will be presented in the next section. Our model aims at redesigning an existing food bank collection and distribution network over a multi-period horizon while simultaneously pursuing the following objectives: (i) minimisation of the cost of operating the food bank network, (ii) minimisation of the environmental impacts of food waste and CO_2 emissions and (iii) maximisation of the social benefits generated for organisations supported by food banks. To this end, strategic decisions about locating new food bank warehouses and choosing their capacity levels for storing and transporting different product families are to be made. Moreover, location decisions also affect existing warehouses through facility closure or expansion. The decision set also includes decisions on the number of beneficiary institutions to be supplied, their allocation to operating food banks and the flow of donated food products throughout the network. Organisational conditions for network deployment must also be met. Decisions must be made taking into account that food donations are insufficient and a limited investment budget is available.

4. Model formulation

In this section, we describe a MILP model for the multi-period, multi-echelon, multi-product network redesign problem inspired from the FPBA. Figure 2 depicts the general structure of the food bank distribution network. Facility location decisions include closing existing food bank

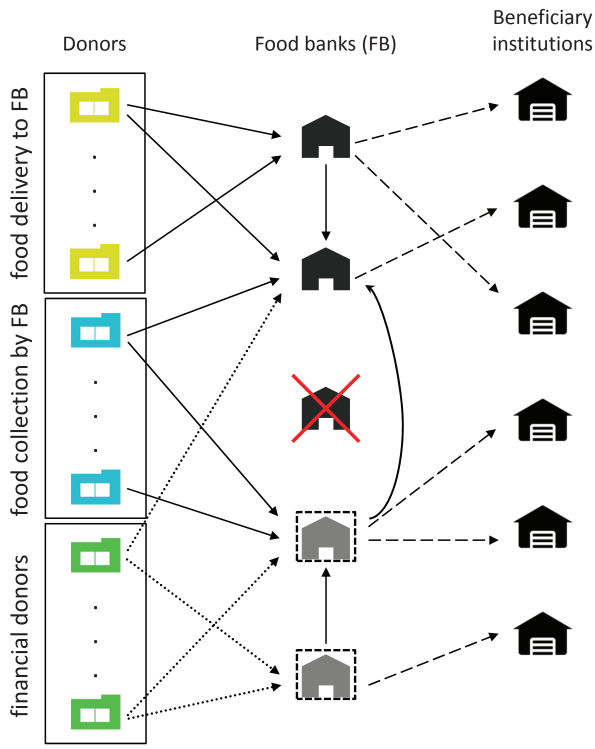

Figure 2: Schematic configuration of a food bank supply chain network

warehouses (this feature is highlighted in Figure 2 by an x mark) and opening new warehouses at potential sites (the facilities in the dashed boxes in Figure 2) over a multi-period finite planning horizon. In addition, capacity planning is also considered through the acquisition of storage space and transport vehicles. Since multiple product families with distinct characteristics are considered, each storage area is dedicated to a specific product family. Storage capacity is chosen from a discrete set of available capacity levels. The same holds for transport capacity. Food bank vehicles are required for the collection of food items from given donors (these are represented by the second group of donors in Figure 2) and for moving food donations from one food bank to other food banks. The flow of financial donations is illustrated by the arrows with dotted lines in Figure 2, whereas the assignment of beneficiary institutions to food banks is depicted by the arrows with dashed lines. Each served beneficiary institution is assigned to a single food bank in each time period, from which it collects food items. Additional assumptions are described next.

- Each donor that delivers products to food banks does so to a pre-defined set of warehouses.
- If an existing food bank warehouse has its capacity expanded then it must operate until the end of the time horizon.
- If a new food bank is opened at 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.
- Storage capacity for different product families may be acquired for the same warehouse but at most one additional storage area per product family can be installed in a warehouse over the planning horizon.
- It is only meaningful to invest in transport capacity for a given product family in a food bank warehouse if that family is stored at the food bank.
- Multiple vehicles for the same product family may be acquired by a food bank in each period as long as they have different capacities.
- Location and capacity acquisition decisions are limited by an available budget in each time period. Due to the sizeable investment associated with these decisions, temporarily closing and reopening of food banks is not permitted.
- All non-profit organisations supported by the food bank association prior to the redesign project must continue to be served. Additionally, organisations on the waiting list of the food bank association may start receiving food assistance. In both cases, demands may not be fully satisfied but certain minimum levels of assistance must be guaranteed to all organisations served by a food bank.

4.1. Notation

Table 1 introduces the index sets that are used.

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 bank warehouses at the beginning of the planning horizon
PB	Potential sites for locating new food bank warehouses
B	All food bank locations, $B = OB \cup PB$ and $OB \cap PB = \emptyset$
B_d	Food banks that can receive food products from donor $d \in DD$, $B_d \subseteq B$
SC	Beneficiary organisations served by some food bank at the beginning of the planning horizon
HC	Non-profit organisations on hold, i.e. organisations on the waiting list of the food bank association
C	All organisations, $C = SC \cup HC$ and $SC \cap HC = \emptyset$
K	Families of food products
P_k	Individual food items belonging to family $k \in K$
P	All food products, $P = \cup_{k \in K} P_k$
L	Discrete capacity levels for storage areas / transport resources

Table 1: Index sets

Table 2 presents all financial data, which are expressed in monetary units. Storage and transport capacity units are measured in tons. This is also the unit used for food product quantities.

Parameters FI^t and FU^t in Table 2 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 and work contracts, expenditures for equipment transfers and payments incurred by disposal activities) of a food bank warehouse in time period t. Acquisition costs for storage capacity ($VSI^t_{\ell k}$) and transport capacity ($VTI^t_{\ell k}$) at both new and existing food bank locations vary according to the capacity installed. These costs 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 among product families. For example, frozen food products must be stored under special temperature conditions and refrigerated vehicles must be used for collecting them. Dismantling costs (VU_k^t) are associated with closing a food bank warehouse and depend on the type of existing storage areas. Costs related to removing transport capacity due to facility closure are considered to be negligible.

Symbol	Description
FI^t	Fixed cost of opening a new food bank warehouse 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 warehouse 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 warehouse in period $t \in T$
FC^t	Fixed cost of serving a beneficiary institution 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 facility location and capacity acquisition decisions
$\widetilde{Q}_d^t$	Financial donation of donor $d \in FD$ to purchase food products in period $t \in T$
τ_p^t	Cost of purchasing one unit of food product $p \in P$ in period $t \in T$
φ_k^t	Cost of disposing one unit of food products belonging to family $k \in K$ in period $t \in T$
ω	Cost of CO_2 emissions due to transportation of one unit of a food product, per km
α_1	Penalty factor per unit of unused transport capacity

Table 2: Financial parameters

The operation of a food bank warehouse incurs fixed and variable costs. The former include administrative and managerial overhead expenses due to serving beneficiary institutions and are specified by FC^t for each institution. Variable costs depend on the available capacity and on the amount of products handled at each food bank. Parameter VS^t_{kb} accounts for the cost of maintaining storage areas (e.g. equipment, energy consumption), and depends on the storage capacity installed for each family of products. Handling costs, represented by parameter VH^t_{kb}, are associated with processing incoming donations and the preparation of food products for redistribution. In both cases, they may vary from location to location to account for different regional cost structures.

Symbol	Description
Q^t_{pd}	Quantity of food product $p \in P$ supplied 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
$M_{\ell k}$	Storage capacity of size $\ell \in L$ for product family $k \in K$ that can be installed in a food bank warehouse
$\overline{N}_{kb}$	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 acquired by a food bank warehouse
R^t_{pc}	Demand of non-profit organisation $c \in C$ for food product $p \in P$ in period $t \in T$
X^0_{pc}	Quantity of food product $p \in P$ received by beneficiary institution $c \in SC$ prior to the redesign project
β_1, β_2	Minimum level of demand satisfaction of non-profit organisation $c \in SC$, resp. $c \in HC$, with $\beta_1, \beta_2 \in]0, 1]$
U_{ij}	Distance between origin i and destination j for every $(i, j) \in A$ (in km)
α_i	Non-negative factors ($i = 2, \ldots, 6$)

Table 3: Capacity and demand parameters

Table 3 introduces additional parameters related to resources, demand for food items and user-specified constants. The latter will be used in two of the objective functions. In each time period $t \in T$, it is assumed that the demand of every non-profit organisation $c \in SC$ satisfies the following condition for every food product $p \in P$: $R^t_{pc} \geq \beta_1 X^0_{pc}$. Moreover, due to the mismatch between supply and demand, it is assumed that $\sum_{c \in C} R^t_{pc} > \sum_{d \in DD \cup CD} Q^t_{pd}$ for every $p \in P$ and $t \in T$.

For notational convenience, we introduce the set A of all origin-destination pairs in the network depicted in Figure 2:

$$\begin{aligned} A \;=\; & \{(d,\, b) : d \in DD,\, b \in B_d\} \cup \{(d,\, b) : d \in CD \cup FD,\, b \in B\} \cup \\ & \{(b,\, b') : b, b' \in B, b \neq b'\} \cup \{(b,\, c) : b \in B,\, c \in C\} \end{aligned}$$

4.2. Decision variables

All decisions are implemented at the beginning of each time period. As indicated in Table 4, strategic decisions on facility location and capacity acquisition are represented by binary variables. Moreover, binary single-assignment variables are also introduced. Logistics decisions are described by the continuous variables in Table 5.

Symbol	Description
y^t_b	1 if the *status* of food bank location $b \in B$ changes in period $t \in T$, 0 otherwise; if $b \in PB$ then $y^t_b = 1$ means that a new food bank warehouse is established in site b in period t; if $b \in OB$ then $y^t_b = 1$ means that the initially existing food bank warehouse b is closed in period t
$w^t_{\ell kb}$	1 if storage capacity of size $\ell \in L$ is installed in food bank warehouse $b \in B$ for product family $k \in K$ in period $t \in T$, 0 otherwise
$v^t_{\ell kb}$	1 if transport capacity of size $\ell \in L$ is acquired by food bank warehouse $b \in B$ for product family $k \in K$ in period $t \in T$, 0 otherwise
z^t_{bc}	1 if non-profit organisation $c \in C$ is served by food bank warehouse $b \in B$ in period $t \in T$, 0 otherwise

Table 4: Binary decision variables

4.3. Network redesign constraints

In this section, we describe in detail the constraints in our MILP model.

Symbol	Description
x^t_{pij}	Quantity of food product $p \in P$ moved from origin i to destination j in period $t \in T$, $(i,\ j) \in A$
θ^t_{kb}	Unused transport capacity for product family $k \in K$ in food bank $b \in B$ in period $t \in T$
γ^t	Amount of capital not invested in period $t \in T$
δ^t_{pc}	Unsatisfied demand of non-profit organisation $c \in C$ for food product $p \in P$ in period $t \in T$
δ^t	Maximum level of unsatisfied demand of any served non-profit organisation in period $t \in T$
ε^t	Maximum distance between any served non-profit organisation and its allocated food bank in period $t \in T$

Table 5: Continuous decision variables

4.3.1. Donor-related constraints

Conditions regarding the three sets of donors displayed in Figure 2 are given by the following constraints:

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

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

$$\sum_{p \in P} \sum_{b \in B} \tau^t_p x^t_{pdb} \leq \widetilde{Q}^t_d \qquad d \in FD,\ t \in T \tag{3}$$

Constraints (1) and (2) ensure that the quantity of each food item supplied by a donor to food banks does not exceed the available amount in each time period. Constraints (3) limit the amount of food purchases in every period to the available financial donations.

4.3.2. Facility location and capacity acquisition constraints

The following constraints impose the required conditions for establishing new food bank warehouses and closing existing warehouses over the planning horizon. In addition, they also rule the installation of storage and transport capacities.

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

$$\sum_{t\in T}\sum_{\ell\in L} w_{\ell kb}^t \leq \sum_{t\in T} y_b^t \qquad b \in PB,\ k \in K \tag{5}$$

$$\sum_{t\in T}\sum_{\ell\in L} w_{\ell kb}^t \leq 1 - \sum_{t\in T} y_b^t \qquad b \in OB,\ k \in K \tag{6}$$

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

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

$$\sum_{\ell\in L} v_{\ell kb}^t \leq \mathcal{M} \sum_{\ell\in L}\sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{9}$$

$$\sum_{\ell\in L} v_{\ell kb}^t \leq \mathcal{M}\left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} + \sum_{\ell\in L}\sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}}\right) \qquad b \in OB,\ k \in K,\ t \in T \tag{10}$$

$$\begin{aligned}&\sum_{b\in PB} FI^t\, y_b^t + \sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} VSI_{\ell k}^t\, M_{\ell k}\, w_{\ell kb}^t + \\ &\sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} VTI_{\ell k}^t\, N_{\ell k}\, v_{\ell kb}^t + \\ &\sum_{b\in OB}\left(FU^t + \sum_{k\in K} VU_k^t\, \overline{M}_{kb}\right) y_b^t + \gamma^t = O^t \qquad t \in T\end{aligned} \tag{11}$$

Constraints (4) enforce the *status* of a food bank to change at most once over the time horizon. This implies that if a new warehouse is established at a candidate location at a given time period then it cannot be closed afterwards. Analogously, if an initially existing food bank warehouse is closed then it cannot be later reopened. Constraints (5)–(6) state that the installation of storage capacity for each product family can occur at most once over the planning horizon. Furthermore, constraints (6) also guarantee that an existing food bank warehouse can only have its storage capacity expanded if the warehouse is operating until the end of the time horizon. In the case of new food banks, constraints (7) are further required to ensure that storage capacity can only be installed in a new site provided that a new food bank warehouse is already operating in that location. Inequalities (8) stipulate that storage capacity must be installed for at least one product family in the same time period in which a new food bank warehouse is opened. Constraints (9)–(10) state that the acquisition of transport capacity by a food bank warehouse for a product family is only possible if that warehouse holds storage capacity for the same product family. Parameter $\mathcal{M}$ that appears on the right-hand side of these constraints is a sufficiently large constant. Notice that in each time period, it is possible to purchase vehicles having different sizes (e.g. a small and a large truck) to transport food products of the same family. Finally, investment costs are limited by the budget available in each time period as stated by equalities (11). Investment spending is incurred for opening new food bank warehouses at potential locations, installing new storage areas, acquiring new transport vehicles and closing initially existing food banks as well as dismantling their storage capacity. Observe that the slack variable γ^t gives the capital that is not spent in period t.

4.3.3. Capacity utilisation constraints

The next set of constraints establishes maximum capacity utilisation limits at food bank warehouses for product storage and transportation. These limits depend on the acquisition of capacity over time.

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{12}$$

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \qquad b \in OB,\ k \in K,\ t \in T \tag{13}$$

$$\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x_{pib}^t + \theta_{kb}^t = \sum_{\ell \in L} N_{\ell k} \sum_{\tilde{t}=1}^{t} v_{\ell k b}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \tag{14}$$

$$\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x_{pib}^t + \theta_{kb}^t = \overline{N}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) +$$

$$\sum_{\ell \in L} N_{\ell k} \sum_{\tilde{t}=1}^{t} v_{\ell k b}^{\tilde{t}} \qquad b \in OB,\ k \in K,\ t \in T \qquad (15)$$

Constraints (12)–(13) guarantee that the total quantity of products of a given family, which are received from donors and other food banks, does not exceed the available storage capacity of each operating warehouse. Equalities (14)–(15) 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 to represent the amount of unused transport capacity. These variables are used in the economic objective function (36) to enforce the acquisition of transport resources only when they are needed and not earlier.

4.3.4. Institution-related constraints

The following constraints apply to the beneficiary institutions.

$$\sum_{b \in B} z_{bc}^t = 1 \qquad c \in SC,\ t \in T \qquad (16)$$

$$\sum_{b \in B} z_{bc}^t \leq 1 \qquad c \in HC,\ t \in T \qquad (17)$$

$$\sum_{b \in B} z_{bc}^{t+1} \geq \sum_{b \in B} z_{bc}^t \qquad c \in HC,\ t = 1, \ldots, |T|-1 \qquad (18)$$

$$z_{bc}^{t-1} - z_{bc}^t \leq \sum_{\bar{b} \in B} y_{\bar{b}}^t \qquad b \in B,\ c \in C,\ t = 2, \ldots, |T| \qquad (19)$$

$$\sum_{b \in B} x_{pbc}^t \geq \beta_1 X_{pc}^0 \qquad c \in SC,\ p \in P,\ t \in T \qquad (20)$$

$$\sum_{b \in B} x_{pbc}^t \geq \beta_2 R_{pc}^t \sum_{b \in B} z_{bc}^t \qquad c \in HC,\ p \in P,\ t \in T \qquad (21)$$

$$x_{pbc}^t + \delta_{pc}^t = R_{pc}^t z_{bc}^t \qquad b \in B,\ c \in C,\ p \in P,\ t \in T \qquad (22)$$

$$\sum_{p \in P} \frac{\delta_{pc}^t}{R_{pc}^t} \leq \delta^t \qquad c \in C,\ t \in T \qquad (23)$$

$$U_{bc} z_{bc}^t \leq \varepsilon^t \qquad b \in B,\ c \in C,\ t \in T \qquad (24)$$

Each institution that was served prior to the redesign project must continue to be supplied in each time period as enforced by equalities (16). Every non-profit organisation on the waiting list of the food bank association may start being served according to constraints (17). If an organisation is removed from the waiting list then constraints (18) ensure that it will receive food assistance until the end of the time horizon. Observe that an institution cannot be assigned to more than one food bank per period, although the designated food bank may vary from period to period. However, for organisational reasons, it is preferable to limit the re-assignment of institutions to food banks over the time horizon. Therefore, constraints (19) restrict re-assignments to periods in which the network configuration changes, i.e. when at least one new food bank warehouse is established and/or an existing warehouse is closed.

Constraints (20) guarantee that initially served institutions receive at least a given percentage of their initial supply of each food product. Constraints (21) ensure that institutions can only be removed from the waiting list if at least a given level of their demand is satisfied in all forthcoming periods. Equalities (22) guarantee that the quantity of each food product supplied to a beneficiary institution does not exceed its demand. Recall that the slack variables δ^t_{pc} account for unsatisfied demand for product p in period t. Constraints (23) enforce the level of unsatisfied demand of a served non-profit organisation to be limited by a threshold δ^t in each time period. Constraints (24) state that the distance between a served beneficiary institution and its assigned food bank does not exceed a threshold value. The thresholds on the right-hand side of constraints (23) and (24) are relevant to the evaluation of the social impact of food redistribution (see also (38)).

4.3.5. Other constraints

$$z^t_{bc} \leq \sum_{\widetilde{t}=1}^{t} y^{\widetilde{t}}_b \qquad b \in PB, c \in C,\ t \in T \tag{25}$$

$$z^t_{bc} \leq 1 - \sum_{\widetilde{t}=1}^{t} y^{\widetilde{t}}_b \qquad b \in OB, c \in C,\ t \in T \tag{26}$$

$$\sum_{c \in C} z^t_{bc} \geq \sum_{\widetilde{t}=1}^{t} y^{\widetilde{t}}_b \qquad b \in PB,\ t \in T \tag{27}$$

$$\sum_{c \in C} z^t_{bc} \geq 1 - \sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b \qquad b \in OB,\ t \in T \tag{28}$$

$$\sum_{i \in D \cup B \setminus \{b\}} x^t_{pib} = \sum_{j \in C \cup B \setminus \{b\}} x^t_{pbj} \qquad b \in B,\ p \in P,\ t \in T \tag{29}$$

$$y^t_b,\ z^t_{bc} \in \{0,1\} \qquad b \in B,\ c \in C,\ t \in T \tag{30}$$

$$w^t_{\ell kb},\ v^t_{\ell kb} \in \{0,1\} \qquad b \in B,\ \ell \in L,\ k \in K,\ t \in T \tag{31}$$

$$x^t_{pij} \geq 0 \qquad p \in P,\ (i,j) \in A,\ t \in T \tag{32}$$

$$\theta^t_{kb} \geq 0 \qquad b \in B,\ k \in K,\ t \in T \tag{33}$$

$$\delta^t_{pc} \geq 0 \qquad p \in P,\ c \in C,\ t \in T \tag{34}$$

$$\gamma^t,\ \delta^t,\ \varepsilon^t \geq 0 \qquad t \in T \tag{35}$$

Constraints (25)–(26) ensure that beneficiary institutions can only be supplied by operating food banks. Conversely, constraints (27)–(28) require each operating food bank warehouse to serve at least one beneficiary institution in each time period. Equalities (29) guarantee the conservation of product flow for each operating food bank in every time period. Finally, constraints (30)-(35) represent binary and non-negativity conditions.

4.4. Objective functions

We now describe how we incorporate the three dimensions of sustainability into our model. The *economic objective* is given by (36) and aims at identifying the network configuration with the least total cost. It includes the total cost for supporting beneficiary institutions (the first term), the total cost for operating storage areas and handling products at food banks (the next three terms) 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 term in the economic objective function represents a revenue due to unspent budget. In this way, we encourage the minimisation of expenditures on food bank location and capacity acquisition (recall constraints (11)).

$$\text{Min } f_1 = \sum_{t\in T}\sum_{b\in B}\sum_{c\in C} FC^t\, z^t_{bc} + \sum_{t\in T}\sum_{b\in OB}\sum_{k\in K} VS^t_{kb}\,\overline{M}_{kb}\left(1 - \sum_{\widetilde{t}=1}^{t} y^{\widetilde{t}}_b\right) +$$
$$\sum_{t\in T}\sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} VS^t_{kb}\, M_{\ell k} \sum_{\widetilde{t}=1}^{t} w^{\widetilde{t}}_{\ell kb} +$$
$$\sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\sum_{p\in P_k}\sum_{i\in D\cup B\setminus\{b\}} VH^t_{kb}\, x^t_{pib} + \alpha_1 \sum_{t\in T}\sum_{b\in B}\sum_{k\in K} \theta^t_{kb} - \sum_{t\in T}\gamma^t \tag{36}$$

The *environmental objective*, given by (37), minimises the weighted sum of the value of food waste and the CO_2 emissions incurred by transport activities. Due to the perishability of food products, unused donated food must be disposed of at a cost. Observe that CO_2 emissions are associated with transports performed by food bank vehicles. Parameters α_2 and α_3 are positive weight scaling factors that are pre-specified by the decision maker.

$$\text{Min } f_2 = \alpha_2 \sum_{t\in T}\sum_{k\in K}\sum_{p\in P_k}\sum_{d\in DD\cup CD} \varphi^t_k \left(Q^t_{pd} - \sum_{b\in B} x^t_{pdb}\right) +$$
$$\alpha_3 \sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\sum_{p\in P_k}\sum_{i\in CD\cup B\setminus\{b\}} 2\, U_{ib}\, \omega\, x^t_{pib} \tag{37}$$

Finally, (38) describes the *social objective* which contributes to providing access to donated food in an equitable manner. The first term maximises the number of non-profit organisations that are removed from the waiting list and start being served by food banks. The second term minimises the sum of the maximum levels of unsatisfied demand among the served beneficiary institutions over all periods. The third term minimises the sum of the largest distances travelled by any served institution to collect products from the designated food bank over the planning horizon. In this way, excessive travel is penalised. The three terms are weighted by positive scaling factors α_4, α_5 and α_6.

$$\text{Min } f_3 = -\alpha_4 \sum_{t\in T}\sum_{b\in B}\sum_{c\in HC} z^t_{bc} + \alpha_5 \sum_{t\in T}\delta^t + \alpha_6 \sum_{t\in T}\varepsilon^t \tag{38}$$

The economic, environmental and social objective functions (36)–(38) reflect the conflicts faced by the food aid supply chain, namely:

(i) to be efficient (through identifying the supply chain design with least total cost),

(ii) to mitigate the environmental impact (by reducing food waste and CO_2 emissions)

(iii) and to promote social sustainability (through serving the largest possible number of beneficiary institutions over the time horizon in the fairest way possible).

The conflicts posed by the above three objectives result in trade-offs for decision making as it will be shown in Part II.

4.5. Related SCND models

The proposed MILP formulation shares some features with other SCND models that have appeared in the literature. In the remainder of this section we will focus on the more relevant contributions in the context of multi-period SCND problems. We will see that no single work captures all the different facets of our problem.

Strategic decisions involving facility location and capacity acquisition for production and/or warehousing in a multi-echelon network were considered by various authors, e.g. Bashiri and Badri (2010), Correia et al. (2013), Cortinhal et al. (2015) and Thanh et al. (2008). Furthermore, Correia et al. (2013) also group products into families and each family is assigned to its own storage location. In contrast to our model, multiple capacity levels for storage areas can be installed in successive time periods for the same product family at a given location. Some models include budget constraints that limit the investment in new facilities, facility closures and capacity acquisition, e.g. Antunes and Peeters (2001), Bashiri and Badri (2010), Correia et al. (2013) and Melo et al. (2012).

An important issue that has not received much attention is the possibility of not satisfying all customer demand. Under a profit maximisation objective, it may not always be optimal to meet all customer requirements as shown by Bashiri and Badri (2010) and Correia et al. (2013). The latter authors also investigate their two-echelon production-distribution system from a cost minimisation perspective with additional constraints enforcing a minimum rate for demand fulfilment.

Typically, in a supply chain network, products flow from raw material suppliers via intermediate plants and distribution echelons to the final customers. For large shipments it is often economical to deliver products directly from higher level facilities to customer locations. In some settings, it may also be meaningful to exchange products between facilities belonging to the same echelon. This aspect, which is captured by our model, has been rarely addressed in the literature. Melo et al. (2012) are among the few authors who included this feature in the context of a facility relocation problem. Finally, as discussed in Section 2, most SCND models primarily focus on the economic performance of the whole supply chain through a single objective function, since they are typically tied to an industrial context. Nevertheless, bi-objective models integrating economic and environmental aspects are increasingly receiving more attention as noted by Eskandarpour et al. (2015). The triple bottom line perspective is an emerging trend in SCND. Our work aims at contributing to this trend by proposing a model that captures important features of a food bank supply chain.

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Keywords: logistics network design/re-design, multiple periods, transportation mode selection, product outsourcing, mixed-integer linear programming

(49 pages, 2014)

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A comparison of reward systems for truck drivers based on telematics data and driving behavior assessments

Keywords: Telematics, driving behavior, incentives, award systems

(9 pages, 2015)

9 I. Correia, M.T. Melo

Multi-period capacitated facility location under delayed demand satisfaction

Keywords: Location, multi-period, capacity choice, delivery lateness, MILP models

(35 pages, 2015)

9 C.L. Martins, M.T. Melo, M.V. Pato

Redesigning a food bank supply chain network, Part I: Background and mathematical formulation

Keywords: Supply chain, sustainability, tri-objective problem, MILP model

(30 pages, 2016)

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