UNIVERSIDADE DE LISBOA

Instituto Superior de Economia e Gestão

Redesign of a sustainable food bank supply chain

Carlos José Lúcio Martins

Supervision: Professor Margarida Vaz Pato

Thesis submitted for the degree of Doctor of Philosophy in
Mathematics Applied to Economics and Management

2019

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Abstract

Food rescue and delivery organizations target concurrently the environmental objective of reducing food waste, and the social objective of supporting underprivileged segments of the population. They secure surplus and about-to-waste food items from producers, manufacturers and retailers, and redistribute them through charitable agencies and parish councils to support the population in need of food assistance. Inspired by the case of the Portuguese Federation of Food Banks, the study addresses the redesign of a food bank supply chain from a multi-dimensional outlook on sustainability. Considering an initial network of food banks, strategic decisions include the opening and closing of food banks, as well as the installation or expansion of storage and transport resources, while tactical decisions comprise the selection of served charities and respective assignment to the operational food banks. Moreover, product flows across the network are also to be determined. The supply chain is formulated as a three-layer network involving the donors, the food banks, and the charities, where multiple products flow in vertical and lateral directions. Based on an extensive literature review, and supported by an in-depth field research, the problem is formulated as a dynamic and capacitated tri-objective mixed-integer linear programming model, accounting for environmental indicators such as the volume of food waste and CO_2 emissions, and social metrics assessing, among others, equity, inclusion, and proximity. The tri-objective problem is studied for regional and national supply chain instances, developed to depict real-life based cases. Non-dominated solutions are obtained for the regional instances appealing to the lexicographic ordering method. Relevant managerial insights are derived from the analysis of the lexicographic solutions. Three decomposition based heuristics developed in this study proved to be effective in solving the national instances. Trade-offs between the economic, environmental, and social objectives are discussed, and properties of the mathematical programming model are proven.

Keyworks: Supply chain; Sustainability; Food banks; Network design; Tri-objective problem

Resumo

As organizações de “resgate e distribuição” alimentar perseguem paralelamente o objetivo ambiental de redução do desperdício alimentar e o objetivo social de apoio à população carenciada. Estas entidades angariam excedentes alimentares e produtos em vias de deterioração de produtores, indústrias e do comércio a retalho que redistribuem, através de instituições de solidariedade e autarquias locais, a pessoas com carências alimentares. Inspirado no caso da Federação Portuguesa de Bancos Alimentares, este estudo aborda o redesenho de uma cadeia de abastecimento de bancos alimentares numa perspectiva de sustentabilidade multi-dimensional. Considerando uma rede inicial de bancos alimentares, as decisões estratégicas envolvem a abertura e o encerramento de bancos alimentares, bem como a instalação ou expansão da capacidade de armazenamento e de transporte, ao passo que as decisões táticas compreendem a seleção das instituições servidas e a sua afetação a algum dos bancos em operação. Adicionalmente, são também determinados os fluxos de produtos que circulam na rede. A cadeia de abastecimento é formulada como uma rede de três níveis envolvendo os doadores, os bancos alimentares e as instituições beneficiárias. Nesta rede existem fluxos verticais e laterais de produtos. Com base numa extensa revisão bibliográfica e apoiado por um aprofundado trabalho de campo, o problema é formulado como um modelo de programação linear inteira-mista, dinâmico, com capacidades e tri-objetivo. Este problema considera indicadores ambientais como o volume de desperdício alimentar e as emissões de CO_2, e como métricas sociais a equidade, a inclusão e a proximidade, entre outros. O problema é estudado para instâncias de cadeias de abastecimento regionais e nacionais, as quais foram desenvolvidas com o objetivo de retratar casos baseados na realidade. São obtidas soluções não dominadas para as instâncias regionais recorrendo ao método lexicográfico, cuja análise revela conclusões relevantes para a gestão. Foram desenvolvidas três heurísticas baseadas em decomposição que provaram ser eficazes na resolução das instâncias nacionais. São discutidos os compromissos existentes entre os objetivos económico, ambiental e social, e provadas propriedades do modelo de programação matemática.

Palavras-chave: Cadeia de abastecimento; Sustentabilidade; Bancos alimentares; Desenho de rede; Problema tri-objetivo

Publications

Martins, C. L., Pato, M. V., 2019. Supply chain sustainability: a tertiary literature review. *Journal of Cleaner Production* 225, 995-1016. doi:10.1016/j.jclepro.2019.03.250.
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Mentioned in Chapters 4, 5 and 7

Martins, C. L., Fonseca, M. C., Pato, M. V., 2017. Modeling the steering of international roaming traffic. *European Journal of Operational Research* 261, 735-754. doi:10.1016/j.ejor.2017.02.030.
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Martins, C. L., Melo, M. T., Pato, M. V., 2016. Redesigning a food bank supply chain network, Part I: Background and mathematical formulation. *Technical Reports on Logistics of the Saarland Business School 10*, Saarland University of Applied Sciences, Germany. Available at: https://www.htwsaar.de/wiwi/Forschung und Wissenstransfer/publikationen/dateien/SchriftenreiheNr10-072016.pdf.
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List of Abbreviations

AHP	Analytic hierarchy process
CSR	Corporate social responsibility
DEA	Data envelopment analysis
EU	European Union
FAO	Food and Agricultural Organization
FBNR	Food bank network redesign
FEBA	European Federation of Food Banks
FPBA	Portuguese Federation of Food Banks
GDP	Gross domestic product
GrSCM	Green supply chain management
HS	Heuristic solution
KPI	Key performance indicator
LCA	Life cycle assessment
LO	Lexicographic ordering
LS	Lexicographic solution
MILP	Mixed-integer linear programming
MOP	Multi-objective programming
MO-MILP	Multi-objective mixed-integer linear programming
NGO	Non-governmental organization
SC	Supply chain
SCM	Supply chain management
SSCM	Sustainable supply chain management
TBL	Triple bottom line
UFL	Uncapacitated facility location
UN	United Nations

Chapter 1

Introduction

This study addresses the **redesign of a sustainable food bank supply chain**.

Dating back to the late 1960s, food banks are non-governmental organizations concerned with two of the most prominent challenges of modern societies: the reduction of food waste, and the improvement of the living conditions of underprivileged segments of the population.

The Food and Agricultural Organization of the United Nations (FAO) estimates that around one third of the total food production is lost or wasted between agricultural production and household consumption (FAO, 2018b). It corresponds to 1.3 billion tons yearly, valued at one trillion US dollars. In the European Union (EU), the FUSIONS project reveals that, in 2012, about 20% of all food items available across the 28 member states were wasted (Stenmark et al., 2016). It equates to approximately 173 kg per capita. The largest portion of **food waste** occurs at the household level (53%). Jointly, food service, and wholesale and retail waste represent around 17% of total waste. Similarly, in Portugal, the 2012 study "Do campo ao garfo - Desperdício alimentar em Portugal" arrived at figures indicating a yearly volume of food losses and waste of 1 million tons, equivalent to 17% of the total food products (Baptista et al., 2012).

Not to mention the associated economic and environmental costs, the paradox lies in the fact that, according to FAO, it would take only about one fourth of the total quantity of wasted food to end world hunger (FAO, 2018a). In the EU, in 2016, 118.0 million people, or 23.5% of the population, were at **risk of poverty or social exclusion** (Eurostat, 2018). Among those, 37.8 million were severely materially deprived people.

Faced with these conditions, in September 2015 the United Nations (UN) established the 2030 Agenda for Sustainable Development (United Nations, 2015). The Agenda sets 17 **sustainable goals**, notably "No poverty" (SGD1), "Zero hunger" (SGD2), and "Responsible consumption and production" (SGD12). The chief objectives are to reduce at least by half the proportion of the world population living in poverty (SGD1), end world hunger and malnutrition (SGD2), and halve the per capita global food waste at retail and consumer levels by 2030.

In response to the UN's 2030 Agenda, the EU has established, among others, the target of lifting at least 20 million people out of risk poverty and social exclusion by 2020 compared to the year 2008 (European Commission, 2010). Recently, the European Parliament, in line with the UN's Agenda and the "EU Action plan for the Circular economy" (European Commission, 2015) has aimed at reducing food waste by 30% until 2025, and by 50% until 2030 (European Parliament, 2018).

FAO's "SAVE FOOD: Global Initiative on Food Loss and Waste Reduction" (FAO, 2018b), and EU's "EU Platform on Food Losses and Food Waste" (European Commission, 2018b) and "EU Food Donation Guidelines" (European Commission, 2018a) are among the most significant on-going official food waste reduction and recovery programmes, designed to address the UN's sustainability goals concerning both food waste and food security.

Those issues are not tackled by governmental entities alone. Social enterprises have a longstanding tradition of engaging individuals and corporations in finding innovative solutions to societal problems, voluntarily and in a non-profit manner. Including **non-governmental agencies** such as cooperatives, associations, and foundations, third sector organizations target "social impact primarily rather than profit maximization in their effort to reach the most vulnerable groups and to contribute to inclusive and sustainable growth" (OECD, 2018).

Particularly in recent years, marked by the 2007-2008 financial crisis and the following worldwide economic recession, social entrepreneurship has gained increased relevance. There are currently two million social economy enterprises in Europe, representing 10% of all businesses in the EU (European Commission, 2018c). A study for the European Economic and Social Committee reports that already in 2016 social economy was responsible for more than 13.6 million paid jobs in Europe, accounting for 6.3% of the total EU-28 working population (CIRIEC, 2017). It involved over 82.8 million volunteers, equivalent to 5.5 million full time workers. The study further reveals that a variety of new social economy concepts and approaches have emerged in Europe.

In Portugal, the Re-Food movement since 2011 (Re-Food, 2018), or the "Zero desperdício" initiative by the "DariAcordar" association from 2012 (DariAcordar, 2018), are examples of innovative responses to major social and environmental challenges. As manifestations of social entrepreneurship, these organizations act nation-wide on **food rescue and delivery** of surplus and about-to-waste items at local community level.

Among the most prominent non-governmental organizations operating in Portugal in the food rescue and delivery activity, the **Portuguese Federation of Food Banks** (FPBA, "Federação

Portuguesa de Bancos Alimentares") is the longest running operation. Launched in 1999, the FPBA currently manages 21 food banks located in mainland Portugal, as well as in the Azores and Madeira archipelagos. Edible food products are secured from corporations and individuals, and redistributed to people experiencing food insecurity through local charitable agencies. Enjoying remarkable visibility, the FPBA generates considerable economic activity focusing on social and environmental objectives, supported mainly by volunteer work and in-kind donations.

Operations such as the FPBA involve a set of activities that, to a large extent, are indistinct from those of a commercial **supply chain**. Products must be sourced from suppliers, processed at facilities, and channeled to end users. Efficiently and effectively managing the food bank supply chain is critical to obtain the largest possible quantity of donations, and to reach as many people in need of food assistance as possible (González-Torre et al., 2017). Yet, given their non-profit nature, they possess specific attributes. As in all **humanitarian logistics**, social and environmental criteria supersede return on investment, and other economic metrics.

The particular features of non-profit supply chains have progressively captured the attention of practitioners and researchers (Behl and Dutta, 2018). "Voluntas" is the official, interdisciplinary journal of the International Society for Third-Sector Research (ISTR, 2018). In the field of **Operational Research**, special issues devoted to humanitarian logistics have been recently published (e.g. Besiou et al. (2018)).

Concurrently, the **sustainability** of supply chains is presently one of the most dynamic research topics in decision and management sciences. It is also undergoing a repositioning. Of relevance to for-profit and non-profit organizations alike, comprehensive approaches to supply chain sustainability, featuring economic, environmental, and social impact evaluations are gradually taking over traditional outlooks concerned solely with the economic dimension.

This study is **motivated** by the application of innovative Operational Research methods in solving real-life decision problems of social economy organizations, namely food banks. Inspired by the FPBA operation, its **objective** is to address frequently identified **research gaps** in the supply chain literature. Accordingly, the study is based on a real case, and incorporates the economic, environmental, and social sustainability dimensions into a novel multi-objective programming model, requiring tailored metrics for each dimension. Although the FPBA food bank supply chain suggests a variety of challenging decision problems, this study focuses on strategic network redesign decisions.

In addition to a state-of-the-art review on the relevant literature, **expected results** include accurately modeling, and efficiently solving the proposed decision problem for a regional, and a national food bank supply chain. To that end, an in-depth field work is required to understand the organization, its drivers, and operating practices. This will enable discerning benefits of redesigning the existing supply chain, aiming at improved economic, environmental, and social results. Moreover, it will allow deriving managerial insights useful for supply chains with a similar profile.

This doctoral thesis is organized as follows.

Chapter 2 consists of a tertiary study regarding supply chain sustainability. The study systematically analyzes literature reviews pertaining to the incorporation of sustainability issues into supply chain management research. Covering both content and formal review features, the study identifies major research gaps and opportunities, and introduces fundamental supply chain, and sustainability terms and concepts.

Chapter 3 presents a literature review focused on the social dimension of sustainability in supply chain research. Key social metrics featured in supply chain network models with multiple objectives are discerned, as well as the most frequently engaged solving methodologies. The chapter further reviews the available research articles dealing with the food bank supply chain.

Chapter 4 introduces the decision problem. The supply chain of the Portuguese Federation of Food Banks that inspired the study is characterized, and the assumptions made, conducive to the modeling of the decision problem, are described.

Chapter 5 presents the mixed integer linear programming formulation, comprising its parameters, variables, constraints and objective functions. The problem is classified as NP-hard. This chapter further discusses the conflicts between the objective functions established.

Chapter 6 describes the procedures followed to generate instances for the problem. Parameters are supported by data profiling of the real-life case inspiring this study. Tailored procedures designed to create realistic yet generic instances are presented, and the distinct input scenarios are explained.

Chapter 7 reports the study performed on the regional instances. After presenting the lexicographic method adopted to study the regional instances, detailed results are discussed based on an illustrative instance. Analysis of different cases favoring specific environmental and social factors, trade-off effects between the optimization objectives, and characterization of the main features of the solutions obtained are discussed. Managerial insights, relevant to the organization that inspired the study, or others with an identical profile, are discussed. The chapter is concluded with the assessment of the computational effort required to solve the problem regarding the regional instances.

Chapter 8 concerns the study of the national instances. Three decomposition based heuristics developed for this study are described, and the results obtained with the novel solving algorithms are reported and discussed.

Chapter 9 concludes the study, reviewing the main findings, and proposing opportunities for future research.

Each chapter includes a summary of the most relevant topics addressed, and respective findings.

Chapter 2

Tertiary study

The content of this chapter corresponds in general to Martins and Pato (2019).

Supply Chain Management (SCM) has been one of the most productive research fields in management and decision sciences for a long time (Laengle et al., 2017). The set of activities performed across the supply chain (SC), from extraction of natural resources to their transformation into manufactured goods, and delivery to consumers offers a wide range of research material that continues to motivate scholars and practitioners alike. Over the years, SCM literature has both consolidated into a widely documented discipline, and originated an array of emerging research streams.

Among those, Sustainable Supply Chain Management (SSCM) is responsible for an increasingly large output, particularly since the early 1990s. Born from the incorporation of the sustainability outlook into the management of supply chains, SSCM was initially devoted mainly to the environmental aspects, in addition to the traditional economic topics. Later it has expanded to also include social concerns, especially following the introduction of the "triple bottom line" (TBL) concept in 1994 by Elkington (1997).

The volume of SSCM original research articles (primary studies) has already rendered a substantial number of literature reviews (secondary studies). Literature reviews are important to acquire a better understanding of a topic, to know what has already been done, and how, and what the key issues are (Hart, 1998). The body of SSCM secondary literature is not only experiencing a fertile period but also undergoing a pivotal change with regard to the methodological approach, with systematic literature reviews rapidly prevailing over traditional literature reviews.

Motivated by this particular moment in SSCM literature, this chapter presents a tertiary study on supply chain sustainability. The aim is to provide an inclusive analysis of the available literature by means of a systematic literature review of SSCM literature reviews (as a review of secondary studies it is denoted as tertiary study). This tertiary study aggregates the available literature under a single analytic framework, allowing a unified perspective on the state of SSCM research.

Despite the large volume of primary and secondary research about SCM and SSCM, the number of tertiary studies on SCM related topics is very limited. Our research indicates that this is the first tertiary study devoted to the topic of SSCM. The study provides an inclusive analysis of the available literature by means of a systematic review of SSCM literature reviews. Its objective is to answer three research questions: which are the existing literature reviews on supply chain sustainability, what are their methodological features, and what are their main objectives and subject matters.

To that end, Section 2.1 reviews key supply chain management concepts, sustainability perspectives, and methodological literature review features, including tertiary studies, to support the systematic review of 198 surveys published between 1995 and 2018. The methodology is presented in Section 2.3. The results obtained are reported in Section 2.4.

2.1 Concepts and framework

2.1.1 Supply chain management

Supply chain has become a familiar concept to academics and practitioners since the early 1980s. In 1982, professional consultants Oliver and Webber conceived the term to describe a "network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer" (Oliver and Webber, 1982). Some essential SC notions surface immediately from this definition: multiple entities, (vertical) connections, material and immaterial actions, and value creation.

Indissociable from the concept of supply chain is the notion of supply chain management. Introduced by the same authors, in their definition the term SCM stands for "the process of planning, implementing, and controlling the operations of the supply chain with the purpose to satisfy customer requirements as efficiently as possible. Supply chain management spans all movement and storage of raw materials, work-in-process inventory, and finished goods from point-of-origin to point-of-consumption". Despite often being used interchangeably, SC and SCM stand for different subject matters. As remarked by Mentzer et al. (2001) "supply chains exist whether they are managed or not".

Over the years, SC and SCM have gained increased interest and popularity. In 2017, a review of the first 23 years of articles published in the Journal of Cleaner Production (JCP), concluded that "the research on supply chain management was the key hotspot of enterprise management addressed by JCP authors" (Zou et al., 2017). The concepts have evolved in scope and in depth, becoming evidently more complex, particularly in the case of SCM. Multiple participants, activities, layers, flows, and objectives have been considered in its definition. Multidisciplinary theoretical and modeling approaches have been followed (Fayezi and Zomorrodi, 2016). A prodigious number of definitions have been put forth (Mentzer et al., 2001), along with multiple discussions and endeavors to frame the research field (see Cooper et al. (1997) and Tan (2001), among others).

This evolution has led to a noticeable shift from a channel-oriented and operational concept of SCM present in the original definition by Oliver and Weber, to a holistic and strategic outlook of what constitutes the management of supply chains. For example, Mentzer et al. (2001) define supply chain as the "set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer", whereas supply chain management is understood as "the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole".

Based on the literature, and for the purpose of this study, Figure 2.1 on page 8 offers a representation of the main supply chain processes and functions in a contextual framework. It appeals to the processes defined by the SCOR model (APICS, 2018) to identify the key supply chain functions from the perspective of a focal firm. Context is provided by the direct stakeholders of the firm, and by the stakeholders of the supply chain, where flows of different natures, and in different directions take place.

This representation provides the background for our survey regarding the concept of supply chain management. It reflects a holistic and integrative view of the various activities performed in reference to the different elements of the supply chain.

The main functions related to suppliers (process: source) are their evaluation, selection, and development, as well as the specific sourcing and procurement activities, including purchasing. At the focal firm, core functions comprise network (re)design, product design and development, (re)manufacturing, in-house logistics, and outsourcing (process: make). Lean and agile production paradigms are also identified. SCM activities that concern the downstream side (process: deliver) include transportation, marketing mix, and customer relationship management (CRM). Reverse logistics and closed-loop supply chain have become common functions in generic SC configurations (process: return).

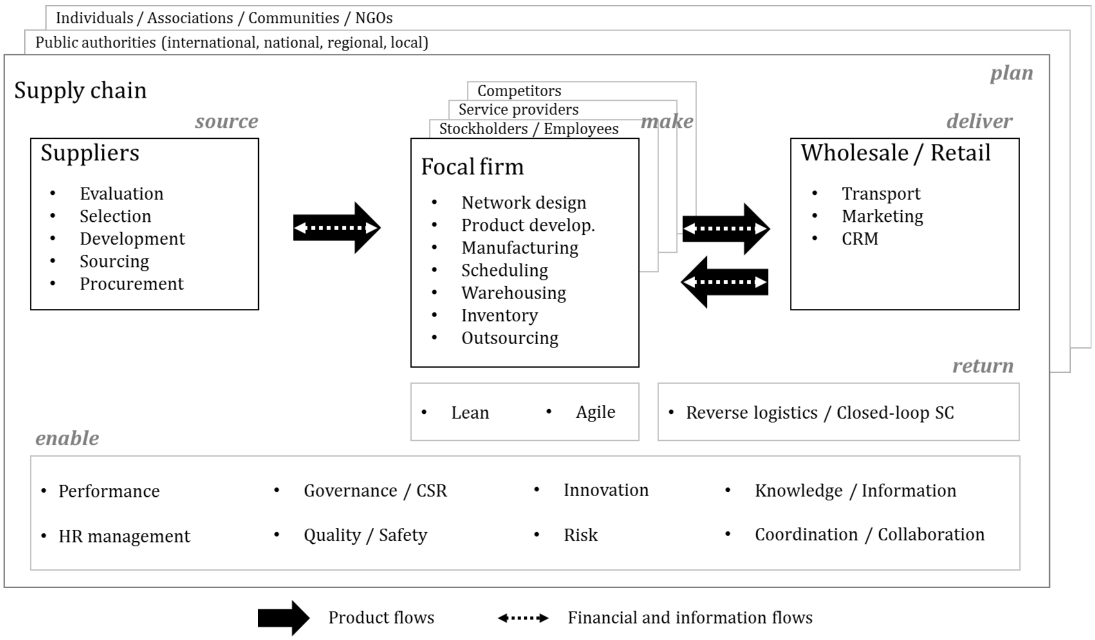


Figure 2.1: Supply chain: processes and functions

This set of functions is performed in the pursuit of operational, tactical, and strategic objectives of the parties involved (process: plan). They are supported by activities relating to performance, metrics and reporting, governance and corporate social responsibility (CSR), coordination and collaboration, and risk management, among others (process: enable).

In this context, supply chain management is understood as the organization and coordination of the set of distinct functions performed intra and inter-firms that constitute the supply chain, in order to create value by the supply of products and services to the market.

This analytic framework is used in Section 2.4 to classify the literature reviewed in this study.

2.1.2 Sustainable supply chain

The incorporation of sustainability concerns into business practices is currently one the most dynamic research issues in the area of supply chain management. Although the origins of the term "sustainable" can be traced back to as early as the 18^{th} century (Geissdoerfer et al., 2017), its profile rose remarkably with the issuing of the "Report of the World Commission on Environment and Development: Our Common Future" in 1987, commonly known as the Brundtland Report (United Nations, 1987). The United Nations-appointed Brundtland Commission defined sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition highlights the notion of "needs" versus "limitations", which is critical in the sustainability debate.

Although indisputable, this outlook is subject to reductive interpretations regarding business sustainability in two ways. One way concerns the strict identification of sustainability with the environmental impacts caused by economic activities.

In fact, the interchangeable use of the terms "sustainability" and "environmental" was particularly prevalent in early conceptualizations of business sustainability (Carter and Easton, 2011). The incorporation of sustainability concerns into SCM literature originated the term "Green supply chain management" (GrSCM) that Srivastava (2007) defined as "integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life". Although this has become the most cited definition of GrSCM, many others have been suggested (Ahi and Searcy, 2013), reflecting different views as to what "integrating environmental thinking into supply-chain management" means. In general, they all mirror the view that economic results (the "needs") are limited by, or at the very least have to take into account, the environmental impact aspect (the "limitations").

Even though many authors continue to interpret business sustainability mainly in the strict GrSCM sense, sustainable supply chain management research maturity has highlighted the importance of including also the social dimension.

In 1994, a more comprehensive concept of business sustainability "officially" entered the decision management taxonomy under the term "triple bottom line". In "Cannibals with Forks: The Triple Bottom Line of 21st Century Business", and appealing to the 3P designation for people, planet and profits, Elkington posited that companies should account not only for the traditional financial profit and loss bottom line, but also for both the social, and the environmental bottom lines (Elkington, 1997). The first - people's bottom line - measures the level of social responsibility of the company, whereas the second - planet's bottom line - records the environmental impact of its operations. This three-pillar perspective became synonym of a more comprehensive approach to business sustainability.

A number of authors presented definitions for SSCM based on this approach, as compiled for example in Ahi and Searcy (2013). In this paper, the authors propose the following definition of SSCM: "The creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term". It should be noted that, while in most SSCM definitions the three dimensions are additional to each other, the United Nations stresses the "balanced and integrated manner" by which they should be considered in sustainable development (United Nations, 2015).

The other way by which the Brundtland definition of sustainability may be interpreted in a minimalistic way in a business context relates to the matter of "limitations". While the presence of trade-offs between the three sustainability pillars is undeniable, it does not necessarily mean that the incorporation of sustainability measures in business activities must represent a limitation for the firms. However, for a period, this was the usual perception. Giunipero et al. (2012) outline the evolution of the major themes in the sustainability literature from the reactive compliance-only policy of the 1960s, to the emergence of an environmental-focused approach in the 1980s, until finally the realization of a holistic and proactive sustainability attitude as a strategic objective in the 2000s.

As advocated by Srivastava (2007) in reference only to the environmental aspect, sustainability "is a business driver and not a cost centre". Competitive advantages are expected to ensue from differentiation corporate strategies based on proactive sustainability positioning. Improvement of the company's bottom line through cost savings, increased market share, and stronger brand images are some of the benefits that have been identified (Min and Kim, 2012). The same applies a fortiori to the social element. A social and environmentally committed supply chain is becoming the default positioning expected by the SC internal and external stakeholders, turning the TBL sustainability approach into a "license to do business in the twenty-first century" (Carter and Easton, 2011).

This study, bearing in mind its objective, adopts a broad SSCM concept that includes all outlooks on supply chain management that go beyond the economic perspective, i.e. all sustainability approaches that encompass the environmental and/or the social perspectives.

2.1.3 Literature reviews

Literature reviews play a particular role in the development of any research field. They summarize and establish connections between primary works, promote dialogues among different research streams, identify gaps and opportunities, and propose research directions. Often, they support the introduction of taxonomy and analytic frameworks, and express the critical appraisal of the author about the material reviewed. Consequently, literature reviews contribute to the structuring of a research field, and provide a background for its development.

With regard to the methodological approach, literature reviews can be divided into systematic and narrative reviews [1]. Fink (2014) defines the former as a "systematic, explicitly, and reproducible

[1] Some authors define meta-analysis as a third type of literature reviews (Kitchenham and Charters, 2007). This type is defined by the way the research synthesis is reported, which is primarily based on quantitative statistical methods.

method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners". Systematic literature reviews involve, and to a certain extent are defined by a methodical process followed to collect and analyze the source material. The methodology aims to ensure that key qualities associated with systematic literature reviews are featured. These reviews are characterized as comprehensive (strive to include all known relevant works), objective and valid (answer well-defined research questions), verifiable, and reproducible (transparent concerning the selection of source material). Given the rigorous methodological process demanded by systematic literature reviews, Denyer and Tranfield (2009) consider that "a systematic review should not be regarded as a literature review in the traditional sense, but as a self-contained research project in itself".

Inspired by the practices of medical research, Tranfield et al. (2003) propose a comprehensive methodological process to perform systematic reviews in management sciences comprising nine phases aggregated into three stages (plan, conduct, and report and disseminate). Seuring and Gold (2012) make a significant contribution to the consolidation of this approach, with substantial influence in the specific field of SCM. Influenced by Mayring (2000), the authors design a procedure to conduct literature reviews based on content analysis, which is defined as "a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use" (Krippendorff, 1980). In Seuring and Gold (2012) this translates into a process defined by four steps. First, *material collection* delimits the source material and defines the unit of analysis. Next, formal features of the source material are assessed in a *descriptive analysis*, providing the background for the subsequent review. In *category analysis*, the structural dimensions and respective analytic categories for material evaluation are set. Finally, *material evaluation* is performed according to those analytic categories. This approach can be seen as a particular type of systematic literature reviews, characterized by stressing the application of content analytical tools in the methodological process (Jia et al., 2014), in which "categories are in the center of analysis" (Mayring, 2000).

Narrative reviews take a much less formal approach in conducting surveys. That is, in fact, their most identifying feature. Based essentially on the experience of the researcher (Cipriani and Geddes, 2003), they are obscure with regard to the methodology. Tranfield et al. (2003) signal the lack of thoroughness, permeability to bias, and lack of rigor that often characterize this type of reviews. Additionally, they do not allow neither audit nor reproduction, which limits their transparency, reliability, and reduces their intrinsic value for later updates.

However, Tranfield et al. (2003) consider meta-analysis an "associated procedure" to systematic reviews, while Seuring and Gold (2012) argue that they are an alternative to literature reviews.

2.1.4 Tertiary studies

Tertiary studies are a particular type of literature review. Unlike secondary reviews, whose source material are primary research articles, tertiary reviews aim to identify literature reviews on a given research topic, and map them according to a classification framework. These reviews of literature reviews are particularly fitting for scientific fields with large publication output because they are able to provide a "compact and comprehensive overview of the state-of-knowledge in a specific research area" (Abedinnia et al., 2017).

For such a prolific research field, only a small number of tertiary studies relating to supply chain management are identified. Table 2.1 presents a brief characterization of these studies, following their year of publication.

Article	Journal	Period covered	No. of articles	Type of review	Subject (SC functions)
Hochrein and Glock (2012)	Int. J. Integr. Supply Manag.	1980-2011	20	SY	Purchasing and supply manag.
Seuring and Gold (2012)	Supply Chain Manag. Int. J.	2000-2009	22	SY	Supply chain manag.
Glock et al. (2014)	Int. J. Prod. Econ.	1974-2012	52	SY	Inventory lot sizing models
Kache and Seuring (2014)	Supply Chain Manag. Int. J.	1989-2012	103	SY	Integration/Collaboration and Risk/Performance
Bushuev et al. (2015)	Manag. Res. Rev.	1954-2014	39	NR	Inventory lot sizing models
Hochrein et al. (2015)	Mang. Rev. Q.	1993-2011	121	SY	Supply chain manag.
Abedinnia et al. (2017) (1)	Comput. Ind. Eng.	1959-2016	129	SY	Machine scheduling problems

(1): Period covered refers to years of publication of primary research surveyed in secondary works reviewed

SY: Systematic; NR: Narrative

Table 2.1: Tertiary studies on supply chain management

Besides reviewing the source material, Seuring and Gold (2012) and Hochrein et al. (2015) also feature a strong methodological component on the process of conducting literature reviews. Actually, the latter remark in reference to tertiary studies that they are intended to "evaluate secondary research with a strong emphasis on the methodology of the secondary studies and (if possible) on consolidating research findings of primary studies as reported in the secondary works".

2.2 Context

The volume of published research on the subject of supply chain sustainability has increased substantially since the early 1990s. Almost 30 years later, this research field has produced a consolidated and vast body of literature comprising multiple topics studied from various and multidisciplinary perspectives. A brief search on the ScienceDirect database for the terms "supply chain" and "supply chain management" on 22 May 2018 returned 62,931 and 18,143 results, respectively. These figures increase to 456,062 and 136,052 for queries without the quotation marks in the search terms.

The number of hits obtained when the sustainability perspective was included (search "supply chain management" AND sustainability) amounted to 7,848. Based on the figures for the most recent years, there is no indication that this volume of research will decline in the near future. In the last complete year (2017), the research output reached its peak to date: 1,071 results for "supply chain management" AND sustainability. The number of occurrences obtained for the ongoing year (2018 year to date: 728) has already surpassed the total of just four years ago (2014: 701).

Along with the steady growth of primary research, the increase of the number of secondary studies is also remarkable: 3,228 hits for the search "supply chain management" AND sustainable AND "literature review". Evidently, SSCM literature reviews have become an important source to gather insight into the current state of supply chain sustainability research, which makes this tertiary study opportune. The following section presents the study conducted, and reports the results obtained. The study adopts a content analysis methodology following Seuring and Gold (2012), while reporting acknowledges the guidelines presented by Budgen et al. (2018), and is comprised of a descriptive analysis, a category analysis, and a thematic analysis.

2.3 Methodology

One of the decisive factors in performing a successful literature review is the formulation of clear and feasible research question(s). The question informs the audience about the purpose of the study and its expected outcome. It shapes the collection and selection of the source material, and determines its analysis. It is also a valuable resource for the reviewers by ensuring that the focus of the study is not lost. This last aspect is particularly meaningful when the research field is vast and there is a large number of potential relevant sources.

On that premise, Table 2.2 on page 14 introduces the research questions that prompt this study. The objectives are the identification of the existing literature reviews on supply chain sustainability (Research question A.1), discerning their methodological reviewing approach (Research question A.2), and mapping the supply chain function(s) studied, as well as the review objective, namely in terms of the prevailing sustainability pillar(s) (Research question A.3).

To that end, a search protocol with the features described in Table 2.2 was executed. The search protocol includes the steps taken to collect the source material (A through D), and the criteria applied to select and analyze the works relevant to answering the research questions (E and F). The final results of the search protocol are reported at the end (G).

A	Research questions				
		A.1	Which are the literature reviews on supply chain sustainability?		
		A.2	What are their formal review features?		
		A.3	What are their main subject(s) and objective(s)?		
B	Databases		Scopus and Web of Science (WoS)		
C	Search criteria				
		C.1	Language:	English	
		C.2	Scientific areas(s):	All	
		C.3	Journal(s):	All	
		C.4	Article type(s):	Review	
		C.5	Search field(s):	Title, abstract and keywords	
		C.6	Date of publication:	Until present	
		C.7	Date of search:	23 March 2018	
D	Search terms				

	Keywords			Scopus	WoS	Total (1)
D.1	"supply chain"	AND	sustainab*	380	320	562
D.2	"supply chain"	AND	"triple bottom line"	15	17	27
D.3	"supply chain"	AND	environment*	625	450	894
D.4	"supply chain"	AND	green*	177	170	293
D.5	"supply chain"	AND	ecologic*	40	30	57
D.6	"supply chain"	AND	social*	299	176	404
	Total (1)			948	644	1,333

(1) After elimination of duplicate records

E	Inclusion criteria				
		E.1	Article is a literature review	AND	
		E.2	Follows sustainability approach	AND	
		E.3	Subject is one or more supply chain functions		
F	Exclusion criteria				
		F.1	Editorials or conference proceedings	OR	
		F.2	Tertiary studies	OR	
		F.3	Only economic sustainability	OR	
		F.4	Not supply chain perspective	OR	
		F.5	Focus on local geographies		
G	Search results				
		G.1	From keyword search		1,333
		G.2	After abstract review		224
		G.3	After article screening		132

Table 2.2: Search protocol: tertiary study

2.3.1 Material collection

The search was performed on 23 March 2018. It included all English language articles registered as "review", without any limitation of scientific areas, journals, or date of publication. The search was performed on the title, abstract, and keyword fields. Six search terms were defined. Each term is a combination of the keyword "supply chain" with an additional keyword (see D. Search terms). The modifier asterisk was used in the boolean search as a root word for all derivative keywords. Based on a preparatory survey, the selected keywords were chosen to attempt the most comprehensive collection of relevant records possible.

For supplementary purposes two databases were used. Scopus includes over 71 million records from more than 23,700 journals (Scopus, 2018). The Web of Science platform offers access to upwards of 100 million references from 33,000 journals (Web of Science, 2018). All essential peer-reviewed publication outlets in the research area, such as those published by Elsevier, Emerald, Inderscience, and Springer are accessible via the selected databases.

The search returned 1,333 unique hits, with Scopus providing the largest number of records (close to 1,000). The search term that originated the largest number of hits was "supply chain" AND environment* (almost 900), while the one that produced the fewer results was "supply chain" AND "triple bottom line" (27 unique hits). For each search term, the number of unique records varies between 80% and 85% of the total records obtained from the two databases (including duplicates). This indicates that, for the study at hand, the databases are complementary to a large extent.

2.3.2 Material selection

After the material collection, sources were selected based on inclusion and exclusion criteria presented in steps E and F of Table 2.2. These criteria set the boundaries that delimit the scope of the study.

In order to be selected, an article has to be a literature review addressing one or more supply chain functions (see Figure 2.1 on page 8) from a sustainability perspective. The majority of collected material that failed to meet cumulatively all the inclusion criteria are articles that, albeit classified as "reviews" in the databases consulted, are not literature reviews, such as Linton et al. (2007), or Pagell and Wu (2009).

Additionally, editorial articles, e.g. Santibanez Gonzalez et al. (2017), conference proceedings, e.g. Xu et al. (2012), or tertiary studies, e.g. Bushuev et al. (2015) were not included due to criteria F.1 and F.2. Enforcing criterion F.3 meant excluding frequently cited literature in the supply chain domain that was not held apt for the design of the study. This applies to literature reviews about supply chain functions or topics such as reverse logistics and closed-loop supply chains (Govindan et al., 2015b), risk management (Fahimnia et al., 2015b), and humanitarian logistics (Jabbour et al., 2017), in which both the environmental, and social sustainability perspectives are absent. Although these topics concern undisputed environmental and/or social sustainability enablers, in the affected articles the economic pillar outlook prevails, or is the sole perspective. In compliance with the sustainability concept assumed in this study (see end of Section 2.1.2), articles were excluded accordingly.

Finally, articles were also rejected if the preferred organizational business paradigm adopted is not the supply chain, e.g. Patala et al. (2014), or in case the review places particular emphasis on a local geography, e.g. Chaudhary and Chanda (2015).

Selection of articles was performed in two stages. A first selection was carried out on based on the review of the abstracts. Next, articles were further filtered after screening the full manuscript. In order to ensure a correct and coherent enforcement of the inclusion and exclusion criteria, a sample of 67 randomly selected articles, corresponding to five percent of the total collected material, was reviewed by the author and the supervisor. Considering that two raters were involved, the statistical measure chosen to evaluate the level of reliability was Cohen's kappa (Cohen, 1960). The inter-rater agreement value obtained was $\hat{\kappa} = 0.74$, which falls in the upper range of the substantial strength of agreement interval proposed by Landis and Koch (1977). Divergences were discussed and ultimately agreed upon. At the end of the first stage 224 articles were identified for full content analysis. In the second stage, a total of 88 articles were abandoned: 31 due to criteria F.1 and F.2, 46 following F.3, nine because of F.4, and two according to F.5. Four articles were not available for analysis, setting the final number of articles identified by way of the search protocol at 132 (see step G in Table 2.2).

In addition to the sources identified by the protocol-driven search strategy, relevant material was also checked by other means. Browsing and pursuing previously known references secured the identification of 36 new articles meaningful to the study. Tracking down references in the selected material (backward snowballing) yielded 30 more valid sources, raising the total number of articles suitable for content analysis and coding to 198 (see Table 2.3).

i)	From search protocol	132
ii)	From informal approaches	36
iii)	From snowball methods	30
	Total	198

Table 2.3: Number of articles selected (N)

2.3.3 Analysis structure

The unit of analysis of this study is an individual article (single source). In light of the research questions, the analysis structure presented in Table 2.4 on page 19 comprises nine categories. The first research question A.1 concerns the identification of the relevant literature reviews. This question is answered by the bibliographic data of the selected articles, and by complementary information included in Category I.

Categories I through VI address the second question A.2. They establish the formal features chosen to characterize each article with regard to its methodological review approach. These categories are largely derived from the classification scheme presented in Seuring and Gold (2012). Likewise, the coding of each of these categories is taken mainly from the same reference, and also from Greenhalgh and Peacock (2005). Notwithstanding, both category and coding taxonomy differ in some cases from the original material.

In Category I, "Country" is the country of the corresponding author, and "Period covered" refers to the date of publication of the articles (primary research) reviewed in each unit of analysis. If this information is not available in the manuscript, the source is classified as "NM" (not mentioned). Regarding "Number of articles", if this information is not clearly included in the manuscript, then the number of references is recorded instead and signaled by the letter "R". Category II classifies the articles according to the two main types of reviews, narrative or systematic.

Multiple coding is allowed in Category III. "Protocol-driven" collection is used whenever keyword structured searches are performed, irrespective of the level of detail provided about the specific protocol features. Articles that mention browsing, serendipitous discovery, or discussions with colleagues as collection resources are classified as "Informal approaches". This classification also applies to those sources in which information about the collection method is missing. "Snowball methods" includes forward and backward reference searching from a given source selected for review.

Category IV classifies the articles according to the selection procedure followed. When authors allude to discussions held among the review team but abstain to quantify them, it is considered that a "Cross-analysis" was carried out, and a qualitative agreement was obtained (corresponds to "discursive alignment interpretation" in Seuring and Gold (2012)). If statistical measures of the level of agreement between the reviewers are declared, then the article is coded as "Inter-rater agreement". If no information is disclosed, then the article is classified as "NM" (not mentioned).

For the material synthesis classification, coding options of Category V are "Descriptive", "Category", "Thematic", and "Bibliometric". The first refers to the characterization of the sources based on their formal identification (year and outlet of issuing, country of authors, etc). The second and third apply to the narrative synthesis of the analysis performed (not to be confused with narrative reviews - see Popay et al. (2006)). If the synthesis is structured in line with analytic categories defined to support the material review, then the classification is “Category”. “Thematic” synthesis signifies that reporting is organized on the basis of topics that emerged from the literature review rather than (or in addition to) following predefined analytic categories. Articles are coded as “Bibliometric” when meta-analysis quantitative techniques such as author, affiliation, (co-)citation, and cluster analysis are included. In this category, multiple coding may apply to the same article.

With regard to the main material source, there are four classifications defined for Category VI. “Operations Research/Management Science” (OR/MS) includes all normative and descriptive modeling approaches (mathematical programming and simulation models, analytic and heuristics methods), but excludes metrics and indicators (Euro, 2018). “Theoretical and conceptual” relates to qualitative works. “Empirical” includes case studies, surveys, interviews, and other forms of empirical research, whereas “Mixed” applies to articles where sources include two or more of the previous classifications, or other types of material.

Categories VII to IX concern the third research question A.3. In these cases, categories were inductively designed, based on an iterative review process of the selected material (Mayring, 2000).

For the classification of articles according to their objective(s), five multiple choice options are established in Category VII. These options correspond to the most frequently identified objectives of the reviewed material, and were set after scanning the content of a large number of the selected articles. The objectives of carrying out an up-to-date survey of the existing research in a given scientific field (“State-of-the-art”), and critically identifying research gaps and opportunities for future research (“Gaps and directions”) are among the most recurrent goals for conducting literature reviews. Classification “Research consolidation” applies to reviews that aim to aggregate a scattered or fragmented body of literature about a research topic, by an integrative analysis and synthesis. If a conceptual analysis framework, and/or taxonomy proposal is put forth for a particular theme, industry, scientific area, or decision problem, then the article is classified as “Framework”. Finally, reviews that champion an emergent research topic, or the confluence of distinct research streams are coded as “New issue”.

Category VIII classifies articles in terms of their chief sustainability focus, as considered in this study: environmental, social or triple bottom line. Category IX records three distinct subject matters: supply chain function, industry, and OR/MS technique. The first follows the taxonomy presented in Section 2.1. All sources are coded conforming with at least one function. Furthermore, if the review is devoted to a particular industry, and/or OR/MS technique, it is also coded accordingly.

I	Description	II	Review type	III	Material collection
I.1	Year		SY - Systematic		PD - Protocol-driven
I.2	Journal		NR - Narrative		IA - Informal approaches
I.3	Country				SB - Snowball methods
I.4	Period covered				
I.5	Number of articles				
IV	**Material selection**	**V**	**Material synthesis**	**VI**	**Material source**
	CA - Cross-analysis		DS - Descriptive		OR - OR/MS modeling
	IR - Inter-rater agreement		CT - Category		TC - Theoretical and conceptual
	NM - Not mentioned		TH - Thematic		EM - Empirical
			BB - Bibliometric		MX - Mixed
VII	**Objective**	**VIII**	**Sustainability**	**IX**	**Subject**
	SA - State-of-the-art		ENV - Environmental	IX.1	SC function
	GD - Gaps and directions		SOC - Social	IX.2	Industry
	RC - Research consolidation		TBL - Triple bottom line	IX.3	OR/MS model
	FR - Framework				
	NI - New issue				

Table 2.4: Analysis structure: categories

2.4 Results

This section presents the quantitative and qualitative results of the study. A descriptive analysis of the source material provides the background for the category analysis that follows. Discussion of the results, and answers to the research questions complete this section. Selected information about the methodological and content features of each literature review included in this study can be found in Appendix A. From this section on, cited references include a reference number between square brackets used for identification in the tables that map the reviewed literature.

2.4.1 Descriptive analysis

The identified and selected literature reviews that tackle the issue of supply chain sustainability are published in 67 different journals (Category I.2). 44 of those account for only one article, while the other 23 journals accumulate close to 80% of the set of reviewed articles. Journal of Cleaner Production stands out as the title with the largest number of published reviews (53). Figure 2.2

shows the number of articles per journal with two or more articles. In Appendix A, the detailed record of each review includes the respective publication journal.

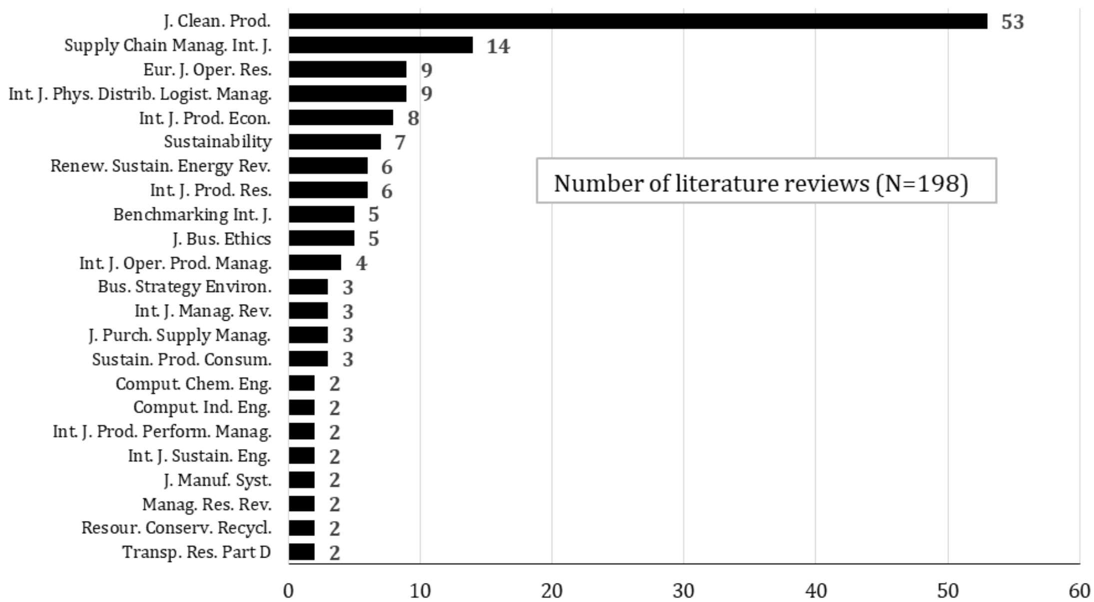


Figure 2.2: Number of literature reviews per journal (1995-2018). Category I.2

The geographical origin of the reviewed material is spread across 31 countries (Category I.3). The United States of America with 31 articles, the United Kingdom with 24, and Germany with 23 are the countries with the greatest output. India (15) and Brazil (13) follow as the countries with the most titles. Overall, most geographies are represented, from Canada (10) to Australia and China (both with eight), Turkey (three) or Russia (one). For identification of all countries see Appendix A.

Figure 2.3 depicts the number of literature reviews published per year, and the period covered by the reviews (Categories I.1 and I.4). The earliest literature review on the topic of sustainable supply chain management was publish in 1995 ([28] Bloemhof-Ruwaard et al. (1995)), about the interactions between Operations Research and environmental management. In the following 15 years, the total number of reviews published per year varied between zero and two. In 2010, there was a first noticeable increase to a total of nine reviews, only to be more than doubled to 22 just two years later. Since then, there has been a steady growth in the number of published reviews. The largest number of articles published in a single year was reached in 2017, when 46 literature reviews were issued. Data concerning 2018 is limited to the beginning of the year but as of 23 March 2018 (date of material search) there were already 13 titles identified.

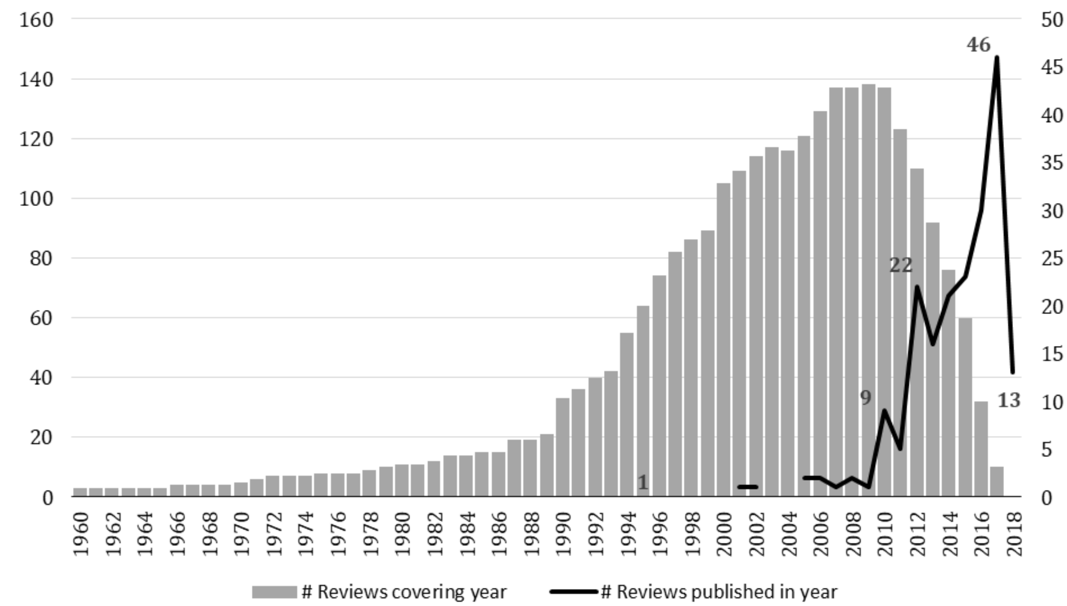


Figure 2.3: Number of literature reviews covering, and published in year. Categories I.1 and I.4

The period covered by each review is not identified in all sources (see Appendix A). In 51 titles this information is not available in the manuscript. Most frequently, this occurs in narrative reviews (42), but some systematic reviews also do not report this information in a clear manner. It is perceptible from Figure 2.3 that bars representing the number of secondary studies covering primary research published in each of the years exhibit an evolution similar to the line that depicts the number of reviews published per year. There is a recognizable gap of approximately 10 years between the two, which is likely to be attributable to a period of required research maturity between the publication of the primary and secondary research. The chart also suggests a tendency for the closing of this gap. Primary works covered by the reviewed material date as far back as 1949 (included in [154] Pimentel et al. (2016), a review of decision support models for the mining industry accounting for environmental and social impacts). The first year depicted in Figure 2.3 is 1960, covered by two additional reviews: [127] Lin et al. (2014), a survey of green vehicle routing problems, and [111] Jensen (2012) concerning carbon footprint.

The volume of primary research covered in literature reviews clearly and consistently takes off from the late 1980s, further to the issuing of the Brundtland report. Afterwards, the four years between 2007 and 2010 form the period with the greatest coverage: 138 reviews include primary research published in 2009, and 137 reviews cover works issued in each of the other three years.

2.4.2 Category analysis

2.4.2.1 Methodological features

To support the answer to the second research question A.2, the source material is hereinafter assessed in terms of its methodological features. Figure 2.4 shows the yearly evolution of the number of systematic and narrative literature reviews (Category II).

A fairly loose classification of articles as systematic was adopted. Often, it deferred to the aim expressed by the authors of conducting a comprehensive literature review, in detriment of confirming the presence of the methodological features that define systematic reviews. With this caveat, that does not significantly influence the interpretation of the results obtained, the ascendancy that systematic reviews have acquired over narrative reviews in recent years is remarkable. Until 2012 the majority of reviews followed a narrative methodology. From that year on, systematic reviews clearly prevail over narrative reviews to the point that, in 2017, which is the last complete year under review in this study, all but one of the 46 reviews published are systematic. Overall, in the period 1995-2018, 146 systematic (74%) and 52 narrative literature reviews (26%) about SSCM are identified.

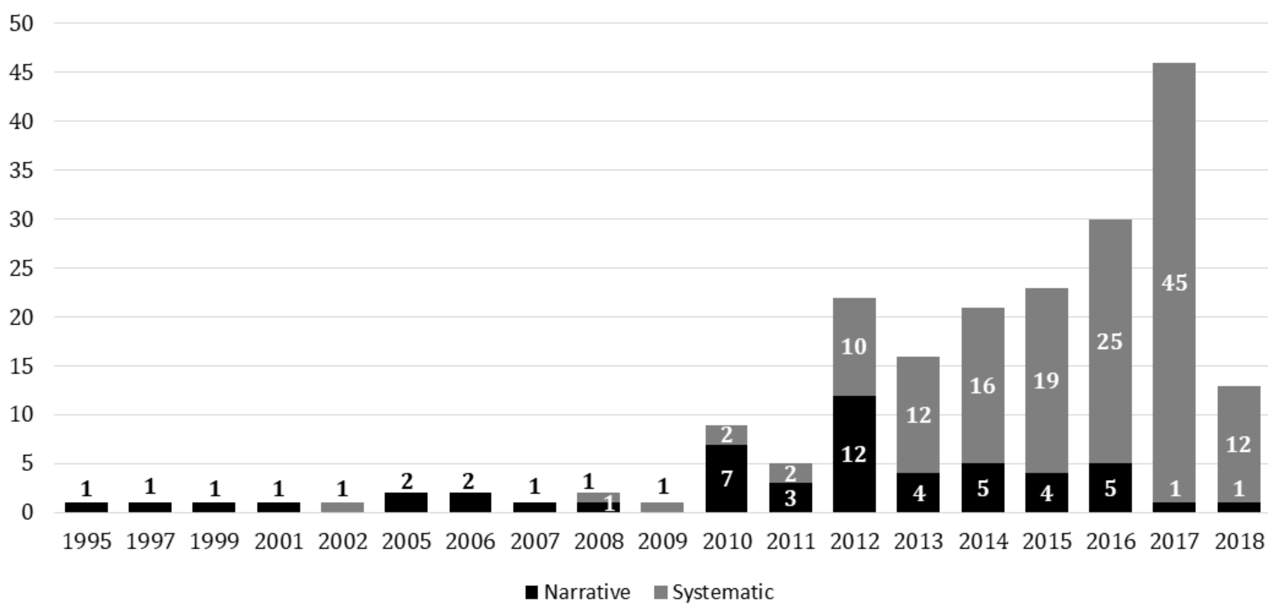


Figure 2.4: Number and type of literature reviews published per year. Category II

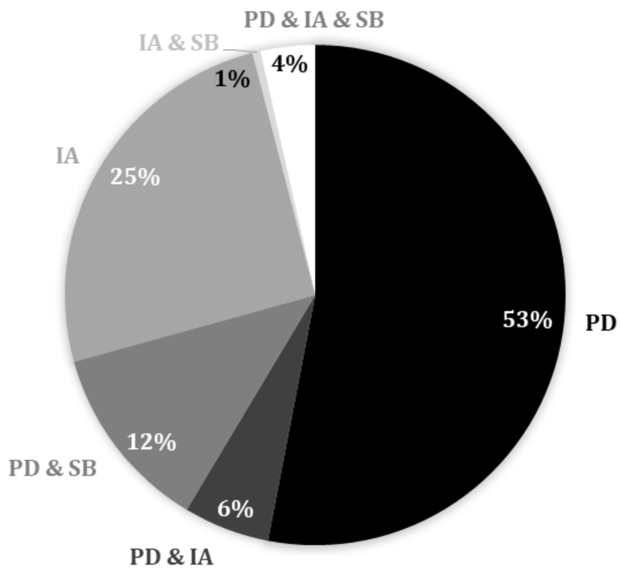
Data relating to Category I.5, excluding papers that tackle bibliometric analysis, usually performed on large bodies of literature (e.g. [149] Movahedipour et al. (2016) with 1,610 sources, devoted to the use of optimization methods and techniques in supply chain management), is reported in Table 2.5. Results reveal that most literature reviews do not exceed 200 sources (or references, as the case may be), and that only in five cases ([4] Ahi and Searcy (2013), [41] Chatha and Butt (2015), [106] Ilgin and Gupta (2010), [143] Min and Kim (2012), and [188] Winter and Knemeyer (2013)) that number is over 400. The average number of papers reviewed per source is 126 (134 for references, when information about the number of articles reviewed is missing) but there is a large standard deviation of 101 (72). Table 2.5 registers a minimum number of 10 - [7] Ahmad et al. (2017) focused on the oil and gas industry -, and a maximum of 629 sources - [95] Gurtu et al. (2015) for a survey on the most frequent keywords in green supply management literature.

	Minimum	Maximum	Mean	Standard deviation	Mode	Median
Sources	10	629	126	101	87	100
References	31	364	134	72	147	122

Table 2.5: Statistics for sources or references per literature review (1995-2018). Category I.5

The majority of literature reviews (53%) resort to some kind of protocol-driven approach (PD) to collect their source material (Category III). As depicted in Figure 2.5 on page 24, only in a few cases this method is complemented with informal approaches (IA, 6%), snowball methods (SB, 12%), or both (4%). Informal approaches (25%), as the sole method or jointly with snowball methods, are only employed by narrative reviews. Observe that papers that do not disclose information about the collection method are classified as informal approaches. As this happens frequently with narrative reviews, it explains the association between the number of this type of reviews, and the number of sources appealing to the informal approaches collection method.

In spite of the majority of literature reviews being classified as systematic, one of the key elements of that type of reviews - reliability - is conspicuously absent from the reporting presented in the papers. Analysis of results for Category IV reveals that, of all 198 sources, only in seven (4%) do authors quantify the quality measures implemented during the selection process (IR). Notably among those are [35] Carter and Easton (2011), "based on the proportion of total pairwise agreements between the coders", [79] Gao et al. (2017) using Fleiss' kappa, and [188] Winter and Knemeyer (2013) with Krippendorff's alfa. Figure 2.6 on page 25 shows that in most cases (69%) the authors opt not to provide any information about the reliability measures executed (NM), and in 27% of the cases only allude to them to inform that discussions between the reviewers took place, and agreement about



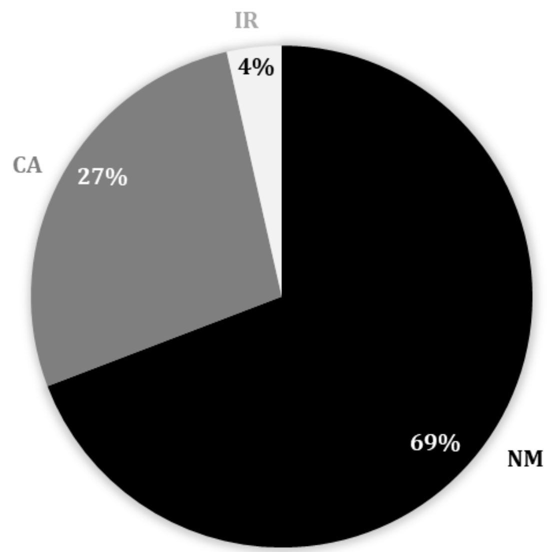
PD: Protocol-driven; IA: Informal approaches; SB: Snowball methods

Figure 2.5: Percentage of literature reviews per type of material collection (1995-2018). Category III

the materials selection was eventually reached (CA).

Figure 2.7 on page 26 reports the number and percentage of literature reviews per type of reporting (Category V, material synthesis). 121 papers (61% of the total) present some background information about the reviewed material, e.g. evolution of sources per year, and per journal of publication (DS). Synthesis following the analytic categories defined (CT) is carried out in 104 reviews. Frequently (in 46 cases - not showed in Figure 2.7), it is accompanied by a thematic synthesis (TH) that offers additional insights into the material reviewed. At any rate, thematic is the preferred reporting method, followed in 66% of papers. This is not surprising considering that all but one narrative reviews ([56] De Meyer et al. (2014)) endorse a thematic synthesis, to which must be added 36 systematic reviews that choose this as the single type of synthesis, and 43 that use it along with a category synthesis. Among the narrative reviews, [94] Gungor and Gupta (1999), [162] Rugani et al. (2013), and [175] Soysal et al. (2012) also use concurrently both types of syntheses. Bibliometric analysis (BB) is present in a smaller number of reviews (19), and only in nine of those it is the main form of reporting (see for example [73] Fahimnia et al. (2015a) on green supply chain management, or [75] Feng et al. (2017) devoted to the issue of corporate social responsibility).

The last of the methodological-related categories concerns the type of material source (Category



CA: Cross-analysis; IR: Inter-rater agreement; NM: Not mentioned

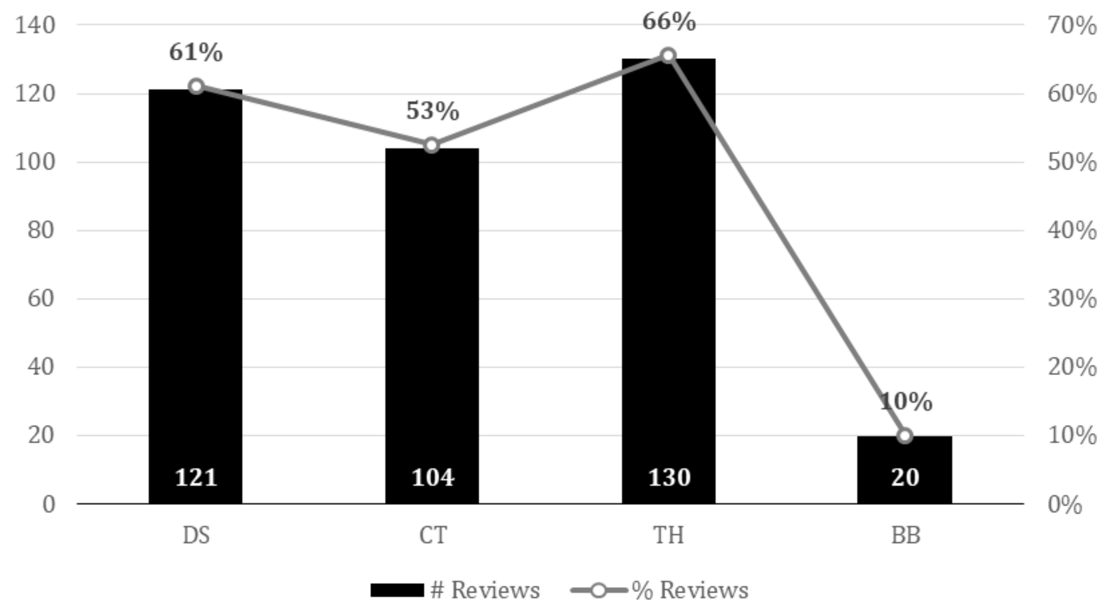
Figure 2.6: Percentage of literature reviews per type of material selection (1995-2018). Category IV

VI). A large number of reviews (75%) is supported by mixed sources (MX). The single most used type of source is OR/MS material (OR, 19% of reviews), with theoretical/conceptual (TC), and empirical sources (EM) being accountable for only 3%, and 4% of the total number of reviews, respectively, as the sole type of material sources.

2.4.2.2 Objectives and subjects

Turning the attention to the third research question A.3, Figure 2.8 on page 27 shows the number and percentage of literature reviews per type of objective (Category VII). Only one paper ([145] Moldavska and Welo (2017)) expressly avoids attempting to perform a state-of-the-art review (SA). Yet, the content analysis of that paper reveals that it is not distinct in this respect from others that are classified as state-of-the-art. Therefore, this classification should be interpreted with some latitude. As mentioned in Section 2.3.3, this is a default objective for conducting literature reviews, and the classification reflects it: 97% of the sources are coded as "State-of-the-art".

A significant portion of the sources (70%) identifies research gaps and opportunities, and proposes research directions (GD). Research consolidation and framework proposals are also recurrent objectives. The integration of different research streams into a cohesive field (RC) drives reviews such as



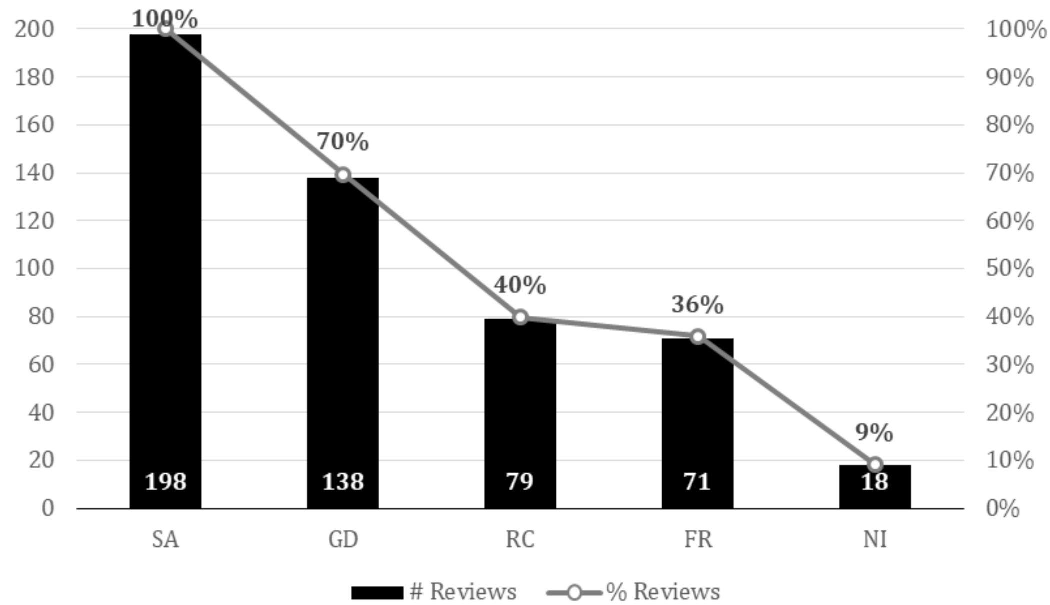
DS: Descriptive analysis; CT: Category synthesis; TH: Thematic synthesis; BB: Bibliometric analysis

Figure 2.7: Number (#) and percentage (%) of literature reviews per type of material synthesis (1995-2018). Category V

[47] Cicculło et al. (2018) on the integration of the Lean and Agile paradigms with the sustainability outlook, [51] Dania et al. (2018) about behavioural factors enabling collaboration in the agrifood supply chain, and [113] Jia et al. (2018) converging SSCM with developing countries literature.

Often, research consolidation is accompanied by the proposal of conceptual frameworks (FR). This latter objective has originated some of the most influential papers in the sustainable supply chain literature. Among them it is worth citing the works of [36] Carter and Rogers (2008), [165] Sarkis (2012), and [170] Seuring and Müller (2008), all dealing with the broader issue of SSCM. Other papers motivated by the objective of submitting research frameworks for particular supply chain functions or industries are [129] Liu et al. (2017) for the service supply chain, [185] Varsei et al. (2014) concerning multidimensional performance indicators, and [198] Zsidisin and Siferd (2001) with regard to green purchasing.

The introduction of new research topics in the sustainable supply chain literature (NI) is the least frequently identified objective (9%). It applies mostly to emerging concepts, or notions imported from other research fields like water footprint in [8] Aivazidou et al. (2016), circular economy in [82] Geissdoerfer et al. (2017), or big data and predictive analytics in [99] Hazen et al. (2016).



SA: State-of-the-art; GD: Research gaps and directions; RC: Research consolidation;
FR: Framework; NI: New issue

Figure 2.8: Number (#) and percentage (%) of literature reviews per type of objective (1995-2018). Category VII

Figure 2.9 on page 28 displays the percentage of literature reviews according to the sustainability focus (Category VIII). The triple bottom line approach, whether or not explicitly, is assumed in just over half the sources (51%). As expected, the environmental perspective appears more prominently in the reviewed literature than the social aspect. When considered as the dominant outlook on sustainability, environmental oriented articles account for 42% (83 reviews) of the total number of sources, whereas the social perspective is engaged by only 7% (14 reviews). Interestingly, some papers focus specifically on both outlooks. This is for instance the case of [102] Hoejmose and Adrien-Kirby (2012) about responsible procurement, and [180] Tang and Zhou (2012) regarding sustainable operations. In Appendix A all sources are individually classified according to the sustainability focus adopted.

The classification of the material in terms of the main research subject (Category IX) is presented in three tables. Table 2.6 on page 32 appeals to the processes and functions presented in Section 2.1.1 (p. 8) to map the sources according to the SC function that they mainly pertain to. Clearly, the global topic of supply chain management has generated the largest number of literature reviews, but overall most of the individual SC functions have been the subject of individual reviews. Even

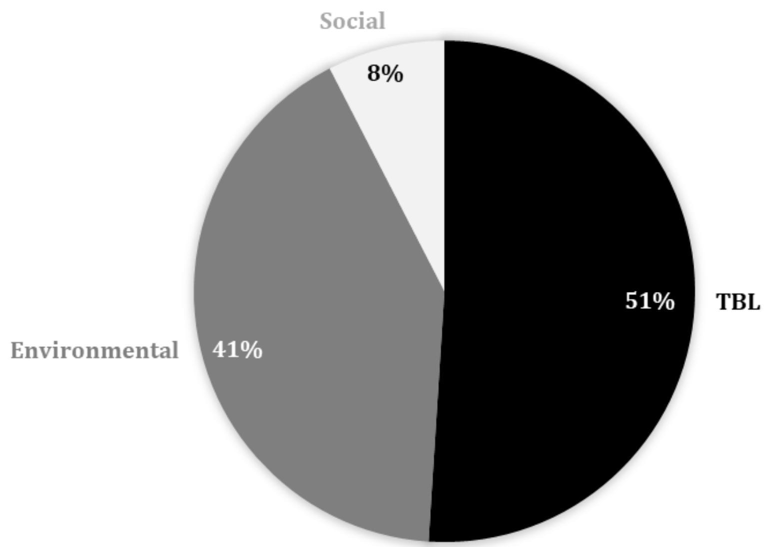


Figure 2.9: Percentage of literature reviews per sustainability focus (1995-2018). Category VIII

though a considerable number of reviews adopt the environmental perspective, the triple bottom line approach is embraced by the largest number of supply chain literature surveys. On the contrary, there are very few sources that consider only the social outlook on sustainability.

Literature reviews directed at particular industries are identified in Table 2.7 on page 33. Table 2.8 on the same page displays the allocation of reviews oriented to OR/MS models. A paper engaged in a balanced manner in both an industry, and a OR/MS model has entries in both tables. This is for example the case of [63] Djekic et al. (2018) reviewing environmental analytical models for the food supply chain, or [71] Ellram and Murfield (2017) concerning optimization models for network design in the energy supply chain.

The main findings regarding the outcome of this classification, as well as conclusions derived from previous results are discussed in the next section.

2.4.3 Thematic analysis

Having moved from the content analysis of the qualitative arguments of the source material to the quantitative indicators presented in the previous section, in this section the study goes back to the qualitative interpretation of findings (Yawar and Seuring, 2017).

The 198 literature reviews identified (research question A.1) reveal that SSCM literature is undergoing a methodological-related change from narrative to systematic reviews. The increase in the volume of secondary studies published since 1995 has been accompanied in the last five years by an explicit attempt to analyze the relevant body of primary research in a comprehensive and systematic manner. This evolution can significantly contribute to the consolidation and development of the SSCM research field (research question A.2).

The systematic review can be a very effective scientific technique, but also very time consuming. It demands that reviewers comb through many hundreds of sources until finally identifying the relevant articles. On the one hand, it has the advantage of bringing to the attention of the reviewer meaningful sources that could otherwise remain unidentified. On the other hand, the efficiency of the collection process is certainly dependent upon the adequacy of search strings, but also affected by both the consolidation of SSCM taxonomy, and database classification of articles. For example, the execution of the search protocol of this study produced 1,333 hits, from which only 132 were ultimately found adequate for the purpose of the study. Admittedly, the search terms were designed to be as inclusive as possible, so a high ratio of false positives was anticipated. However, material articles such as Gold et al. (2010b), Ahi and Searcy (2013), or Brandenburg et al. (2014) were not identified by keyword search.

In this regard, Greenhalgh and Peacock (2005) argue that, particularly in fields of complex and heterogeneous evidences like management and policymaking, relying exclusively on formal protocol-driven search strategies may not be sufficient. These techniques, as verified in this study, may fail to identify relevant sources. While protocol-driven searches are important to collect a diversity of articles that help avoid research bias, informal approaches and snowball methods are also important strategies to complement that material. Yet, as mentioned in Section 2.4.2.1, few sources reviewed in this study opt for this approach, which may impact their comprehensiveness and validity objectives.

Perhaps more meaningful though is the fact that frequently the methodological procedure followed does not entirely correspond to the features that define systematic literature reviews. In particular, transparent reporting of the methodological rigor enforced in the review process is often found to be insufficient. Indeed, some works fail to include in a clear way elementary information such as the identification of the sources reviewed.

Information about the date(s) or delimited period of search, number of hits returned for each search string executed and/or databases used, and quantitative information about levels of agreement between reviewers, if reported, can greatly contribute to increase the transparency of the review. Disclosing detailed information about the rigor applied in the methodological process enables its auditing and reproduction, conferring reliability to the results reported, and substantiates their validity. On the contrary, their omission can curtail the materiality of the work to foster the development of the research field, namely as the basis for future updates.

Almost 10 years after Denyer and Tranfield (2009) observed that systematic literature reviews were proliferating and becoming a standard methodology in medical research, the same can be said regarding the management field, particularly in the case at hand of sustainable supply chain literature. However, unless methodological improvements are registered, there is a risk that systematic review methodology in the SSCM field becomes a synonym for structured database searches.

Research question A.3 is directed at the objectives and subject of the literature reviews on SSCM. Based on the analytic categories established, the mapping of the literature presented in the previous section allows the identification of the main trends in the SSCM secondary literature.

After an initial period when the environmental outlook dominated the sustainability literature, the triple bottom line is becoming the prevailing perspective. Although single social-oriented reviews are still manifestly under-represented in comparison with environmental-oriented surveys, this study identified a number of recent reviews that consider the social outlook, either as its chief perspective, or as an integral part of the triple bottom line approach. This suggests that previous calls for the inclusion of social accountability of the supply chain in the literature are being addressed.

Most frequently, social themes are considered as part of the TBL approach. The three pillar outlook on sustainability is particularly adopted in reviews involving broad scope subjects like network design (10 reviews) or supply chain management (44 reviews). Studies devoted to such issues often have a quantitative nature. In these cases, integration of the social dimension occurs via topics like the assessment of the regional development impact in the supply chain service area. Social impact measures pertaining to the number of jobs created by the supply chain, or with reference to health and safety, as expressed by the number of work days missed by employees due to health problems, are frequently engaged. Naturally, some specific supply chain functions are more disposed to the inclusion of the social factor than others, warranting studies where the social angle prevails. Governance and CSR (five reviews in which the social point-of-view is dominant), similar to coordination and collaboration (two reviews) are markedly social supply chain functions. To a large extent, relationships with suppliers are also susceptible to studies focused primarily on the social perspective (two reviews). Some of the major social topics that have been examined in the reviews surveyed, namely those of a non-quantitative nature, include ethical supply chains, equitable treatment of stakeholders, education and training, social justice, and diversity.

Nevertheless, the environmental perspective still occupies a significant portion of the SSCM research. Whether resulting from official or self-established objectives, environmental performance in terms of CO_2 emissions, natural resources utilization, and product recovery among others, continues to attract considerable attention, individually or integrated in the TBL approach. Environmental issues are particularly relevant with regard to functions like transport (eight reviews) or manufacturing (seven reviews) that experience some of the most immediate environmental challenges. Similarly, return processes involving reverse logistics and closed-loop supply chains (a total of 10 reviews) are more susceptible to environmental evaluation and study.

Overall, most key SC functions have been the subject of literature reviews since 1995. In line with the diagnosis of [15] Asgari et al. (2016), some, like scheduling, and inventory appear to register a decline, possibly due to research saturation. In contrast, complex decisions pertaining to network design, and high sustainability impact functions involving multiple SC participants, namely suppliers, are still compelling research subjects, even though they have reached a certain research maturity. Singly, performance is the function that has motivated the largest number of reviews (28). Performance relates to non-complex decisions involving metrics and indicators that have an important role supporting strategic, tactical, and operational decisions, which can explain this attention. The most notable function-related gap concerns risk management. This topic has been the subject of multiple literature reviews, e.g. Ghadge et al. (2012), and Fahimnia et al. (2015b), but, as at the time of material collection, not one was identified as adopting a sustainability perspective.

The secondary SSCM literature reviewed also offers multiple perspectives, from specific types of focal firm ([120] Klewitz and Hansen (2014), and [150] Nakamba et al. (2017) concerning Small and Medium-sized Enterprises) to particular country profiles ([113] Jia et al. (2018) for developing countries), or segments of the population ([117] Khalid et al. (2015) for base of the pyramid). It is also worth noting that, among the 198 literature reviews analyzed, only [57] de Oliveira et al. (2018) propose to update a previous review. In this case it refers to [176] Srivastava (2007), concerning green supply chain management. Literature updates are frequently involved in advancing research fields, and can also play an important part in the development of the study of SSCM. In this regard, the recent methodological shift favoring systematic reviews indicates that future surveys can benefit from the existing material as the basis to update and reassess the available source material. However, in order to achieve that, it is required that the methodological features of the literature reviews are improved. This constitutes one of the chief research gaps, and consequently opportunities, identified in this study.

Process	Function	Reviews		
		Environmental	Social	Triple bottom line
Source	Supplier evaluation and selection	[83] [92] [105]		[86] [196]
	Sourcing and procurement	[13] [198]	[118] [197]	[85] [102] [112] [115] [142]
Make	Network design	[136] [151] [193]		[34] [42] [56] [70] [72] [84] [104] [149] [153] [182]
	Product development	[20] [40] [106] [114] [140] [159] [194]		[14] [48] [137]
	Manufacturing	[46] [94] [106] [107] [122] [128] [194]		[39] [41] [145] [161]
	Scheduling	[78]		
	Inventory	[22]		
Deliver	Transport	[2] [52] [60] [71] [125] [127] [132] [173]		[21]
	Marketing	[38] [50]		[124]
Return	Reverse logistics	[22] [53] [94] [95] [106] [107]		
	Closed-loop supply chain	[95] [106] [160] [164]		
Enable	Performance	[6] [8] [81] [101] [111] [144] [152] [162] [171]	[24] [123]	[5] [27] [49] [64] [77] [90] [96] [97] [98] [148] [168] [175] [179] [181] [185] [190] [195]
	HR management	[109]		
	Governance and CSR	[143] [189]	[1] [75] [130] [156] [192]	[32] [87] [91] [102] [113] [115] [138]
	Quality and safety			[9] [19]
	Innovation	[54] [55] [100] [120] [140] [191]		[3] [79]
	Knowledge and information	[76]		[77] [91] [99] [183] [186]
	Coordination and collaboration	[140] [160] [189]	[51] [74]	[43] [86] [87] [88] [178]
Others	Lean and agile	[33] [45] [69] [80] [114] [146]		[44] [47] [126] [134]
	Globalisation	[146]		[29] [32] [112]
	Circular economy	[82]		[103] [135]
Plan	Supply chain management	[2] [4] [28] [37] [52] [57] [58] [59] [61] [63] [67] [68] [73] [93] [95] [108] [131] [132] [133] [136] [141] [143] [157] [163] [165] [166] [172] [174] [176]	[1] [121] [150] [187] [192]	[7] [9] [10] [11] [12] [15] [16] [17] [18] [21] [23] [25] [26] [29] [30] [31] [35] [36] [62] [65] [66] [87] [89] [110] [113] [116] [117] [119] [129] [138] [139] [147] [154] [155] [158] [167] [169] [170] [175] [177] [178] [180] [184] [188]

Table 2.6: Literature reviews according to SC function (1995-2018). Category IX.1

Industry	Reviews		
	Environmental	Social	Triple bottom line
Agrifood and mining	[8] [61] [63] [136] [162]	[51] [130]	[9] [26] [154] [167] [175]
Automotive and electronics			[64] [77] [137]
Chemical and pharmaceutical	[53] [93] [151]		
Energy	[163] [193]		[7] [17] [34] [56] [70] [84] [87] [153]
Services	[37]		[129]
Textile and apparel		[121]	[116]

Table 2.7: Literature reviews according to Industry (1995-2018). Category IX.2

OR/MS model	Reviews		
	Environmental	Social	Triple bottom line
Analytical	[40] [63] [107] [128] [136] [159] [174] [194]	[123]	[14] [48] [104] [137] [155] [195]
Mathematical programming	[22] [93] [125] [127] [141] [151] [173]		[56] [70] [72] [84] [149]
Simulation	[163]		[147]
Hybrid and multi	[28] [46] [59] [60] [68] [78] [92] [94] [106] [133] [157] [176] [193]		[9] [12] [17] [18] [23] [25] [30] [34] [39] [49] [170] [175] [180] [182] [186] [196]

Table 2.8: Literature reviews according to OR/MS model (1995-2018). Category IX.3

Summary Chapter 2

This chapter provided a comprehensive review on the current status of SSCM research. Its timeliness is justified by the volume of published primary and secondary research, and its recent evolution. The tertiary study presented in this chapter renders a comprehensive critical survey of the current status of research on supply chain sustainability.

The review consisted of a content analysis of 198 literature reviews on supply chain sustainability published since 1995. The source material was collected and selected following a thorough process involving the author and the supervisor, which asserts the validity of the results obtained. Each article was classified according to deductive and inductive analytic categories defined to answer the research questions. In particular, classification of articles according to the main supply chain function(s) reviewed was based on an analytic framework developed for this study, which is one of the contributions to the literature. The framework identifies chief supply chain functions according to the processes of the SCOR model from the perspective of the firm and of the supply chain. Although classification was mostly conducted by the author, it was followed by conciliation discussions with the supervisor whenever necessary in order to avoid bias. Nevertheless, this can be considered a limitation of the study.

The methodology established for this study was presented in detail, and reporting of results followed the best practices found in the literature, ensuring its audit and reproduction. In this regard, the methodology of the review is in itself another contribution of this tertiary study to the literature.

The study addressed research questions pertaining both to the methodological features, and to the objectives and subject matters of the sources. Concerning the methodological aspects, it was concluded that in recent years most surveys on SSCM have adopted systematic literature reviews features. Frequently, it signifies that source material was identified on the basis of a database search protocol, which is presented with different degrees of detail. Taking into account the considerable effort required to assess the relevance of the usually large number of potential sources identified by the execution of the search protocol, it is considered worthwhile engaging in complementary search strategies. Informal and snowballing processes can add relevant source material, contributing to the comprehensiveness goals of the reviews. Similarly, often the information disclosed concerning the review methodology is limited to the search strategy, and to the selection criteria set to identify significant articles. Providing additional information about the methodological steps followed, and respective outcomes can enhance the

reliability and validity of the reviews. The adoption of solid, comprehensive and transparent review methodologies if therefore identified as a research opportunity for future literature reviews.

Among the main objectives that have prompted SSCM literature reviews, presenting a state-of-the-art survey of original research papers on selected SSCM topic(s) was recognized in this study as the chief goal, common to practically all reviews. It is frequently accompanied by the identification of research gaps and proposals of promising research directions. Often, literature reviews offer a new and consolidated perspective on related yet as of then disperse SSCM issues. They also support the submission of analytic frameworks for some particular SSCM subject or, less frequently, the introduction of a new research topic.

Concerning the subject matters of the literature reviews surveyed in this tertiary study, it is concluded that most of the major SC functions have been the theme of reviews focusing on sustainability. A considerable portion of the reviews is devoted to the generic issue of supply chain management although specific topics such as sourcing and procurement, network design, performance, or coordination and collaboration have also warranted a number of secondary studies revealing a considerable research interest in those functions. Likely, the notable exception is the “enabler” function risk. In spite of being a frequently studied SC function, no reviews on the issue adopting a sustainability perspective were identified. This gap provides research opportunities that can also be explored regarding other SC “enablers” like innovation or knowledge and IT systems. In these cases, even though the issues have already been covered by a number of secondary studies, further research opportunities continue to exist given the relevance and prospective role of the topics in the development of supply chain management.

Regarding the sustainability approach, it is clear that social aspects are still underrepresented in the literature and continue to offer significant research opportunities. Nevertheless, the study revealed that already around half of the SSCM literature reviews surveyed adopt a triple bottom line perspective. This suggests that previous calls for inclusion of the social aspect in sustainability approaches have resulted in an increasing accountability of the people’s bottom line, along with the economic and environmental factors. In spite of this evolution, this issue can continue to benefit from additional research, and in fact is identified as the main research opportunity in SSCM literature. Specifically, SC functions involved in the “return” process (reverse logistics and closed-loop supply chain) have not yet been the subject of literature reviews accounting for the social factor.

Finally, the study identified a limited number of SSCM literature reviews devoted to specific

industries. As expected, core industries such as agrifood or energy have been the subject of surveys. It is suggested that systematically reviewing the SSCM literature focusing on individual industries, particularly if accounting for real-life based research, also represents a promising research opportunity that can further promote the development of SSCM literature. The above mentioned gaps provide rich research opportunities that can contribute to the evolution of a field that has attracted substantial attention over the past 30 years, and that, based on the results of this review, is undergoing significant methodological and content changes.

Keywords: Tertiary study; Systematic literature review; Content analysis; Supply chain; Sustainability

Chapter 3

Literature review

The tertiary study presented in the previous chapter identifies several literature reviews devoted to the specific topic of sustainable supply chain network design. In particular, Table 2.6 on page 32 lists 10 reviews concerned with the network design function from a triple bottom line perspective. Those reviews were published over the last four years and provide an updated and comprehensive survey on the state of research on supply chain network design, simultaneously covering economic, environmental, and social sustainability objectives [1].

[42] Chen et al. (2014) address the sustainability of global supply chains. The authors systematically review 81 research papers (1990-2011) with a view to submitting a decision-making framework for sustainable manufacturing facility location. The survey identifies several factors impacting location decisions, from natural resources availability and costs, to market conditions. Among the social factors, the authors include corruption, political stability, and trade barriers as governance determinants, civil and human rights local policy, equity, safety, and community cohesion.

The energy supply chain has concentrated significant research attention with regard to sustainable network design. [56] De Meyer et al. (2014) review 71 articles published between 1997 and 2012 focusing on methods to optimize the design and management of biomass supply chains. The review is mainly oriented toward the mathematical methodology followed in the source material, analyzing the decision problem and objectives of the research articles regarding optimization approaches, including mathematical programming, heuristics, and multicriteria decision methods. The authors conclude that most articles reviewed turn to mixed-integer linear programming (MILP) models to formulate location problems comprising product flow and transport operation decisions. They further conclude that frequently solving these problems involves resorting to heuristic techniques by virtue of the

[1] Cited literature reviews are hereinafter identified by the reference number between square brackets defined in Appendix A and used in Chapter 2.

associated "large number of decision variables (...) required to describe complex issues like supply chain". In this respect, they highlight evolutionary heuristics like genetic algorithms and particle swarm optimization as especially suited to solve these problems.

Also related to the energy supply chain, [70] Elia and Floudas (2014) encompass research dealing with other energy sources besides biomass, such as coal and natural gas supply chains. In this work, 157 articles issued until September 2013 are reviewed in terms of the supply chain scope (i.e. functions included) and structure, in relation to which the authors posit the concepts of converging (multiple sources to a single facility or network node), diverging (the opposite case), and multinodal networks. While not ignoring social aspects, environmental issues assume the chief sustainability perspective. The articles reviewed are characterized in terms of the type of model and decision variables involved in the operational, tactical or strategic decision problems defined, but attention is directed essentially toward studies that evaluate the supply chain impact in a delimited regional area, account for multiperiod optimization, or else include uncertainty in the decision process.

[72] Eskandarpour et al. (2015) present a literature review on sustainable supply chain network design angled toward optimization models and solving methodologies. The 87 research papers (1990-2014) included in the review are analyzed in reference to the prevailing environmental or social sustainability dimension. Owing to the considerably larger volume of available primary research, the former is discussed in greater detail. The most common methods employed to include environmental issues in supply chain network design decision making processes - Life cycle assessment (LCA), Analytic hierarchy or network process (AHP or ANP), or Data envelopment analysis (DEA) - are reviewed. Similarly, frequently used environmental metrics like Greenhouse gas (GHG) emissions, energy consumption, or volumes of waste and recycled products are mapped according to the source material. Regarding what is denoted as "Social supply chain network design", the authors recognize that the modeling and quantitative assessment difficulties involved result in far less research output. The authors conclude that concrete social indicators often resort to accounting for the number of jobs created, occasionally involving specificities related to balanced regional development, or distinction between fixed and variable job positions. Safety and security measures are also mentioned in relation to work conditions, as well as more generic issues such as the improvement of health, education and culture in relation to societal commitments. Modeling approaches are classified on the basis of the number of objectives (single or, most frequently, multiple), their linearity, and on the presence of uncertainty (deterministic or stochastic). Lagrangean relaxation, in the case of single objective problems, and weighted sum of objectives, variants of the ε-constraint method, goal programming, metaheuristics, or interactive methods, regarding multi-objective problems, are cited as recurrent solving techniques. The authors suggest several research opportunities in this field, namely

the simultaneous consideration of economic, environmental, and social objectives, paying particular attention to the definition of appropriate social metrics, the integration of strategic with tactical and operational decisions in real-life application problems, and the development of efficient heuristic methods to solve large and complex MILP models.

[34] Cambero and Sowlati (2014), [84] Ghaderi et al. (2016), and [153] Pérez et al. (2017) also cover optimization-oriented topics, albeit restricted to research concerned with the biomass supply chain. Cambero and Sowlati (2014) list several generic social factors affecting the sustainability of biomass operations, from “people’s way of life, culture, community, political systems, environment, health, well-being, personal rights, property rights, and even fears and aspirations”. However, in acknowledging the quantification issues involving these factors, the authors isolate job and income creation as the most common social factors included in optimization models. In this regard, the authors stress the importance that Social LCA frameworks can have in quantifying the social dimension of sustainability. Based on the systematic review of 146 articles (1997-2016), Ghaderi et al. (2016) arrive at similar conclusions as Eskandarpour et al. (2015), calling for further research that factors in the complexities derived from considering diverse stakeholders and activities, managing various products over multiple planning periods in multi-objective decision problems. Additionally, non-linear modeling approaches featuring uncertainty are considered more fitted to represent actual biomass supply chains, leading to the suggestion of exact decomposition-based algorithms to obtain improved solutions, and fuzzy logic or robust optimization as appropriate solving methods to tackle the uncertainty element. Pérez et al. (2017) briefly mention a “Triple bottom line extended” (TBL+) concept that, besides the economic, environmental, and social facets, also comprises the technological and political dimensions. According to the authors, these sustainability outlooks are particularly relevant for the biorefinary supply chain.

The remaining literature reviews offer complementary surveys on specific network design aspects. [104] Ibáñez Forés et al. (2014) focus on sustainable technology selection using multi-criteria decision making methods, where the social factor, although included, plays a secondary role. Sustainable facility location is reviewed in [182] Terouhid et al. (2017), while [149] Movahedipour et al. (2016) report a bibliometric and network analysis of 1,610 publications (1994-2016) on supply chain management optimization, partially covering the sustainability topic.

This overview of the literature reviews on TBL network design introduced in the previous chapter provides a summary of the most frequently engaged features, as well as of the most cited research gaps in the supply chain sustainability literature.

In short, research strives to include quantified social metrics, but results often fall short of adequately depicting the complex relationships and social factors influencing the sustainability of supply chains. Likewise, the holistic inclusion of long, medium and short-term decisions, along with the various upstream and downstream supply chain elements in mathematical models is pursued, particularly in applications of real-life problems. Yet, this target is accompanied by the admission that exact solving methods face serious and regularly insurmountable computational limitations addressing larger problems that can actually approximate real-life situations.

It is therefore deemed material for the present study to review primary research in order to identify in greater detail how the social factor has been included in the supply chain literature, specifically in multi-objective optimization models.

Thus, Section 3.1 establishes the main objectives of this survey, and reports the literature review methodology adopted. The results obtained are discussed in Sections 3.2 and 3.3. The chapter is concluded with a supplementary overview of research articles concerned with the specific topic of the food bank supply chain, presented in Section 3.4.

3.1 Methodology

The main purpose of this literature review is to discern the metrics engaged in expressing the social dimension of the triple bottom line sustainability approach. Subsidiarily, the review also seeks to understand how those indicators are included in multi-objective optimization models, and what solving methodologies are most frequently employed.

These research questions are addressed following a systematic review and content-analysis method. The search protocol established to collect and select relevant sources is presented in Table 3.1.

Articles considered material to answer the research questions must include optimization models (keyword "model") representing supply chains (keyword "supply chain") as networks (keyword "network"). Considering that multi-dimension sustainability approaches involve two or more objectives, and in view of the decision problem tackled in this study, several terms were included in the search strings to identify articles concerned exclusively with multi-objective optimization models. These terms are "bi-objective" (and "biobjective", not mentioned in Table 3.1), "tri-objective", "triple objective", and "multi-objective" (and "multiobjective"). The social factor is conveyed by the keywords "sustainab*", "social", and "triple bottom line". In all cases, double quotation marks were used as indicated in Table 3.1.

The search performed on 24 May 2018 returned 243 results, which were eventually filtered down to 50 after abstract review and content screening (six articles were not available for analysis). This lot includes all previously known relevant articles except one (Mota et al., 2015), presumably because it does not include the term "network" in its title, abstract or keywords. Hence, this paper was

A	Research questions			
	A.1	How is the social factor featured in multi-objective supply chain network models?		
	A.2	What are the methodologies used to solve the respective decision problems?		
B	Databases		Scopus and Web of Science (WoS)	
C	Search criteria			
	C.1	Language:	English	
	C.2	Scientific areas(s):	All	
	C.3	Journal(s):	All	
	C.4	Article type(s):	Research article	
	C.5	Search field(s):	Title, abstract and keywords	
	C.6	Date of publication:	Until present	
	C.7	Date of search:	24 May 2018	
D	Search terms			

	Keywords										Scopus	WoS
D.1	"supply chain"	AND	model	AND	network	AND	sustainab*	AND	"bi-objective"		17	15
D.2	"supply chain"	AND	model	AND	network	AND	sustainab*	AND	"tri-objective"		-	1
D.3	"supply chain"	AND	model	AND	network	AND	sustainab*	AND	"triple objective"		-	-
D.4	"supply chain"	AND	model	AND	network	AND	sustainab*	AND	"multi-objective"		174	156
D.5	"supply chain"	AND	model	AND	network	AND	"t.b.l."	AND	"bi-objective"		1	-
D.6	"supply chain"	AND	model	AND	network	AND	"t.b.l."	AND	"tri-objective"		-	-
D.7	"supply chain"	AND	model	AND	network	AND	"t.b.l."	AND	"triple objective"		-	-
D.8	"supply chain"	AND	model	AND	network	AND	"t.b.l."	AND	"multi-objective"		15	9
D.9	"supply chain"	AND	model	AND	network	AND	social	AND	"bi-objective"		5	6
D.10	"supply chain"	AND	model	AND	network	AND	social	AND	"tri-objective"		-	-
D.11	"supply chain"	AND	model	AND	network	AND	social	AND	"triple objective"		-	-
D.12	"supply chain"	AND	model	AND	network	AND	social	AND	"multi-objective"		82	125
	Total (1)											243

"t.b.l.": "triple bottom line"
(1) After elimination of duplicate records

E	Inclusion criteria			
	E.1	Article with supply chain network model	AND	
	E.2	Featuring multiple objectives	AND	
	E.3	Including social factor		
F	Exclusion criteria			
	F.1	Editorials or conference proceedings	OR	
	F.2	Literature reviews		
G	Search results			
	G.1	From keywords search		243
	G.2	After abstract review		70
	G.3	After article screening		50

Table 3.1: Search protocol: literature review

added to the group of selected articles, resulting in a total number of 51 sources (N=51). The unit of analysis for this review is a single research article (single source).

3.2 Descriptive analysis

Despite the fact that no particular year was set as the earliest publication date, the first collected articles modeling a supply chain network with social sustainability concerns were issued just six years ago, in 2012. As shown in Figure 3.1, three articles matching the search criteria were published in that year, revealing that, from early on, the energy supply chain was a privileged subject of sustainability studies adopting a social perspective, as two of those three precursory articles concern biofuel networks.

Pérez-Fortes et al. (2012) apply a multi-objective MILP model to design bio-based networks for electricity generation in a region of Ghana, considering the positive social impact of creating work positions in every new facility. Based on input-output multiplier analysis, You et al. (2012) account for the direct, indirect, and induced social impacts on the regional economy resulting from the installation of cellulosic biofuel supply chains. Direct impacts are associated with the number of jobs created during the construction and operation phases, while indirect impacts derive from the increase in economic activity of agents providing products or services to those directly involved in the set-up and running of the biorefineries. Moreover, the social function of the multi-objective MILP model factors in, as induced impacts, the benefits on the regional economy from the local expenditures made by all supply chain stakeholders (employees, suppliers, contractors, etc). Unlike the previous two articles, whose models have economic, environmental, and social individual objective functions, the other article published in 2012 only considers economic and social objectives. Pishvaee et al. (2012) maximize the supply chain social responsibility under uncertainty conditions using robust possibilistic programming. For a generic industry location problem, the authors express the social factor based on the ISO 26000 classification of social responsibility issues (ISO, 2010), electing the following four criteria: number of potentially hazardous products for consumers, lost work days from work damages, number of jobs created, and product waste volumes (note that one of the core subjects of ISO 26000 is "the environment").

As reviewed in the next section, most social factors currently used in the literature still revolve around these topics, most notably, with occasional derivations, the number of jobs created by the supply chain.

The literature reviewed registered an initial significant increase in 2016, when 10 articles were published. This number almost doubled in the following year to 19, and, based on the number of records identified for the current year by date of search, it will likely be surpassed in 2018.

Even though the total volume of research output corresponding to the subject of this review is objectively small, particularly in comparison with the figures presented in the beginning of Chapter 2, the evolution illustrated in Figure 3.1 reveals its topicality and materiality within the sustainable supply chain literature.

Based on the country of the corresponding author, the 51 articles reviewed originate from only 16 countries. Iran leads with 14 articles, greatly due to the activity of M. S. Pishvaee that accounts for five articles, either as author or co-author. Partly due to the small total number of articles, the research efforts of specific scholars greatly influence the distribution of literature by country. For example, four of the five articles attributed to Denmark are authored by K. Govindan, who also co-authors one article assigned to Iran. Similarly, J. D. Darbari authors two of the four articles from India, and is co-author of one paper from Denmark. The United States of America is the second most represented country with six publications. Among the countries with a noteworthy number of publications are Australia, Canada, China, and France, all with three articles each, and Portugal and Spain, both with two references each. The remaining countries (Germany, Greece, Malaysia, Netherlands, Taiwan, and Turkey) have one publication each.

As for the outlets selected to issue the research, Journal of Cleaner Production stands out as the publication with the largest number of articles included in this literature review (eight, as depicted in Figure 3.2 relative to journals with two or more articles published). Annals of Operations Research, with four articles, and Computers & Operations Research, with three, are the only two other journals with more than two research articles published concerning multi-objective supply chain network models that specifically account for the social factor. Overall, a total of 32 journals released articles pertaining to the review topic.

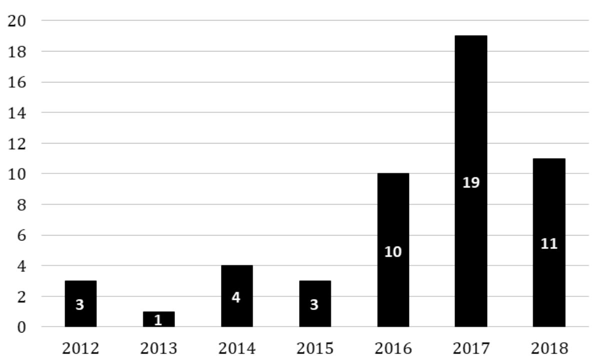


Figure 3.1: Number of research articles published per year.

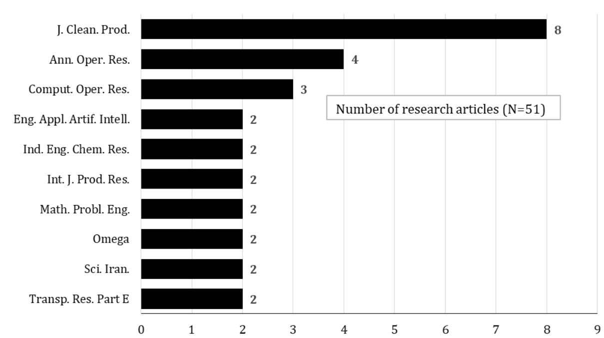


Figure 3.2: Number of research articles per journal (2012-2018).

3.3 Social dimension

Difficulties of integrating quantified social metrics into decision problems are widely recognized in the literature. They are in fact the most singled out motive for the considerably fewer number of research studies featuring the social sustainability dimension than the number of articles concerned with the economic and/or environmental facets.

As one of the primary gaps in supply chain sustainability literature, the incorporation of the social factor into quantitative supply chain models is also perceived by the generality of authors as one of the most promising opportunities in this research area.

The limited number of works that has attended the call to establish and include social metrics in supply chain problems has often relied on international standards or guidelines like ISO 26000, GRI, and SA8000®. ISO 26000 "International Guidance Standard on Social Responsibility" proposes various ways to integrate socially responsible behaviour into all types of organizations (ISO, 2010). It encompasses a variety of social issues aggregated into the following seven core subjects: (1) organizational governance, (2) human rights, (3) labor practices, (4) the environment, (5) fair operating practices, (6) consumer issues, and (7) community involvement and development. The Global Reporting Initiative (GRI, 2018) offers a framework for sustainability reporting covering economic, environmental, and social topics. The set of 19 social standards include, among others, employment, labor/management relations, occupational health and safety, training and education, diversity, equal opportunity, and non-discrimination. An alternative framework to measure, and in this case also to certify the social performance of companies is recommended by the NGO Social Accountability International (SAI, 2014). The SA8000® standard assesses social performance according to eight areas concerned with internal work practices of the organizations: (1) child labour, (2) forced or compulsory labour, (3) health and safety, (4) freedom of association and right to collective bargaining, (5) discrimination, (6) disciplinary practices, (7) working hours, and (8) remuneration.

Among the social indicators proposed by these international bodies, variations over job creation metrics are the expression of social impact most frequently engaged in the reviewed multi-objective models. The majority of articles include indicators accounting for the number of work positions generated by the supply chain. In fact, some models rely exclusively on those indicators to evaluate the social sustainability dimension, while others use them jointly with supplemental social metrics.

The first case includes works such as Cambero and Sowlati (2016), Eskandari-Khanghahi et al. (2018), or Mota et al. (2018).

In Cambero and Sowlati (2016) the creation of new work positions in less developed regions, and for specific sets of job skills is addressed in the implementation and operation of a forest-based biorefinery supply chain. Eskandari-Khanghahi et al. (2018) integrate the disaster relief literature by designing a blood platelet bank supply chain comprising blood collection facilities, distribution centers, and hospitals. The authors, similar to Yue et al. (2014) regarding the design and operation of cellulosic bioelectricity supply chains, distinguish between fixed and variable jobs as the only social factor, with the last of which depending on the size of the facilities or production yield. Mota et al. (2018) present a social indicator that also only takes into account the number of jobs created. In this work, applied to the network design of an electronic components closed-loop supply chain, the social impact is evaluated on the basis of an indicator favouring facility location in regions with a lower Gross domestic product (GDP). Distinct work force requirements depending upon the selected technology and transport mode are additionally taken into account in the social objective function of the proposed MILP model. Another version of inclusion of the social factor as a synonym of the number of accrued jobs is found in Miret et al. (2016). Akin to You et al. (2012), described in the previous section, the authors formulate the social effects derived from the number of direct (at biomass plants), indirect (at subcontractors), and induced (at local economy) new jobs. Allaoui et al. (2018) consider both the number of jobs created and suppressed by the opening or closing of facilities in an agro-food supply chain.

Safety in the work place, usually measured by the number of work days missed due to health and safety issues is also frequently used as an expression of social sustainability. In several cases, this indicator accompanies the number of jobs created metric, and is especially suited for supply chains whose economic activity is more prone to work-related accidents.

Such is the case of the reverse logistics network design problem formulated by Rahimi and Ghezavati (2018) for a recycling construction and demolition waste supply chain. Besides maximizing the number of fixed and variable jobs positions brought about by the supply chain, the social objective function minimizes the number of lost work days due to damages inflicted by establishing or operating recycling centers, which depend on the particular site, technology involved and period of time. An identical approach is followed, among others, by Govindan et al. (2016) for a medical syringe recycling system, and by Rezaei and Kheirkhah (2018) concerning the design of a closed-loop supply chain network with cross-docking operations. While disregarding the job creation impact, Chen and Andresen (2014) include workers' safety considering distinct incidence rates of the various degrees of injuries and illnesses severity caused by working conditions. As in the previous examples, this factor is translated into the number of missed working days.

Another typical social indicator present in reverse, or closed-loop supply chains, concerns the impact of hazardous products on the health of consumers. Social commitment toward the community by minimizing the number of potentially hazardous products for consumers from technology and production materials used is considered in Tsao et al. (2018). Similarly, Zhu and Hu (2017) invoking the GRI guidelines, propose a social objective function for network design decisions involving facility location, technology selection, production and demand allocation, that includes four factors. Employment is accounted for observing the different regional unemployment rates registered in the potential sites for facility location. Local development corresponds to the total economic value of products manufactured weighted by the local development rate. Safety in the work place is conveyed by the number of lost working days. Finally, customer risk is measured by the average percentage of risky products due to technology selection and production decisions. The social score of the solutions obtained is normalized by the difference between the largest and smallest possible values of each social criterion, and weighted following an AHP analysis to determine the relative importance of each factor.

Acknowledgment of the social impact of supply chains on local development independently, or, as appraised by Zhu and Hu (2017), in addition to the number of jobs created, is also frequently recognized in the literature. Ghaderi et al. (2018), Daghigh et al. (2016), and Shokouhyar and Aalirezaei (2017), among others, predicate regional benefits from the deployment of local supply chain facilities. In Ghaderi et al. (2018) benefits are determined upon assigning a particular economic value to each type of facility in the switchgrass-based bioethanol supply chain. The same approach is followed by Daghigh et al. (2016) regarding cross-docking and distribution centre facilities of the proposed location-inventory model for third-party logistics providers. Appealing, in both cases, to the regional development level of the various supply chain locations, the valuation of facilities is instrumental in assessing the social objective of balanced economic development. Shokouhyar and Aalirezaei (2017) incorporate an identical local development social objective in the design of a recovery network for waste from electrical and electronic equipment, applying an AHP approach to social criteria that also includes employment and damages to workers.

Daghigh et al. (2016) further assess the social factor according to an equity measure that is not often observed in the reviewed literature. Equitable access aims to increase fair distribution of products by minimizing the maximum shortage for each product in each period and customer region. Along with the above mentioned balanced economic development, as well as job creation goals, the equitable access criterion is considered within a single normalized social objective function.

Other less frequently engaged social metrics include benefits relating to the decrease in distance travelled by workers from their homes to the workplace, and increase of job stability as given by the difference between the total number of hires and lay-offs in a lumber supply chain where transfers of workers between production sites are possible (Boukherroub et al., 2015). On-job training hours, community service hours, and in-kind donations to non-profit organizations (Darbari et al., 2017), reduction of overtime hours required from the workers (Hahn and Brandenburg, 2018), job enrichment and job security as criteria in an AHP assessment (Inghels et al., 2016) are other examples of occasionally applied expressions of the social sustainability dimension.

By establishing an evaluation, and pairwise comparison or ranking of alternative decision scenarios based on the social criteria considered, the AHP does not demand quantification of the individual social goals as model parameters. Accordingly, it agrees to consider harder to quantify social criteria in the decision process while avoiding its direct inclusion in the optimization models. This approach is followed for instance by Allaoui et al. (2018), ranking and maximizing supplier performance based on criteria pertaining to worker satisfaction, although, as mentioned earlier, in the multi-objective optimization model only the number of jobs factor is directly included as a parameter. Weighted supplier social scores are also maximized in multi-objective models proposed by Varsei and Polyakovskiy (2017) for the wine industry, or Fahimnia and Jabbarzadeh (2016) for a global sportswear clothing supply chain. Although the former work only includes the regional unemployment rate and GDP, the latter extends the social assessment of suppliers to such generic topics as "labor practices and decent work (including fair wages, working condition, occupational health and safety, and training and education), human rights (including child labor, forced labor, and discrimination incidents), society (including local community investment and public policy involvement), and product responsibility (including product labeling and customer privacy)".

Nearly all reviewed sources include the social factor in the proposed optimization models as an objective function to be maximized, together with individual economic and environmental minimization goals. Deviations from this approach are followed, for example, by Niakan et al. (2016), Pishvaee et al. (2012), or Ransikarbum and Mason (2016) that do not establish a distinct environmental factor among the optimization objectives. However, while Pishvaee et al. (2012) address both social (creation of jobs, lost working days, and quantity of potentially hazardous products), and environmental (waste produced) objectives in a single objective function, Niakan et al. (2016) focus exclusively on the economic and social dimensions of sustainability, considering, with regard to the latter, the maximization of job opportunities and the minimization of potential machine hazards. Affiliated with the disaster relief literature, Ransikarbum and Mason (2016) design a humanitarian logistics supply chain for the response and recovery phases in post-disaster operations excluding the environmental impact of decisions. Barring the minimization of economic costs required to restore disrupted facilities, attention is fully directed toward minimizing the unsatisfied relief demand, both in absolute terms, as well as equitably among all affected areas (fairness). A similar approach is endorsed by Cao et al. (2018) for a relief distribution network providing assistance in post large-scale natural disasters. In this case, only the social dimension is regarded in the two objective functions of the proposed mixed-integer nonlinear programming model. Adopting the disaster victims' perspective, the sole optimization criteria are the maximization of the lowest level of the victims's perceived satisfaction with the assistance provided, and the minimization of the largest deviation of perceived aid satisfaction among victims located at all demand points, during all relief phases.

As for the solving methodologies involved in the decision-making problems that account for the social factor, authors frequently resort to heuristic techniques to obtain solutions. Largely due to the difficulties in solving the complex models that incorporate multiple sustainability objectives, namely pertaining to the social factor, a considerable research effort has been made to develop efficient heuristics or meta-heuristics.

Particle swarm (Govindan et al., 2016), simulated annealing (Eskandari-Khanghahi et al., 2018), or evolutionary algorithms (Rezaei and Kheirkhah, 2018) find diverse applications in the reviewed literature. Among the latter, genetic algorithms, and in particular the Pareto-based Non-dominated Sorting Genetic Algorithm II (NSGA-II) introduced by Deb et al. (2002) (Niakan et al., 2016; Kumar et al., 2017), have been widely applied in the literature, with reports of benefits over other heuristic methodologies concerning the quality of solutions obtained, and the computational effort demanded.

Elsewhere, Devika et al. (2014) compare the performance of several meta-heuristics hybridization techniques based on imperialist competitive algorithms and variable neighborhood search to solve a multi-objective problem in which the social factor is expressed by the fixed and variable number of jobs created, as well as by a workers' damages metric.

Solving approaches that involve exact methods vary from elaborate techniques like the Benders decomposition method (Pishvaee et al., 2014) to more straightforward approaches such as the weighted sum of the objectives. Although traditionally the weighted sum method is cited, along with the ε-constraint method, as the most widely used solving approach to multi-objective problems, it is present in only two of the articles reviewed (Hahn and Brandenburg, 2018; Chen and Andresen, 2014), likely due to its shortfalls regarding, in particular, multi-objective MILP problems (Mavrotas, 2009). Also among the more undemanding approaches, Mota et al. (2018) solve three separate single objective problems, one for each optimization objective established, and two additional problems in which the job creation social objective is maximized subject to minimum given economic thresholds.

Whether based on its classic formulation (Arampantzi and Minis, 2017), on own versions of the method (for example in Allaoui et al. (2018), incorporating a reduced version of the lexicographic method), or yet more frequently on the augmented versions proposed by Mavrotas (2009) (AUGMECON), and Mavrotas and Florios (2013) (AUGMECON2), the ε-constraint method is the preferred solving option of several reviewed sources. Among others, Cambero and Sowlati (2016) and Rahimi and Ghezavati (2018) employ the AUGMECON version, which relies on the lexicographic method to define the range of values relevant for each objective affected by the ε scalar. The method is accelerated by avoiding redundant iterations (early exit from loops upon finding infeasible solutions) and the generation of weakly Pareto optimal solutions. Anvari and Turkay (2017) opt for the AUGMECON2 version that further improves the computational efficiency of the ε-constraint based method through a tuning parameter procedure that uses information collected from the slack variables in every iteration.

Finally, weighted or sequential goal programming are other regularly engaged methods found in the reviewed literature (Boukherroub et al., 2015; Ransikarbum and Mason, 2016), including in integrated approaches featuring stochastic fuzzy programming (Fahimnia and Jabbarzadeh, 2016), in order to address the supply chain ability to tolerate disruptions or unexpected risks. Indeed, supply chain resilience in the presence of uncertainty is often appraised in the reviewed material, involving the use of non-deterministic methods, mainly fuzzy or robust possibilistic programming (Eskandari-Khanghahi et al., 2018; Ghaderi et al., 2018; Pishvaee et al., 2012).

Regarding the distribution of the studies reviewed according to the industry of application, clearly the energy supply chain attracts considerably more research attention than any other industry. The textile and apparel supply chain, namely in the context of global supply chains for which the social performance of suppliers is frequently a major concern, and humanitarian supply chains for disaster relief are among the topics covered by multiple articles. Such is also the case of the agro-food industry. However, the food bank supply chain, at the intersection of the food and the humanitarian supply chains is not to be found in any of the sources comprised in this literature review. Hence, as the topic is particularly relevant to the present study, the following section presents a review on the available food bank supply chain literature.

3.4 Food bank literature

Food bank supply chain research occupies a very particular position within the supply chain literature. It can rightfully be considered part of the humanitarian logistics research stream. Yet, humanitarian logistics, recently reviewed by Behl and Dutta (2018), is frequently associated with disaster situations. The VUCA environments - Volatile, Uncertain, Complex, Ambiguous - where several humanitarian organizations operate (Besiou et al., 2018), and that engage most of the research in this area, do not fully correspond to the food bank supply chain context. It can also be included within the food supply chain literature. However, one of the distinctive features of the food supply chain - product perishability - is especially meaningful in operational decision problems, for which time is a critical factor. If the food bank supply chain problem concerns mostly long, or medium term decisions, then it can equally relate to supply chains of other industries. Nevertheless, as non-profit organizations, food banks operate under different principles from most commercial organizations. Even though, as discussed in Chapter 2, the research devoted to for-profit supply chains increasingly adopts a triple bottom line sustainability outlook, it can reasonably be accepted that environmental and social issues are more influential to the activity of food banks than to the generality of commercial supply chains.

Given the particularities of the food bank supply chain, it is not surprising that the volume of published research on the subject is manifestly scarce. As mentioned at the end of the previous section, the literature review devoted to the social factor presented earlier does not include any article concerned with the food bank supply chain.

Among the available works pertaining to the food bank supply chain, Davis et al. (2014), Solak et al. (2014), and Reihaneh and Ghoniem (2018) address similar location-assignment-scheduling problems. Davis et al. (2014) consider the distribution of food supplies to remotely located charitable agencies, or to agencies scantly equipped with appropriate transport resources. They formulate the collection of single product donations by a single food bank, and their delivery to the beneficiary agencies at specific network points observing maximum lead times. Following a two-phase solution approach, firstly the assignment of agencies to active food delivery sites is decided on the basis of the capacitated set covering problem, where the single objective is to minimize the number of active delivery points. Afterwards, the weekly transport schedule for food collection and distribution by the food bank vehicles that minimizes total distance travelled is determined by employing a periodic vehicle routing problem with backhauls.

Solak et al. (2014) and Reihaneh and Ghoniem (2018) are concerned with identical decisions regarding the location of delivery sites, assignment of charities, and schedule routes for the delivery vehicles from a single food bank supplying a single food product. In these cases, the authors consider, further to the travel cost of the food bank vehicles, the travel cost incurred by the agencies to collect food donation from the delivery sites. The two economic criteria are weighted in a single objective function of a 0-1 mixed integer programme in Solak et al. (2014), and of a vehicle routing problem with demand allocation in Reihaneh and Ghoniem (2018). As solving methods, Solak et al. (2014) propose two integrated Benders decomposition approaches, one is a linear programming relaxation-based algorithm, and the other a logic-based cuts heuristic. Reihaneh and Ghoniem (2018) opt for an iterative multi-start heuristic embedded with local neighbourhood search and solution perturbation schemes.

These three cases correspond to food rescue and delivery operations that distribute product donations to the beneficiary charities at network points external to the (single) food bank facility.

The importance that delivery scheduling and routing decisions have in such operations is reflected by the number of articles that include or, as the following, are exclusively concerned with product distribution by food bank supply chains. Nair et al. (2018) develop a tabu search heuristic to minimize the total transport cost of a periodic unpaired pickup and delivery vehicle routing problem for two types of food items (perishable and long life products) over multiple time periods (days). Orgut et al. (2017) and Orgut et al. (2018) address uncertainty regarding the capacity of charities to received food donations, whose quantities are assumed to be known in advance. The single-period, single-product stochastic models aim to distribute the available food items equitably among the beneficiary institutions. The two-stage stochastic model presented in Orgut et al. (2017) maximizes the value of distributed food items, differentiating between the value of first stage shipments (higher), and second stage shipments (lower) that are determined once the capacity of local charities is known. In Orgut et al. (2018) robust optimization is used to solve an identical problem.

Schneider and Nurre (2018) focus on a singular task performed by food banks that is unrelated to food collection or distribution. The authors formulate a multi-criteria capacitated vehicle routing problem with multiple time windows for auditing on-site regulatory compliance at the beneficiary agencies. The simultaneous minimization of number and length of routes, and maximization of audit scheduled time is solved by a tailored constructive heuristic. The efficiency of food bank operations is also targeted in Mohan et al. (2013). Appealing to a simulation model, the authors redesign the layout and operational procedures of a food reclamation center, where food donations are received, processed and stored, in order to increase its throughput. A DEA assessment of the efficiency of European food banks on the basis of, on the one hand (input), the food bank age, number of volunteers and staff members, and on the other hand (output), the amount of food items distributed and number of people assisted, is presented in González-Torre et al. (2017). Finally, Brock III and Davis (2015) compare four methods to forecast the quantity of food available for donation at supermarkets, and Giuseppe et al. (2014) determine the optimal donation timing for simultaneously maximizing the profit of the retailer, through cost savings and tax benefits, and the "profit" of the food bank, from the received donations.

Particularly relevant to this study, Martins et al. (2011) model the food distribution problem for the case of the FPBA. The decision problem, concerning a single food bank, and a single time period, considers two kinds of products, dry and fresh. It accounts for the respective demand volume of each served charity, the type of service they provide (meals - breakfast, lunch, snacks, and/or dinner -, and/or delivery of uncooked food supplies), and the demographic profile of the population assisted (children, adults and elderly people). The distribution of food items incorporates equity criteria in the satisfaction of the nutritional needs of the end beneficiaries, which is the (maximization) objective established. The problem is solved in two stages, first for dry products (monthly) distribution, and then for the (weekly) supply of fresh products that supplement the nutritional needs already met by the dry products. The corresponding linear programming models are solved using a rounding heuristic designed to convert continuous into integer solutions.

As mentioned initially, the available literature on food bank supply chain is rather limited (note that only articles published in peer-reviewed publications have been considered in this survey). Regardless, this small body of literature covers a wide spectrum of topics relevant to the operation of food banks. Quite meaningful is the fact that all these articles are applied in solving real-life situations, mostly located in Europe and North America.

The overall vitality of sustainable supply chain literature (see Chapter 2), combined with an increasing interest in humanitarian and non-governmental operations (see Chapter 1), suggest that the food bank supply chain is an emerging topic warranting further research. In this regard, it should be noted that the triple bottom line sustainability perspective is not adopted by any of the identified food bank supply chain articles reviewed in this section. In particular, the environmental objective, which, as will be discussed in the following chapter, is a major driver of food bank activities, is notably absent from the majority of articles reviewed. Furthermore, the few available studies generally focus on the operations of a single food bank, managing one food product in a single time period.

Summary Chapter 3

After recalling the literature reviews presented in the previous chapter devoted to supply chain network design from a triple bottom line perspective, this chapter reported a systematic literature review of 51 articles featuring the social dimension of sustainability.

The review was designed to identify the key social metrics involved in supply chain network models with multiple objectives, and respective solving approaches.

The majority of articles, all published from 2012 on, include metrics expressing social impacts mainly at the level of the focal firm. At the core of the supply chain, the focal firm offers immediate assessment opportunities regarding, in particular, the number of jobs created, and safety in the workplace. The former is acknowledged by a variety of indicators, from fixed to variable job positions, directly or indirectly created, or dependent upon selected technology and transport modes, among others, whereas the latter is usually translated into the number of missed working days due to job related injuries or illnesses.

Often these metrics are extended to other supply chain participants, namely suppliers. Assessment of the social performance of suppliers is mostly engaged for the purpose of ranking and selection. These processes involve analytic methodologies enabling the inclusion of such social factors as workplace conditions, discrimination and training corporate policies, product responsibility, and human rights practices.

Beyond the focal firm and other supply chain elements, social metrics concern impacts on consumers, and on the hosting communities. Consumers are frequently considered with regard to potential health issues resulting from the commercialization of hazardous products. Moreover, equitable product distribution, in commercial supply chains, or fair provision of assistance, in humanitarian supply chains, are equally among the social measures relating to downstream stakeholders. Finally, the overall social impact of supply chains on the communities is present in a number of sources reviewed, with indicators such as regional unemployment or GDP rates being included in location decisions for balanced development objectives.

Given the complexity and largeness of the multi-objective optimization models that account for the social factor, usually in addition to distinct economic and environmental objectives, solving methods regularly apply heuristic and meta-heuristic techniques. Prominent among the most efficient and effective heuristic methodologies is the genetic algorithm NSGA-II. When opting for exact techniques, the ε-constraint method, increasingly in the AUGMECON or AUGMECON2 versions including lexicographic ordering and acceleration procedures, is the

most commonly used technique.
As the survey on the social factor did not comprise articles dealing with the food bank supply, a complementary review focused on food bank literature was performed and reported in this chapter.
The limited number of available articles devoted to the food bank supply chain concerns essentially operational problems, in particular the distribution of items from a central warehouse to charities that provide direct assistance to the population in need of food aid. Decisions regarding the location of supply points, and assignment of charities to those points are usually part of single product, and single period models. All studies reviewed are applied to real-life situations. Significantly, and possibly due to the intrinsic social nature of the activity performed by the food bank supply chain, an explicit triple bottom line sustainability outlook is not featured in any of these studies.

Keywords: Systematic literature review; Social factor; Multi-objective network model; Solving approaches; Food bank literature

Chapter 4

Decision problem

The content of this chapter is partially included in Martins et al. (2019).

The concept of food banks originated in the USA in the late 1960s. Recognized as the world's first food bank, the St. Mary's Food Bank is located in Phoenix, Arizona, and was founded in 1967 by John van Hengel, who is credited as being the "father of food banking". Moved by the realization that severe hunger was affecting a large part of the population, while grocery stores were forced to dispose of food items with damaged packing, or nearing expiration, van Hengel envisioned the food bank as a nonprofit hub "where individuals and companies with excess food could "deposit it", and those in need could "withdraw" it" (St. Mary's, 2018). The concept soon spread across North America, in particular during the early 1980s recession when the highest growth in the number of food banks was registered. Afterwards, it reached Europe in 1984 where it was first introduced in Paris, France (FEBA, 2018).

Acknowledging the benefits of coordination among the European food banks, the European Federation of Food Banks (FEBA) was established in late 1986. Currently FEBA represents an extensive network of food banks, distributing 756,000 tons of products to 8.1 million people through collaboration with 44,700 charitable organizations, including 297,000 tons of edible products saved from going to waste (FEBA, 2018). Portugal is one of the 24 member countries represented at FEBA, having joined in 1994, two years after the launch of the first Portuguese food bank located in Lisbon. In 1995 the Oporto food bank began operations, and later in 1997 four more were set-up: Évora, Coimbra, Aveiro, and Setúbal. In the following year, the first food bank located outside mainland Portugal was created in São Miguel, Azores. Since then, the national network of food banks has grown to the current number of 21 food banks, 18 of which are located in mainland Portugal.

The Portuguese Federation of Food Banks was founded in 1999 to promote the coordination of the national food banks (FPBA, 2018). Similar to other food bank associations, its mission is to combat food waste by recovering surplus and about-to-waste food items for human consumption. Free-of-charge distribution of edible products to the disadvantaged population simultaneously addresses relevant social and environmental challenges.

This chapter is devoted to the presentation of the decision problem. Section 4.1 presents the main facts and figures that characterize the FPBA, its operation, and results. In Section 4.2 the assumptions made with a view to the mathematical modeling of the problem are described. Finally, the decision problem is formally introduced in Section 4.3.

4.1 Food bank supply chain

Food banks are nonprofit organizations that act to obtain edible food products from donor entities, either private or public, collective or individual, process the food items at warehouses, and distribute them to the population in need of food assistance. Mainly, food banks can operate according to the "warehouse model", or to the "frontline model". In the first case, distribution of food donations to the beneficiaries is made indirectly via charitable or other third sector institutions. These entities are supplied by the food banks and, in turn, deliver the donations to the people benefiting from food aid. Donations are delivered according to the type of service provided by charities. This can consist of the preparation of meals with donated products, the redistribution of those products, or a mix of both. In the "frontline model", besides acting as intermediaries between the donors and the beneficiaries, food banks also play the role of frontline agencies, serving the population directly.

The 21 food banks represented by the FPBA operate according to the "warehouse model". From their locations across the country they secure products from donors, ensure their transport to the warehouses where they are inspected, sorted, stored, or disposed of if they are not deemed fit for human consumption. The food banks are then used as distribution depots, from where charities collect donations on predetermined time slots. Typically, each served charity receives a basket of dry products once a month, and baskets of fresh and frozen products weekly. Distribution of products by charities takes into account the available quantity of products, and the profile of the agency in terms of the service provided and demographic characteristics of the population it serves. The role of the FPBA is essentially the coordination and institutional representation of the individual food banks. Each of the 21 facilities is managed locally and, to a considerable extent, autonomously from the others.

In 1992, the year that marked the launch of the first food bank in Portugal, about 260 tonnes of food products were delivered to 45 frontline agencies that supported a total of approximately 15,000 people in the Lisbon area. The following years witnessed the installation of another 17 food banks in mainland Portugal, and three in the islands of Azores and Madeira. Figure 4.1 shows the location of the 18 food banks that cover the mainland territory (source: FPBA).

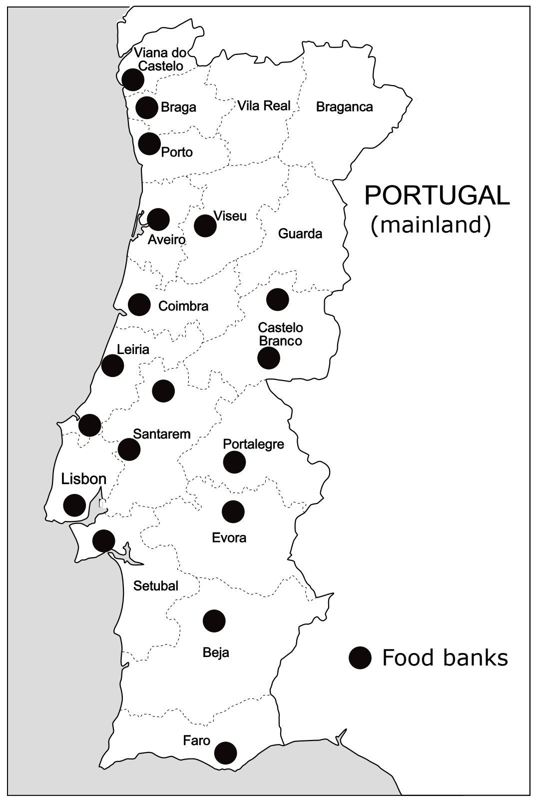


Figure 4.1: FPBA network

Expansion of the network of food banks halted in 2014 with the opening of the Castelo Branco facility. Since then the network has not registered location changes, and as depicted in Figure 4.1 displays a relatively uneven distribution across the 18 administrative districts of mainland Portugal. Population density is not the same in all districts, nor are the needs for food aid, and the location of the food banks reflects those differences. However, while the districts of Leiria, Castelo Branco, and Santarém benefit from the presence of two food banks each, Vila Real, Bragança, and Guarda districts do not host any FPBA facility. Consequently, the population in need of food aid in the latter districts either are not supplied by the FPBA network, or charities must travel longer distances to collect products from the nearest food bank.

The evolution of the total number of operating food banks, and respective quantity of products redistributed since 2000 is presented in Figure 4.2 (source: FPBA). The largest quantity of products managed by the supply chain occurred in 2011 at a total of 29,119 tonnes. Since then the total volume has fluctuated around 25,000 tonnes per year. It is estimated that 30 to 40 million euros worth of food products are managed by the FPBA supply chain each year.

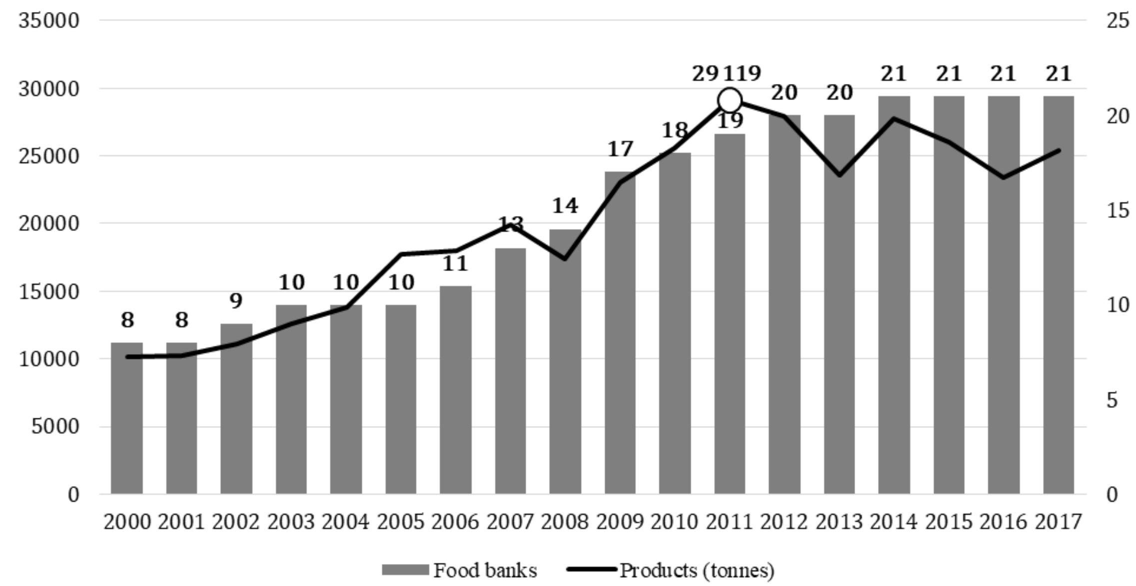


Figure 4.2: Evolution of number of food banks and product donations in the FPBA (2000-2017)

The 21 food banks coordinated by the FPBA contribute very differently to the total volume. The Lisbon facility is the largest national food bank, responsible for around 30% of the total volume of products processed by the supply chain. Together with the Oporto and Setúbal food banks, it concentrates about two thirds of the national quantity.

By contrast, there are a number of very small food banks that typically account for less than 1% of the total volume each. This is the case of food banks located in the interior regions of the country, like Cova da Beira and Castelo Branco, both in Castelo Branco district. Usually, the contribution of each of the other inland food banks, located in Portalegre, Évora, and Beja does not reach 2% of the total quantity.

Facilities also diverge considerably in terms of their human and material resources. In 2015, the FPBA mobilized more than 500 volunteers working part time as the majority of the institution work force. The other 40% of the human resources involved in the operations include employees of the food banks, and workers under social contract. Approximately one third of all human resources of the FPBA are assigned to the Lisbon food bank. Smaller food banks work with considerably less human resources. Often they rely solely on the volunteer work of a group of 10 to 20 people working part time throughout the year.

An identical unbalance characterizes the material resources available at the food banks. In total, the FPBA network has over 18,000 m^2 of storage area, cold chambers with around 2,500 m^3 capacity, and close to 2,000 m^2 of office space. In the warehouses, cargo handling equipment comprises around 130 pallet jacks, and 30 forklifts. Larger facilities like the food banks of Lisbon and Oporto perform logistics operations in fully equipped warehouses with multiple docking stations, and dedicated areas for the storage of dry, fresh, and frozen products. This profile differs considerably from the storage resources available in most of the other (smaller) food banks. Although all food banks are able to store dry products, only some can keep fresh or frozen products. Overall, storage areas are mainly determined by permanent or temporary donation opportunities, including rentals at preferential rates, and can be inappropriate for the volume of food products processed by the facilities.

FPBA policy with regard to the transport of goods is to promote the delivery of product supplies at the food banks' warehouses by the respective donors. However, this only covers around 20% of the total volume of products handled. More than 60% of the transport needs is ensured through a long-term partnership with a road freight operator that donates the transport service of goods at the request of the food banks. For the remaining movement of goods from donors, and for the exchanges between food banks, a fleet of about 40 self-owned vehicles is available in the network, including for controlled-atmosphere transport. Whenever necessary, food banks also resort to vehicle rentals at discounted rates.

Product exchange between food banks occurs but it is not expressive. Mostly, items are dispatched from the food banks that are able to attract bulkier donations from big businesses, industries and institutional partners to the smaller food banks.

Traditionally, the agro-food industry is the single main source of donations. It is also the most stable. Annually, this source contributes with about one third of the total volume of products managed by the food bank network. It includes both large and small farmers and food manufacturers, donating from their premises or from central wholesale markets. Grocery chains donate from the various stores throughout the country, accounting for around 5% of the yearly volume. Besides donating food items, these sources often deliver them to the food banks warehouses, in which case deliveries may be integrated in their commercial distribution routes, or made exclusively for that purpose.

Institutional sources are key strategic suppliers of FPBA but their individual contributions vary depending on the applicable official guidelines. In the last five years, the two chief institutional suppliers were the EU Fund for European Aid to the Most Deprived (FEAD), via the national Social Security Administration, and the Portuguese financing body for agriculture and fisheries (IFAP - “Instituto de Financiamento da Agricultura e Pescas”). Both distribute complimentary surplus agricultural products like fruit and milk. The volume of products donated by these suppliers typically reaches 40% of the total volume, but individual contributions have changed considerably over the last few years. The EU source used to be the main institutional supplier, with over 30% of the total quantity, but positions have reversed and in the most recent years the national source has become the principal institutional donor. Uncertainty regarding the expected donation volume is therefore a feature characteristic of the activity of the FPBA.

Product collection campaigns play a strategic role in the FPBA activity. Taking place twice a year, they are mobilizing and involving events that promote public perception about the mission, values, and activity of the FPBA. Besides engaging more than 40,000 volunteers in the collection of private donations at supermarkets spread across the country, these campaigns regularly raise around 20% of the total quantity of products. Campaign donations comprise exclusively dry products that are stored for future distribution to charities. Additionally, FPBA maintains ongoing product-voucher and fund-raising campaigns throughout the year.

Financial donations by private citizens, companies or public institutions can be made to selected food banks, or to be managed at the FPBA discretion. These donations are mostly used to purchase food items, often at discounted prices, that can supplement in-kind donations. Lastly, other revenue streams include traffic tickets, whose payment can be replaced by an equal amount donation to the FPBA, or the selling of paper, cardboard, and carton packages gathered by the charities and delivered to the food banks at the moment of collection of food baskets.

The exact number of annual donors shows considerable volatility and unpredictability, and is heavily influenced by the socio-economic context. The supplier portfolio includes a set of public and private entities that are regular suppliers, alongside a number of mainly private smaller donors that do not repeat donations every year. Although it is difficult to be precise, estimations suggest that around 2,000 product donors supply the network of food banks yearly. Concurrently, about 400,000 people benefit from the donations. The number of directly supported charities, and indirectly assisted people, has increased consistently until 2015. Figure 4.3 depicts this evolution in the period 2000-2017 (source: FPBA).

The steep increase registered from 2000 to 2001 is attributed to the fact that data of the first year only includes the activity of the Lisbon food bank, while in 2001 the information relating to the other seven operational food banks at that time is also accounted for. The effects of the financial

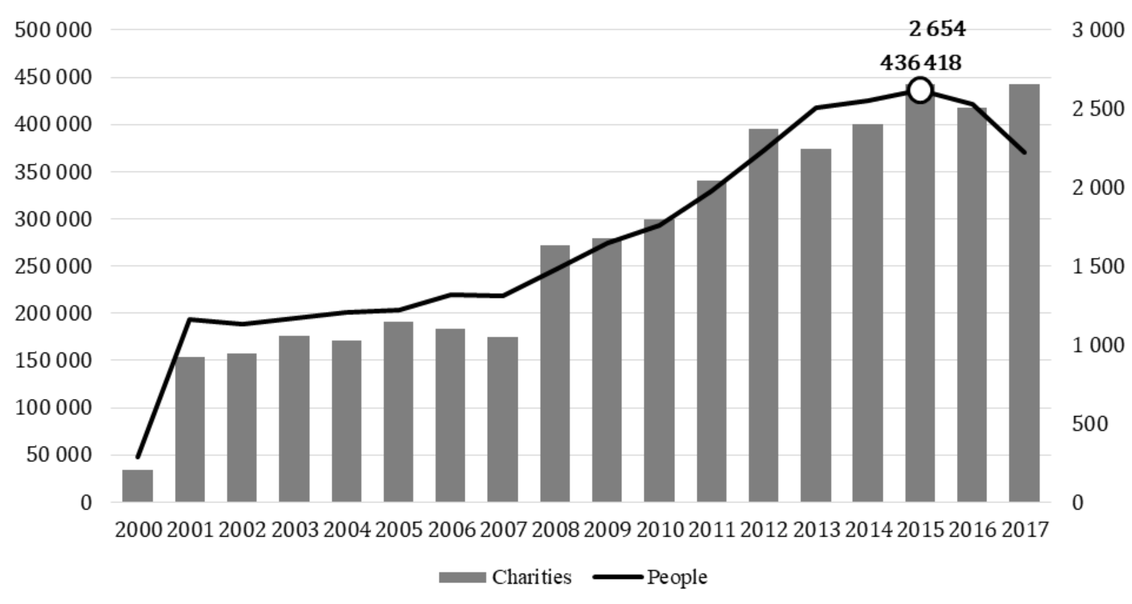


Figure 4.3: Evolution of number of charities and people assisted by the FPBA (2000-2017)

crisis of 2007-2008 on the number of supported charities and people are quite noticeable in the chart. In 2015, a peak of 2,654 frontline agencies benefited from support provided by the FPBA food banks. In turn, these charities were able to deliver food aid to 436,418 people. In 2017, following a decline initiated in the previous year, the number of assisted people has receded to the level of 2012.

The demographic profile of the population served can be quite different from charity to charity. Frontline agencies include nonprofit organizations such as hostels for the homeless, parish social centers, elderly care centers, and nursing homes. Food banks try to supply food items that best meet the particular nutritional needs of each recipient (Martins et al., 2011). In view of that, when applying for food aid from the FPBA, charities provide a full characterization of the charity, its beneficiaries, and the types of services that are provided to them. Information pertaining to the level of deprivation of the population, and of the charity, socio-economic features of its neighbourhood and proximity to other charities are also considered in the evaluation of applications for assistance.

Once charities are selected, they establish a formal protocol with the FPBA that determines the frequency of delivery of food baskets of dry, fresh, or frozen products, and the level of supply (above, below, or on average quantities) to be provided. Prior to, and during the provision of assistance, teams of FPBA volunteers pay regular observation visits to the charities. The application and selection process is conducted locally at each food bank.

With the exception of a very restricted number of charities that are certified by the FPBA to collect products directly at donors, charities pick-up donations from the food bank they are assigned to. For that, charities need to guarantee their own transport resources, and follow the designated collection calender. The FPBA distributes dry products, and fresh and frozen products on alternate week days. Charities collect dry products once a month, and fresh and frozen food weekly.

It is noticeable that the FPBA supply chain features are distinct from the typical characteristics found in most commercial supply chains. Possibly the most unique feature is related to the fact that while the latter are demand-driven, in the FPBA supply chain the quantity of products available for redistribution to beneficiaries is the major influencer of the overall level of activity. In fact, demand for food assistance is usually greater than the available donations, meaning that all products delivered to charities are consumed. Additionally, social and environmental objectives play a more prominent role in the food banks supply chain than in for-profit supply chains. The FPBA mission statement is clear in this respect, identifying the reduction of food waste, and the fight against poverty and social exclusion as its main objectives. Fairness, proximity to the disadvantage population, and social engagement values are equally integrated in the FPBA activity. But, similar to commercial organizations, food banks are also aware of the importance of economic viability for their sustainability. Effective and efficient cost management of the supply chain is recognized as a chief concern of the institution in order to sustain operations in the long-term.

The supply chain network redesign problem modeled in Chapter 5 is based upon the FPBA case described above. The model adopts a set of assumptions that are inspired by the FPBA operation. Certain features emulate the managerial approach observed in the FPBA case, while others purposely deviate from FPBA practices. These assumptions are presented in the next section.

4.2 Assumptions

Figure 4.4 represents the general structure of a three-layer food bank supply chain. Each layer represents one category of stakeholders involved in the provision of food relief. The layer on the left includes all entities that make in-kind or financial donations ("the donors" or "the suppliers"). The set of beneficiaries is depicted in the right layer ("the charities" or "the agencies"). The middle layer comprises the facilities that distribute the donations to the beneficiaries ("the food banks" or "the facilities"). The organization that manages the food banks is henceforth denoted as "the institution".

It is therefore assumed that management of the food banks is conducted centrally by a single entity. Decisions are made in view of the global results obtained by the supply chain, in which the institution plays the part of the focal firm. Moreover, the time horizon of the decisions is comprised of multiple planning periods.

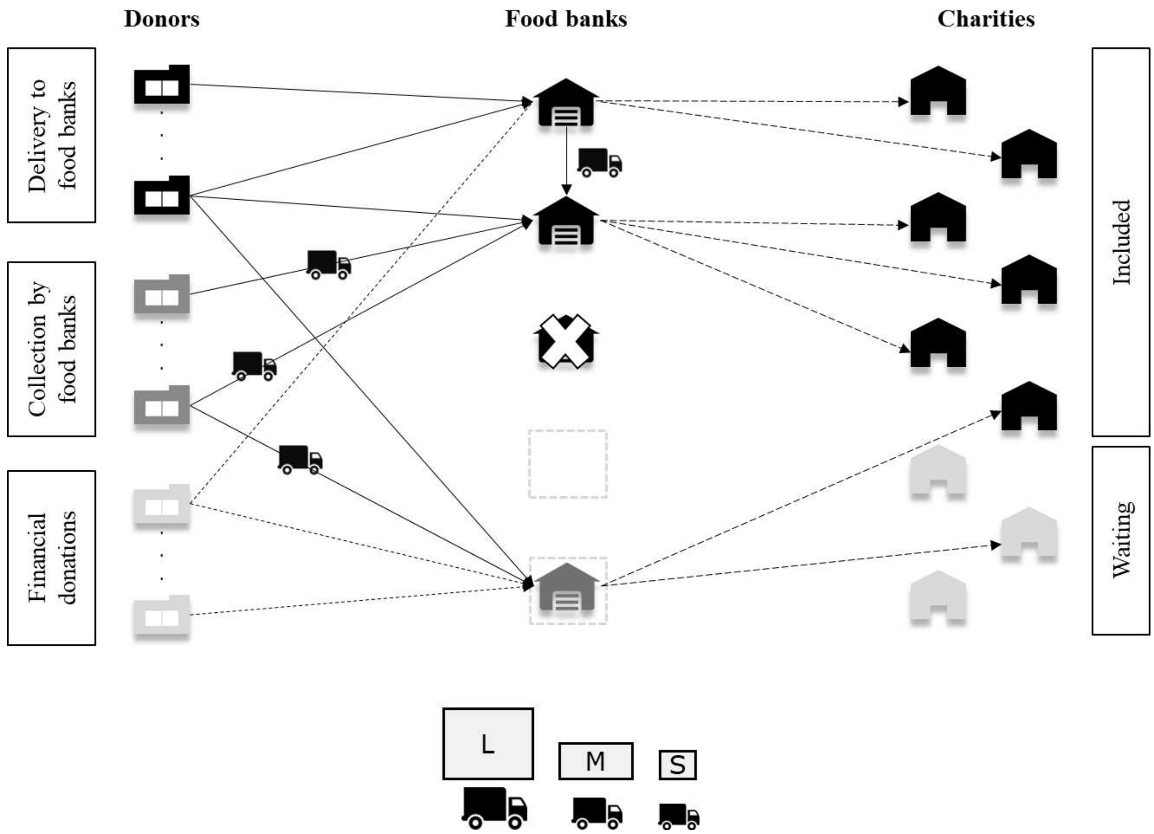


Figure 4.4: Representation of a food bank supply chain

The supply chain has a forward orientation, from suppliers to food banks, and from these to the beneficiaries. In the middle layer products can also flow vertically between food banks. All product donors supply exclusively the food banks, meaning that direct flows from donors to charities are not admissible. Multiple food products are moved through the supply chain. As in the FPBA supply chain, each product belongs to one of three families of products: dry, fresh, and frozen.

There are also three types of donors. “Delivery donors” use their own vehicles to distribute in-kind donations to food banks. Only food banks located in the proximity of the donor’s warehouse (local service area), or alongside the donor’s commercial distribution routes (national service area) are eligible for delivery by these donors. On the contrary, “collection donors” may supply any food bank on the condition that food donations are picked-up at the donor’s location. To that end, food banks must ensure the necessary transport resources.

It is assumed that the institution only receives or collects in-kind donations that are actually redistributed to the charities. This constitutes a minor divergence from the FPBA operational approach. Currently, the FPBA operates under the assumption that all products made available for donation by delivery donors are accepted by the food banks, and that all items available for collection are picked-up. In doing so, in general the FPBA does not recognize differences between the quantity of food products made available for donation and the actual volume of food donations. In fact, FPBA records pertain exclusively to the latter. Once all donated products arrive at the food banks, a selection is performed. Edible products are stocked for redistribution to charities, while non-edible items are destined for industrial transformation into bioenergy or composting, or disposed of. The model deviates slightly in this respect from the managerial approach followed at the FPBA. It is considered more meaningful for the institution to handle only food products that contribute to meet the demand requirements of the charities, and subsequently ensure that all quantities received are fully redistributed. Accordingly, a distinction is made between food items that are made available for donation by product donors, and the portion of those items that is in fact received or collected by the institution for redistribution to the frontline agencies, i.e. the actual donations. The implications are twofold. On the one hand, as not all available donations are guaranteed redistribution through the supply chain, food waste may occur at the donors' locations. On the other hand, food banks become zero waste facilities. Although this approach can impact the level of involvement of the donors with the food aid supply chain, it allows an increased level of operational efficiency at the institution, and is therefore incorporated in the model.

Also note that the model does not include product stock management between periods, i.e. all items received in a period are meant for redistribution in the same period. Moreover, due to the strategic nature of the decision problem, product perishability is not considered in the model.

The third type of donors provide monetary donations. The contribution of the "financial donors" is exclusively meant for the purchase of food products. Bearing in mind that one of the main value propositions of the institution is the reduction of food waste, it would be untenable to substitute in-kind donations by products bought with financial donations. Accordingly, financial donations are regarded as subsidiary to in-kind donations. They can be instrumental in filling specific supply gaps, but are not meant to replace product donations. Unlike product donations, financial donations not used in one period can be transferred to the next. It is assumed that all financial donations are made on behalf of the institution. In turn, the institution determines what quantities of which food products are purchased for each of the operating food banks. The corresponding decisions are signaled in Figure 4.4 by the arrows with the dotted lines from the financial donors to the food banks. This assumption also differs from the FPBA practice that permits direct donations from financial donors to chosen food banks. In fact, in some cases FPBA financial donors consign their donations to the purchase of specific food products, which is also not observed in the model.

The food bank network comprises initially operating facilities, as well as predetermined sites for possible installation of new facilities. The latter are represented by the dashed squares in the middle layer of Figure 4.4. During the planning horizon, some of the initial food banks may close, while others may be set-up in new locations. As in the FPBA supply chain, initial food banks differ in size, and in storage conditions. In particular, not all initial facilities hold storage and transport resources for all types of food products.

Investment in a food bank is made by the acquisition of storage space, and/or transport capacity (office space and cargo moving equipment are disregarded in the model). It is assumed that storage or transport capacity dedicated to either one of the three product families is available for installation in three sizes: small, medium, and large. For existing food banks, additional storage capacity for dry products, for example, can be obtained by acquiring or renting co-located warehouse areas. In the case of fresh and frozen products, chambers for positive and negative cold can be installed as needed, in the available sizes. Dedicated transport resources can also be added, choosing the adequate vehicle size or renting capacity. For new facilities, it is assumed that the various sizes of storage and transport resources are available for acquisition in the prospective sites. Acquisition costs for both types of capacity are unitary per tonne of capacity, and do not differentiate between purchase or renting. Note that capacity resources of food banks are often obtained from donations. Notwithstanding, these donations have an associated economic value that is considered indistinctly from the purchasing or renting costs, i.e. these assumptions do not differentiate capacity acquisition costs on the basis of the means by which they are obtained.

It is assumed that it is not meaningful to invest in food banks that will be later shut-down. Consequently, if an existing facility benefits from investment in one period, then it must remain operational until the end of the planning horizon. Likewise, if new facilities are deployed, then they must operate until the last planning period. In order to ensure a desired level of stability in the network configuration, there is a limited number of facilities that can open or close in any given period.

Costs of setting-up new facilities, closing existing ones, or installing new or additional capacity are supported by an investment budget. The amount spent in each period has to be raised through private or public partners by the institution. Accordingly, the investment sum needed in each period determines the institution's capital raising effort, but is not limited to a fixed amount. It is assumed that the institution is able to ensure the required capital in each period, but strives to keep investment expenses under control. In this sense, the investment budget of each period acts as the reference amount of capital that the institution expects to obtain from its partners with a reasonable effort.

This approach imposes some capital spending rules. Temporarily closing and reopening of food banks is not permitted. Also, as previously mentioned, if investment is made in a food bank, either by expanding the capacity of an already operational food bank, or by deploying a new facility, then it cannot close until the final planning period. Furthermore, storage capacity installation in any food bank can occur only once for each family of products. To that end, the storage size level appropriate for all forthcoming storage needs until the end of the planning horizon must be selected.

Transport capacity, on the other hand, can be acquired over multiple periods. Moreover, each one of the available capacity sizes can be selected once per period. Transport resources must, however, conform to the available storage capacity, i.e. food banks can only invest in transport capacity for a given product family if they hold storage capacity for that same type of products.

In addition, for the particular case of new facilities, it is required that storage capacity is installed, for at least one type of product family, from the first period in which the food bank is deployed. This imposition does not apply, however, to transport capacity, which is installed only if necessary.

Food banks, initially existing or new, are not to be used exclusively for transshipment between facilities. Consequently, any operational facility must serve at least one charity.

Each served charity receives assistance from just one food bank per planning period. Assignments of charities to food banks can change only in periods that register modifications in the supply chain configuration by the closing or the opening of facilities. As charities included in the supply chain must travel to the designated food bank to collect their donations, a maximum distance allowed between charities and the assigned food bank is established. All frontline agencies included in the supply chain prior to the redesign project are ensured food assistance throughout the planning horizon. Similarly, if a new charity starts receiving aid, then it must be served in all forthcoming periods.

It is assumed that the overall quantity of food products available for donation is insufficient to meet the total demand for food assistance. Moreover, minimum levels of assistance are guaranteed to the served charities. It follows that, as represented in Figure 4.4, it may not be possible to guarantee food aid to all charities waiting to be served by the institution. It is however ensured that the demand profile of the each charity is observed in the redistribution of donations. Namely, it is assumed that charities are not supplied more than their demand for each food product. This assumption does not entirely reflect the FPBA approach. The FPBA implicitly assumes that all products that can be supplied to charities are consumed by the beneficiary population, i.e. their demand is unlimited. While observing the demographic profile of the population assisted by the charities, as well as the type of service provided by the charities, the main driver of the FPBA activity is to gather the largest volume of edible food products, and to equitably distribute it among the largest number of beneficiaries. In order to achieve a fair supply to all served charities, the FPBA distributes the available products based upon a *pro rata* allotment process. Distinctively, the model incorporates the concept of fixed and limited demand of food products by the charities, traditionally present in supply chain models. Not only can this notion be incorporated in a food bank supply chain operational approach, it is also in keeping with the assumption that not all edible products available for donation are forcibly redistributed to charities.

The above assumptions define all supply chain features relevant for the decision problem presented in the following section.

4.3 Decision problem

Food bank supply chains are the result of the committed actions of groups of volunteers toward social and environmental causes. Prompted by the will to improve the living conditions of the disadvantaged fringe of the population, and contribute to the better use of the natural resources, these volunteers build food distribution networks featuring characteristics similar to standard commercial supply chains. More than the result of a planning exercise, food bank supply chains are usually the outcome of a series of expansion opportunities determined by the logistic resources granted by private and public entities.

However, as in any distribution network, location is a fundamental aspect of the food bank supply chain. It determines the food banks' ability to attract donations, and influences the level of service that can be provided to the target population. The Food Bank Network Redesign (FBNR) problem aims to identify changes to an existing supply chain configuration that can improve its performance with regard to predetermined objectives. In particular, and subject to the assumptions presented in the previous section, the FBNR problem comprises the following strategic decisions:

(i) which, if any, existing food banks should be closed, and in what planning period?

(ii) which, if any, new facilities should be deployed, and in what period?

(iii) what storage and transport size capacities, if any, should be installed in each facility?

Additionally, the following tactical decisions are expected:

(iv) which charities are served by the operating food banks in each period?

(v) what are the flows of products in the supply chain in each period?

Following a TBL outlook on sustainability, economic, environmental and social objectives are established. Economic objectives are defined by the minimization of the operational costs of running the network of food banks. Overhead expenses of supporting charities, variable costs depending on the installed storage capacity, and on the volume of products handled at the food banks are accounted for. Moreover, transport capacity efficiency, and proper use of financial donations are also regarded as economic criteria. Regarding the former, it is meant to avoid untimely purchases of additional transport capacity. The latter envisages restricting the use of financial donations for its purpose, i.e. to supplement, but not substitute, the redistribution of in-kind donations.

The minimization of costs deriving from food waste and from CO_2 emissions are assumed as the environmental objectives. Not all products supplied by the food banks to charities help to reduce food waste. In the FPBA case, food products bought with financial donations and items originating from public in-kind collection campaigns, although important to provide food assistance, cannot be incorporated in the environmental results. The model does not include in-kind collection campaigns as a donation source, but foresees financial donations. Accordingly, products bought with these donations are excluded from the environmental results obtained from food waste minimization.

Transport is a core element of any supply chain. The food bank supply chain involves the movement of goods from donors to food banks, between food banks, and from food banks to charities. However, it is only considered meaningful to include in the decision problem CO_2 emissions costs resulting from transport decisions under the control of the institution. These concern travels to pick-up donations from collection donors, and to exchange products between food banks. As the decision problem does not include the design of pick-up routes by the vehicles of the food banks, it is assumed that for each collection of products, be it at donors' or at other food banks facilities, vehicles travel empty on the outbound journey, and with cargo on the inbound journey.

Lastly, maximizing the social value created by the food bank supply chain is expressed through multiple criteria. The ultimate objective of reaching all the population in need of food assistance is measured by the number of new charities served by the supply chain. Fairness values are conveyed by seeking a balanced distribution of products. Promoting the proximity of charities to the assigned food banks is another social target. The work value created by the supply chain ascertains the level of social engagement achieved by the activity of the institution. Limiting the investment capital raising effort that falls upon the institution, and its partners is the last factor included as a social objective of the decision-making problem.

Reflecting a TBL approach on sustainable operations, the FBNR problem aims to redesign an existing network of food banks taking into account the three above mentioned distinct objectives. Solving the FBNR problem involves obtaining efficient solutions (in the Pareto sense) considering all the objectives established.

Following, the corresponding multi-objective MILP model is introduced in Chapter 5.

Summary Chapter 4

This chapter presented the FPBA supply chain. Established almost 30 years ago, the FPBA represents 18 food banks located in mainland Portugal, and three situated in the islands of Azores and Madeira. It is the main nonprofit organization in Portugal acting in the collection and redistribution of about-to-waste food. All but three mainland districts host one FPBA facility, and some benefit from the services of more than one food bank.

The FPBA operates under the “warehouse model”, receiving donations and redistributing them to the charities that directly serve the population in need of assistance. In 2017, the network of food banks coordinated by the FPBA supplied over 25,000 tonnes of products to more than 400,000 beneficiaries through approximately 2,700 partner charities. More than two thirds of the products delivered to the frontline agencies are donated by agro-food suppliers or institutional partners, and would otherwise be wasted. Although the last two years reveal a slight decrease in the level of activity of the FPBA, its humanitarian and environmental role is indisputable.

Based on a field work developed during several months at the FPBA and at its largest food bank located in Lisbon, a comprehensive characterization of the food bank supply chain was described in Section 4.1. The supply chain benefits from the participation of different types of donors. In-kind donors comprise farmers, food manufacturers, and grocery chains that either deliver products to the FPBA, or ask for their collection by the food banks. National and international public organizations deliver production surpluses. The general public is also a key contributor, namely during the bi-annual product collection campaigns. Supplementary to in-kind donations, food bank use financial donations to purchase unavailable food products. All products are received, sorted, selected, and stored at the food banks’ warehouses, observing their specific preservation conditions. The majority of operational activities are performed by more than 500 volunteers working part time throughout the year. Activities include also the distribution of products to charities, which occurs every week day. Baskets of dry products are supplied once a month, while fresh and frozen products are distributed weekly to the served charities. Although the FPBA is unable to supply all charities requiring food aid, it strives to achieve an equitable distribution of available products among the ones that are included in the supply chain. Charities are required to travel to the food banks’ location by their own means to pick-up the baskets of food.

Based on the characterization of the FPBA, Section 4.2 presented the assumptions made in view of the mathematical modeling of the supply chain. To a large extent, the assumptions reflect the FPBA supply chain. Notable divergences concern the supply and demand concepts. For modeling purposes, it is assumed that not all products available for donation are received by the FPBA. It is further assumed that food banks are zero waste facilities. Subsequently, all items that arrive at the facilities are redistributed to the charities. Regarding demand, it is assumed that deliveries to the frontline agencies observe their demand profile, and that supply does not exceed demand. Moreover, the total quantity of products available for donation is insufficient to meet the assistance requests of all charities, either initially served and awaiting assistance.

Finally, Section 4.3 introduced the decision problem FBNR. The network redesign problem aims to determine if, what, and when operating facilities are closed and/or opened, and decide the adequate storage and transport capacities. Furthermore, assignment of charities to food banks in each period, and flows of products from donors to food banks, between food banks, and from these to charities are also to be determined. Respecting the positioning assumed by the FPBA and other institutions operating in the food rescue area, network redesign is framed in a triple bottom line outlook. The FBNR problem is to be solved by obtaining efficient solutions (Pareto sense) that account for the three distinct objectives established. Accordingly, the multi-objective model presented in the following chapter incorporates economic, environmental, and social objectives in a mixed-integer linear programming formulation.

Keywords: FPBA supply chain; Model assumptions; Model taxonomy; Decision problem

Chapter 5

Tri-objective MILP model

The content of this chapter is partially included in Martins et al. (2019).

The decision problem presented in Chapter 4 for a supply chain of food banks, denoted Food Bank Network Redesign problem, is formulated in this chapter as a multi-objective mixed-integer linear programming model (MO-MILP). The MO-MILP model presented in this chapter formulates the supply chain of the FBNR problem as a three-layer network: the first layer includes the nodes representing the donors, the intermediary layer is comprised of nodes identifying the food banks, and nodes standing for the beneficiary agencies constitute the third layer.

Multiple products flow through this multi-echelon network in forward (from donors to food banks, and from food banks to charities) and sideways (among food banks) directions.

The strategic decisions of the problem concern (i) the opening and closing of food banks in given locations, (ii) the storage and transport capacities of each operational food bank, and (iii) the inclusion of charities in the supply chain. Additionally, (iv) all served charities must be assigned to some food bank, and (v) all flows of products through the supply chain are to be determined. As decisions concern multiple periods, consider a previously existing food bank supply chain, and facilities have capacities, the FBNR is a dynamic capacitated network redesign problem.

Decisions are taken following a triple bottom-line perspective. Therefore, the model integrates three distinct objective functions, one for each of the three sustainability pillars, i.e. economic, environmental, and social.

Section 5.1 introduces the notation used in the MO-MILP model. Decision and auxiliary variables are presented in Section 5.2. Constraints are grouped following the type of supply chain participants that they mainly pertain to, and are presented in Section 5.3. Finally, Section 5.4 introduces the three objective functions that conclude the presentation of the MO-MILP model for the FBNR problem.

5.1 Parameters

The notation used hereafter is presented and described in the following tables. Table 5.1 introduces the index sets used in the FBRN problem mathematical formulation.

Index set	Description
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
D	All donors, $D = DD \cup CD \cup FD$ (subsets are pairwise disjoint)
OB	Existing food banks at the beginning of the planning horizon
PB	Potential new food banks
B	All food banks, $B = OB \cup PB$, and $OB \cap PB = \emptyset$
B_d	Food banks that can receive food products from donor $d \in DD$, $B_d \subseteq B$
SC	Charities served by food banks at the beginning of the planning horizon
HC	Charities on hold, i.e. charities waiting to be served by the institution
C	All charities, $C = SC \cup HC$ and $SC \cap HC = \emptyset$
C_b	Charities located outside the service area of food bank $b \in B$, $C_b \subset C$
K	Families of food products
P_k	Food products belonging to family $k \in K$, $\cap_{k \in K} P_k = \emptyset$
P	All food products, $P = \cup_{k \in K} P_k$
L	Discrete capacity sizes for storage or transport resources
T	Time periods in the planning horizon

Table 5.1: Index sets

The set of donors D comprise product and financial donors. The former corresponds to donors $d \in DD$ representing the "delivery donors", and donors $d \in CD$ as the "collection donors". Donors $d \in DD \cup CD$ are characterized by the type and volume of food products $p \in P$ that they make available for donation to the food banks in each period $t \in T$, and by their location. Additionally, each donor $d \in DD$ is also characterized by (and characterizes) the subset of food banks B_d that can receive products from it. Financial donors $d \in FD$ are characterized by the amount of available financial donations, and by the fact that they are not associated with a particular location. Accordingly, product flows from these donors to the food banks are understood as virtual flows in the sense that they correspond to products purchased by the food banks with financial donations, without transport from donors involved.

Food banks are divided into initially operational banks $b \in OB$, and potential banks $b \in PB$. The main features of the initial banks are their location, and available storage and transport capacities per family of products $k \in K$ at the beginning of the planning horizon. Potential food banks are solely characterized by their location, i.e. sites identified for possible set-up of new facilities.

Charities are defined by their location and demand per type of product $p \in P$ in each period $t \in T$. Furthermore, initially served agencies $c \in SC$ are also defined by the type and volume of products received in the period prior to the beginning of the planning horizon (period 0). It is assumed that $|SC| \geq |OB|$, otherwise food banks could be operational in the beginning of the planning horizon (same as in period 0) whilst not serving any charity.

Food products moved through the supply chain $p \in P$ are aggregated into families $k \in K$ according to sets P_k. The characteristics of the product families determine which dedicated areas can be used for their storage, and what type of vehicles are fit for their transport. Storage or transport capacity can be installed in any operational facility by selecting the appropriate discrete capacity size $\ell \in L$. All decisions take effect from the beginning of planning periods $t \in T$.

Further to the index sets presented in Table 5.1, A is the set of all admissible origin-destination pairs of nodes in the network. Notice that, besides vertical connections from donors to food banks, and from food banks to charities, horizontal links between food banks are also admissible. However, there are no admissible arcs in the network representing direct connections from donors to charities. The distance between two locations is measured in distance units (d.u.).

$A = \{(d, b) : d \in DD, b \in B_d\} \cup \{(d, b) : d \in CD \cup FD, b \in B\} \cup \{(b, b') : b, b' \in B, b \neq b'\} \cup \{(b, c) : b \in B, c \in C\}$.

Financial parameters are presented in Table 5.2 on page 74. With the exception of the last four, τ_p^t, φ^t, ω^t, and ψ^t which are measured in k€, all others are expressed in monetary units (m.u.). All financial parameters have non-negative value. Tonne is the unit of measurement used for storage and transport capacities, as well as for food product quantities.

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 $t \in T$.

Parameters	Description
FI^t	Cost of opening a food bank in period $t \in T$ (in m.u.)
$VSI^t_{\ell k}$	Cost of installing one unit of storage capacity of level $\ell \in L$ for product family $k \in K$ in period $t \in T$ (in m.u.)
$VTI^t_{\ell k}$	Cost of installing one unit of transport capacity of level $\ell \in L$ for product family $k \in K$ in period $t \in T$ (in m.u.)
FU^t	Cost of closing a food bank in period $t \in T$ (in m.u.)
VU^t_k	Cost of dismantling one unit of storage capacity for product family $k \in K$ in period $t \in T$ (in m.u.)
FC^t_{bc}	Cost of serving charity $c \in C$ by food bank $b \in B$ in period $t \in T$ (in m.u.)
VS^t_{kb}	Cost of operating one unit of storage capacity for product family $k \in K$ at food bank $b \in B$ in period $t \in T$ (in m.u.)
VH^t_{kb}	Cost of handling one unit of food products of family $k \in K$ at food bank $b \in B$ in period $t \in T$ (in m.u.)
O^t	Budget of period $t \in T$ (in m.u.)
$\widetilde{Q}^t_d$	Financial donation available at donor $d \in FD$ in period $t \in T$ (in m.u.)
τ^t_p	Cost of purchasing one unit of food product $p \in P$ in period $t \in T$ (in k€)
φ^t	Cost of disposing of one unit of food product $p \in P$ in period $t \in T$ (in k€)
ω^t	Cost of CO_2 emissions generated from transporting one unit of food product in period $t \in T$ per tonne-d.u. (in k€)
ψ^t	Value of social work required to operate one unit of storage capacity in period $t \in T$ (in k€)

Table 5.2: Financial parameters

The unit costs of installing storage and transport capacity are represented by parameters $VSI^t_{\ell k}$, and $VTI^t_{\ell k}$, respectively. These parameters allow the conveyance of different unit costs according to the level of capacity $\ell \in L$, and the type of product family $k \in K$, in each period $t \in T$. Regarding levels of storage and transport capacity, higher capacity levels are expected to have smaller unitary costs than lower capacity levels, reflecting the notion of economies of scale. Unit cost differentiation based on product families enables accounting for distinct storage and transport requirements per type of family, namely in terms of the preserving temperature.

Dismantling costs (VU_k^t) depend on the existing dedicated storage areas, in terms of the product families $k \in K$, and on the period $t \in T$ in which they occur. These costs are supported only if and when an initially existing facility closes. In these situations, it is further assumed that costs related to the removal of existing transport capacity are negligible, and therefore not accounted for. Capacity downsizing of any type in operational facilities is not permitted.

The running costs of operating a food bank depend mainly upon the charities served (FC_{bc}^t), the installed storage capacity (VS_{kb}^t), and the volume of products processed (VH_{kb}^t). The first includes administrative and managerial overhead expenses for each beneficiary agency that is served in each period $t \in T$. These costs vary according to the dimension and location of the charities $c \in C$, and the profile of the food bank $b \in B$ to which they are assigned to in each period $t \in T$. Costs associated with the available storage capacity (VS_{kb}^t) reflect the expenditures incurred with the maintenance of the storage areas (e.g. operating equipment, cleaning, water and energy consumption). These unit costs depend on the existing storage capacity for each product family $k \in K$, and the location of the food bank $b \in B$, in each period $t \in T$. Including a location-dependent factor in these costs enables the inclusion of different regional cost structures in the model. As seen in Chapter 3, accounting for regional differences is a social nature feature also present in other models devoted to sustainable supply chains. The same feature is also carried in the costs that depend on the volume of products handled by the food banks (VH_{kb}^t). Unit costs of processing incoming donations, storing, and preparing food products for redistribution to charities vary according to the location of the food bank $b \in B$, and the type of product families $k \in K$ processed in each period $t \in T$.

Expenditures incurred by the institution with the set-up or shut-down of food banks, as well as spendings due to storage and transport capacity acquisition are supported by the budget of each period $t \in T$ (O^t). It corresponds to the amount of investment capital that the institution expects to raise with stakeholders - local, regional, national, and international organizations, public or private - with reasonable effort. Distinct from the investment capital amount, financial donations expressed by $\widetilde{Q}_d^t$ are meant exclusively for the purchase of food products. These donations are associated with financial donors $d \in FD$ in each period $t \in T$. Conceivably, financial donations not used by the end of the planning horizon may be allocated to other ends, in particular to support operational expenditures. However, this matter is not covered by the model, and is only briefly mentioned in the discussion of the economic objective function (see Section 5.4).

Unit costs of buying food products $p \in P$ with financial donations in each period $t \in T$ are expressed by parameters τ_p^t. According to the model assumptions presented in Section 4.2, not all food products made available by in-kind donors $DD \cup CD$ are received, or picked-up by the food banks. Products undistributed to charities are assumed to be disposed of by the respective donor in period $t \in T$ at a unit cost of φ^t. It should be noted that donors may find other uses for undistributed products, and that these uses (e.g. animal feed, industrial uses, or composting) may actually result in a revenue rather than a cost. However, this is not factored in the model, and all non-used products are considered to be destined to landfill or incineration at a cost, which is the same for all types of products $p \in P$. Parameters ω^t express the unit costs of CO_2 emissions that are generated by vehicles employed in the transport of products to the food banks. These change from period to period $t \in T$, and are expressed in tonne per distance travelled units (tonne-d.u.). Finally, parameters ψ^t identify the value of work created per unit of storage capacity available in the network of food banks in period $t \in T$. The unit value of social work corresponds to the ratio of the number of full-time workers, valued at the annual national average salary (k€), to the available storage capacity (in tonnes).

Table 5.3 presents the remaining parameters, mainly pertaining to capacity and demand. Unless noted, all capacity parameters are expressed in tonnes, and have non-negative value.

Food donations of product $p \in P$ available at in-kind donors $d \in DD \cup CD$ in each period $t \in T$ are expressed by parameters Q^t_{pd}. Parameters $\overline{M}_{kb}$ and $\overline{N}_{kb}$ indicate storage and transport capacity at the beginning of the planning horizon, respectively. In both cases, parameters are individualized per existing food bank $b \in OB$, and per product family $k \in K$. It is assumed that the existing storage capacity $\overline{M}_{kb} \geq 1$ for all $b \in OB$ that store products of family $k \in K$ (minimum one tonne of storage capacity) [1].

In planning periods $t \in T$, storage and transport capacity can be expanded in existing, or installed in new food banks. Capacities available for installation are represented by parameters $M_{\ell k}$ (storage), and $N_{\ell k}$ (transport) whose values in tonnes depend on the level of capacity $\ell \in L$, and the type of product family $k \in K$.

Regarding the distribution of products to charities, the relevant parameters are R^t_{pc} representing the demand volume during each period $t \in T$ of the planning horizon, and X^0_{pc} corresponding to the volume delivered in period 0. The former is set for all charities $c \in C$, while the latter is only material to those charities that are already included in the supply chain $c \in SC$, and therefore were served in period 0. In both cases, parameters are set per charity, and per product $p \in P$. It is assumed that, at least for one $p \in P$, $X^0_{pc} > 0$ for all $c \in SC$, and $R^t_{pc} > 0$ for all $c \in C$ in every planning period $t \in T$ [2].

Parameter μ is involved in the environmental objective function to determine the volume of CO_2 emissions generated by the food bank's transport activity. It accounts for the volume of emissions

[1] This assumption is relevant for constraints (5.11).
[2] These assumptions are relevant for Lemmas 7.1 and 7.2.

generated by the use of vehicles independently of the load carried. Recall that it assumed that vehicles travel empty on the outbound journeys. On the inbound journeys, additionally to the products transported, a portion of emission generated is attributed to the actual weight of the vehicles. Accordingly μ corresponds to the average tare weight of vehicles used in the transport of food products multiplied by the average number of round trips performed by a vehicle, in one period.

Parameters	Description
Q_{pd}^t	Quantity of food product $p \in P$ made available for donation by product donor $d \in DD \cup CD$ in $t \in T$ (in tonnes)
$\overline{M}_{kb}$	Storage capacity for product family $k \in K$ available at food bank $b \in OB$ at the beginning of the planning horizon (in tonnes)
$M_{\ell k}$	Storage capacity of size $\ell \in L$ for product family $k \in K$ that can be installed in a food bank (in tonnes)
$\overline{N}_{kb}$	Transport capacity for product family $k \in K$ available at food bank $b \in OB$ at the beginning of the planning horizon (in tonnes)
$N_{\ell k}$	Transport capacity of size $\ell \in L$ for product family $k \in K$ that can be installed in a food bank (in tonnes)
R_{pc}^t	Demand of charity $c \in C$ for food product $p \in P$ in period $t \in T$ (in tonnes)
X_{pc}^0	Quantity of food product $p \in P$ received by charity $c \in SC$ in the period previous to the first period of the planning horizon (period 0) (in tonnes)
U_{ij}	Distance between origin i and destination j for every $(i,j) \in A$ (in d.u.)
μ	Average unladen weight of transport resources in one period (in tonnes)
β_i	User-defined constants, $\beta_i \in (0,1]$, $i = 1,2,3$
α_i	Non-negative factors, $i = 1,\ldots,9$

Table 5.3: Capacity, supply, demand, and other parameters

β_1 is a user-defined parameter set to restrict the total number of food banks that can be opened or closed simultaneously in a planning period $t \in T$. It expresses the ratio of the largest number of location changes that can occur in a single period to the total number of food banks. β_2 (for $c \in SC$), and β_3 (for $c \in HC$) are parameters that pertain to the minimum levels of food supply to charities that are included in the supply chain.

In this regard, it is assumed that, in each time period $t \in T$, the demand of every initially served charity $c \in SC$ satisfies the following condition for every food product $p \in P$: $R_{pc}^t \geq \beta_2 X_{pc}^0$. This guarantees that the demand profile of each initially served charity, i.e. their demand volume for each product $p \in P$ is kept throughout the planning horizon, which is pertinent to accommodate the dietary needs of the end beneficiaries of each charity. Due to the mismatch between supply and demand, it is further assumed that demand is greater than in-kind supply for every $p \in P$ and $t \in T$: $\sum_{c \in C} R^t_{pc} > \sum_{d \in DD \cup CD} Q^t_{pd}$ [3].

Parameters α_i, for $(i = 1, \ldots, 9)$, are used in the objective functions as normalizing, weighting, and/or penalizing coefficients. Parameters α_1 and α_2 are used in the economic objective function as a penalty factor for unused resources. Parameters α_3 and α_4 weight the environmental terms considered in the respective objective function. Finally, the social objective function appeals to parameters α_i, for $i = 5, \ldots, 9$ to weight and normalize its five terms.

5.2 Variables

Table 5.4 presents the decision variables used in the MO-MILP model. Strategic decisions related to facility location (y^t_b), and capacity acquisition ($w^t_{\ell kb}$ and $v^t_{\ell kb}$) are represented by binary variables. Single-assignment decisions (z^t_{bc}) are also expressed by binary variables. The flow of food products across the network is modelled by continuous variables (x^t_{pij}). Auxiliary variables are presented in Table 5.5.

Variables	Description
y^t_b	1 if the *status* of food bank $b \in B$ changes in period $t \in T$, 0 otherwise; $y^t_b = 1$ means that a new food bank is established in site b in period t if $b \in PB$; $y^t_b = 1$ means that the initially existing food bank b is closed in period t if $b \in OB$
$w^t_{\ell kb}$	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
$v^t_{\ell kb}$	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^t_{bc}	1 if charity $c \in C$ is served by food bank $b \in B$ in period $t \in T$, 0 otherwise
x^t_{pij}	Quantity of food product $p \in P$ moved from origin i to destination j in period $t \in T$, $(i,\, j) \in A$

Table 5.4: Decision variables

[3] These assumptions are relevant for the generation of instances for the problem, namely concerning feasibility with respect to constraints (5.23) and (5.25) (see Chapter 6).

Variables	Description
ξ_d^t	Financial donation from donor $d \in FD$ not spent in period $t \in T \cup \{0\}$; $\xi_d^0 = 0$, for $d \in FD$, and $\xi_d^t \in \mathbb{R}_{\geq 0}$, for $d \in FD$, $t \in T$
θ_{kb}^t	Unused transport capacity for product family $k \in K$ in food bank $b \in B$ in period $t \in T$; $\theta_{kb}^t \in \mathbb{R}_{\geq 0}$, for $k \in K$, $b \in B$, $t \in T$
γ^t	Deviation from the reference budget O^t in period $t \in T$; $\gamma^t \in \mathbb{R}$, for $t \in T$
ε^t	Maximum distance between a charity and its assigned food bank in period $t \in T$; $\varepsilon^t \in \mathbb{R}_{\geq 0}$, for $t \in T$
δ^t	Maximum level of unsatisfied demand of charities served in period $t \in T$; $\delta^t \in \mathbb{R}_{\geq 0}$, for $t \in T$

Table 5.5: Auxiliary variables

5.3 Constraints

The constraints of the MO-MILP model are presented next, following the main supply chain stakeholders that they pertain to.

The first set concerns constrains related to the donation quantities available at product and financial suppliers. The constraints related to the institution are divided into two sets. The first of those two sets establishes the conditions for facility location, installation or expansion of capacity, and respective budget limitations. The second set of institution-related constraints pertains to the utilization of the available storage and transport capacity. The following set of constraints establishes the charities assignment and supply conditions. The last two sets refer to operating constraints, and to the domains of the decision variables.

Donors-related constraints

$$\sum_{b \in B_d} x_{pdb}^t \leq Q_{pd}^t \qquad d \in DD,\ p \in P,\ t \in T \tag{5.1}$$

$$\sum_{b \in B} x_{pdb}^t \leq Q_{pd}^t \qquad d \in CD,\ p \in P,\ t \in T \tag{5.2}$$

$$\sum_{p \in P} \sum_{b \in B} \tau_p^t x_{pdb}^t + \xi_d^t = \widetilde{Q}_d^t + \xi_d^{t-1} \qquad d \in FD,\ t \in T \tag{5.3}$$

Constraints (5.1) ensure that the total quantity of each food product supplied by a delivery donor to all food banks located within its service area does not exceed the available amount in each time period. Similarly, (5.2) guarantees that not more than the total quantity of each food product available for donation from each collection donor is picked-up by the food banks in each time period. Constraints (5.3) play a similar role with respect to financial donations for food purchase. Given the strategic, long-term nature of the model, food stocks are not allowed to transition from one period to the followings. Unlike food products, financial donations that are not spent in a given time period can be used in later periods.

Institution-related constraints (I)

$$\sum_{t \in T} y_b^t \leq 1 \qquad b \in B \tag{5.4}$$

$$\sum_{b \in B} y_b^t \leq \lceil \beta_1 \, |B| \rceil \qquad t \in T \tag{5.5}$$

$$\sum_{t \in T} \sum_{\ell \in L} w_{\ell k b}^t \leq \sum_{t \in T} y_b^t \qquad b \in PB, \; k \in K \tag{5.6}$$

$$\sum_{t \in T} \sum_{\ell \in L} w_{\ell k b}^t \leq 1 - \sum_{t \in T} y_b^t \qquad b \in OB, \; k \in K \tag{5.7}$$

$$\sum_{\ell \in L} w_{\ell k b}^t \leq \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \qquad b \in PB, \; k \in K, \; t \in T \tag{5.8}$$

$$\sum_{\ell \in L} \sum_{k \in K} w_{\ell k b}^t \geq y_b^t \qquad b \in PB, \; t \in T \tag{5.9}$$

$$\sum_{\ell \in L} v_{\ell k b}^t \leq |L| \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \qquad b \in PB, \; k \in K, \; t \in T \tag{5.10}$$

$$\sum_{\ell \in L} v_{\ell k b}^t \leq |L| \left[\overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} \right) + \sum_{\ell \in L} \sum_{\tilde{t}=1}^{t} w_{\ell k b}^{\tilde{t}} \right] \qquad b \in OB, \; k \in K, \; t \in T \tag{5.11}$$

$$\begin{aligned} &\sum_{b \in PB} FI^t \, y_b^t + \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VSI_{\ell k}^t \, M_{\ell k} \, w_{\ell k b}^t + \\ &\quad \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VTI_{\ell k}^t \, N_{\ell k} \, v_{\ell k b}^t + \\ &\quad \sum_{b \in OB} \left(FU^t + \sum_{k \in K} VU_k^t \, \overline{M}_{kb} \right) y_b^t + \gamma^t = O^t \qquad t \in T \end{aligned} \tag{5.12}$$

The first set of institution-related constraints concerns facility location and capacity acquisition issues.

Constraints (5.4) and (5.5) address exclusively facility location decisions. Constraints (5.4) enforce the *status* of a food bank to change at 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 in later periods. Inequalities (5.5) limit the total number of status changes in the network of food banks in each time period. This limit is set as a fraction of the total number of food banks, existing or potential ($\beta_1 \in (0,1]$).

Concerning capacity acquisition, constraints (5.6) and (5.7) state that the installation of storage capacity for each product family can occur at most once over the planning horizon. Furthermore, constraints (5.7) also impose that an existing food bank can only have its storage capacity expanded if it does not close until the end of the time horizon.

In the case of new facilities, on the one hand, constraints (5.8) are further required to ensure that storage capacity devoted to any of the product families can only be installed if the facility is operational in the period. On the other hand, inequalities (5.9) stipulate that storage capacity must be installed in a new food bank, for at least one product family, in the same time period in which the food bank is deployed.

With regard to the transport capacity of a food bank, it is only material to acquire capacity for the same type(s) of product families that can be stored in that facility. This is ensured by constraints (5.10) and (5.11). In each time period, multiple transport capacity can be acquired to collect food products of the same family. However, multiple capacity must be acquired in different sizes $\ell \in L$. Moreover, no limits are imposed regarding the number of periods in which transport capacity is added, nor is the acquisition by initially existing food banks subject to the operation of those facilities until the end of the planning horizon. Note that the assumption stated in Section 5.1 with regard to the minimum value of $\overline{M}_{kb}$ is required to enforce the intended purposes of constraints (5.11). Otherwise, and provided food bank $b \in OB$ does not close during the planning horizon, it would have to install new capacity for product $p \in P$ in order to be able to acquire, in the same period, each transport capacity size available.

Finally, budget constraints are imposed by equalities (5.12). Investment capital supports opening new food banks at potential sites (first term), installing storage areas at both new and existing facilities (second term), acquiring transport resources (third term), and closing initially existing food banks, as well as dismantling their storage capacities (fourth term). Slack variables γ^t are unrestricted in sign (cf. constraints (5.38)) and express under (positive values), or over (negative values) use of the reference budget O^t. Accordingly, they allow the identification of time periods, and corresponding values, with capital spendings below the reference budget, as well as cases in which extra capital needs to be raised to cover location and capacity acquisition expenditures. As such, they convey the required volume of investment capital raising effort by the institution. In order to minimize that effort level, variables γ^t are maximized over the planning horizon in the social objective function (5.41).

Institution-related constraints (II)

$$\sum_{p\in P_k}\sum_{i\in D\cup B\setminus\{b\}} x^t_{pib} \leq \sum_{\ell\in L} M_{\ell k}\sum_{\tilde{t}=1}^{t} w^{\tilde{t}}_{\ell kb} \qquad b\in PB,\ k\in K,\ t\in T \tag{5.13}$$

$$\sum_{p\in P_k}\sum_{i\in D\cup B\setminus\{b\}} x^t_{pib} \leq \overline{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_{b}\right) + \sum_{\ell\in L} M_{\ell k}\sum_{\tilde{t}=1}^{t} w^{\tilde{t}}_{\ell kb} \qquad b\in OB,\ k\in K,\ t\in T \tag{5.14}$$

$$\sum_{p\in P_k}\sum_{i\in CD\cup B\setminus\{b\}} x^t_{pib} + \theta^t_{kb} = \sum_{\ell\in L} N_{\ell k}\sum_{\tilde{t}=1}^{t} v^{\tilde{t}}_{\ell kb} \qquad b\in PB,\ k\in K,\ t\in T \tag{5.15}$$

$$\sum_{p\in P_k}\sum_{i\in CD\cup B\setminus\{b\}} x^t_{pib} + \theta^t_{kb} = \overline{N}_{kb}\left(1-\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_{b}\right) + \sum_{\ell\in L} N_{\ell k}\sum_{\tilde{t}=1}^{t} v^{\tilde{t}}_{\ell kb} \qquad b\in OB,\ k\in K,\ t\in T \tag{5.16}$$

The second set of institution-related constraints concerns capacity utilization matters.

Constraints (5.13) and (5.14) guarantee that the total quantity of products of a given family, which are received and collected from donors and other food banks, does not exceed the storage capacity available at each operating facility. Equalities (5.15) and (5.16) play a similar role with respect to transport capacity for collecting food items from donors $d\in CD$, and other food banks (food banks collect from rather than deliver products to other food banks). The main difference is that slack variables θ^t_{kb} are included in the latter constraints to represent the amount of unused transport capacity. These variables are required to enforce, in the economic objective function (5.39), that acquisition of transport resources occurs only when needed and not earlier. A similar approach is not necessary with regard to the installation of storage capacity. This issue is discussed in the presentation of the economic objective function (5.39) in Section 5.4.

Charities-related constraints

$$\sum_{b \in B} z_{bc}^t = 1 \qquad c \in SC,\ t \in T \tag{5.17}$$

$$\sum_{b \in B} z_{bc}^t \leq 1 \qquad c \in HC,\ t \in T \tag{5.18}$$

$$\sum_{b \in B} z_{bc}^{t+1} \geq \sum_{b \in B} z_{bc}^t \qquad c \in HC,\ t = 1, \ldots, |T| - 1 \tag{5.19}$$

$$z_{bc}^{t-1} - z_{bc}^t \leq \sum_{\bar{b} \in B} y_{\bar{b}}^t \qquad b \in B,\ c \in C,\ t = 2, \ldots, |T| \tag{5.20}$$

$$\sum_{t \in T} \sum_{c \in C_b} z_{bc}^t \leq 0 \qquad b \in B \tag{5.21}$$

$$U_{bc}\, z_{bc}^t \leq \varepsilon^t \qquad b \in B,\ c \in C,\ t \in T \tag{5.22}$$

$$\sum_{b \in B} x_{pbc}^t \geq \beta_2\, X_{pc}^0 \qquad c \in SC,\ p \in P,\ t \in T \tag{5.23}$$

$$\sum_{b \in B} x_{pbc}^t \geq \beta_3\, R_{pc}^t \sum_{b \in B} z_{bc}^t \qquad c \in HC,\ p \in P,\ t \in T \tag{5.24}$$

$$x_{pbc}^t \leq R_{pc}^t\, z_{bc}^t \qquad b \in B,\ c \in C,\ p \in P,\ t \in T \tag{5.25}$$

$$\sum_{p \in P} \sum_{b \in B} \frac{R_{pc}^t\, z_{bc}^t - x_{pbc}^t}{R_{pc}^t} \leq \delta^t \qquad c \in C,\ t \in T \tag{5.26}$$

Charities-related constraints address two main topics: assignment to food banks (by constraints (5.17) to (5.22)), and supply of charities (by constraints (5.23) to (5.26)). Equalities (5.17) enforce the uninterrupted inclusion in the supply chain of charities that received food assistance prior to the network redesign project. Charitable agencies awaiting food supply may start being served in any of the planning periods according to constraints (5.18). If an agency is included in the supply chain, then constraints (5.19) ensure that it will continue to receive food assistance until the end of the time horizon. Note 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 stability reasons, the re-assignment of charities to food banks is limited by constraints (5.20) to those periods in which the network configuration changes, i.e. when at least one food bank is opened, and/or an existing facility is closed.

Charities must collect food donations from the assigned food bank by their own transport means. Therefore, assignment of charities to distant food banks should be avoided. Based on set C_b that establishes what is considered to be a reasonable service area for each bank, constraints (5.21) impose that only those charities located within the service area of the food bank(s) can be assigned to them. Furthermore, constraints (5.22) introduce auxiliary variables ε^t representing the maximum distance between a food bank and its assigned charities. These variables are minimized in the social objective function (5.41). Hence, on the one hand, constraints (5.21) determine that if a charity is not located within a service area of an operational facility, then it cannot be supplied by that facility. On the other hand, if the charity can be served by more than one food bank, then constraints (5.22) and the objective function (5.41) act to assign it to the nearest facility.

Regarding the level of supply, constraints (5.23) and (5.24) set the minimum level of product that must be delivered to the charities served by the institution. In the case of initially served charities, this level is set in reference to the volume of supply provided in period 0, per food product $p \in P$. Concerning charities initially awaiting food assistance, the level is defined on the basis of their demand, per product $p \in P$, from the period they are included in the supply chain. That is to say that newly served charities can rely on the assurance that at least a minimum level of their demand will be satisfied in all forthcoming periods.

Inequalities (5.25) state that charities do not receive a quantity of food products that is greater than their demand for each product $p \in P$. Thus, these constraints ensure that the demand profile of the served beneficiary agencies is duly taken into account by the institution. These constraints also state that charities may only be supplied by the food bank to which they are assigned to in each period $t \in T$.

Constraints (5.26) impose δ^t as the maximum threshold for the overall level of unsatisfied demand of the served charities in each period, measured by the expression on the left-hand side of the constraints. These inequalities are instrumental to address the objective of achieving an equitable distribution of products. To that effect, similar to variables ε^t with respect to the proximity of charities to food banks, auxiliary variables δ^t are also minimized in the social objective function (5.41) in order to achieve the fairest distribution of products possible among the charities included in the food bank supply chain.

Operating constraints

$$\sum_{c\in C} z_{bc}^{t} \geq \sum_{\widetilde{t}=1}^{t} y_b^{\widetilde{t}} \qquad b \in PB,\ t \in T \tag{5.27}$$

$$\sum_{c\in C} z_{bc}^{t} \geq 1 - \sum_{\widetilde{t}=1}^{t} y_b^{\widetilde{t}} \qquad b \in OB,\ t \in T \tag{5.28}$$

$$z_{bc}^{t} \leq \sum_{\widetilde{t}=1}^{t} y_b^{\widetilde{t}} \qquad b \in PB, c \in C,\ t \in T \tag{5.29}$$

$$z_{bc}^{t} \leq 1 - \sum_{\widetilde{t}=1}^{t} y_b^{\widetilde{t}} \qquad b \in OB, c \in C,\ t \in T \tag{5.30}$$

$$\sum_{i\in D\cup B\setminus\{b\}} x_{pib}^{t} = \sum_{j\in C\cup B\setminus\{b\}} x_{pbj}^{t} \qquad b \in B,\ p \in P,\ t \in T \tag{5.31}$$

Constraints (5.27) and (5.28) require that each operating food bank serves at least one charity in each time period. Conversely, constraints (5.29) and (5.30) ensure that charities can only be supplied by operating food banks. The former are instrumental to ensure that, observing the assumption made in this regard in Section 4.2, only food banks that serve charities are operational. Notice that in some situations it could be meaningful to operate facilities that act only as storage and transshipment hubs for product flows received from suppliers, and exchanged between food banks. Actually, depending on the costs of managing no-activity food banks versus the costs of shutting them down, it could even be advantageous to keep facilities without any activity operational. This is not allowed according to constraints (5.27) and (5.28). Constraints (5.29) and (5.30) play a unique role in the model. As it will be discussed in Section 7.2.6, these are valid inequalities that can help to improve the computational performance of solving algorithms.

Equalities (5.31) guarantee the conservation of product flow at each facility in every time period. These constraints signify that all food products managed at the food bank warehouses are delivered to charities. Subsequently, there is no product waste at the food banks.

Domain constraints

$$y_b^t,\, z_{bc}^t \in \{0,1\} \qquad b \in B,\, c \in C,\, t \in T \tag{5.32}$$

$$w_{\ell kb}^t,\, v_{\ell kb}^t \in \{0,1\} \qquad b \in B,\, \ell \in L,\, k \in K,\, t \in T \tag{5.33}$$

$$x_{pij}^t \geq 0 \qquad p \in P,\, (i,j) \in A,\, t \in T \tag{5.34}$$

$$\xi_d^t \geq 0 \qquad d \in FD,\, t \in T \cup \{0\} \tag{5.35}$$

$$\theta_{kb}^t \geq 0 \qquad b \in B,\, k \in K,\, t \in T \tag{5.36}$$

$$\varepsilon^t,\, \delta^t \geq 0 \qquad t \in T \tag{5.37}$$

$$\gamma^t \text{ free} \qquad t \in T \tag{5.38}$$

Finally, constraints (5.32) through (5.38) define the domains of all variables used.

5.4 Objective functions

The presentation of the model is concluded with the introduction of the objective functions. The three dimensions of sustainability are individually considered in dedicated objective functions.

Economic objective

$$\begin{aligned}\text{Min } z_1 = & \sum_{t \in T} \sum_{b \in B} \sum_{c \in C} FC_{bc}^t \, z_{bc}^t + \sum_{t \in T} \sum_{b \in OB} \sum_{k \in K} VS_{kb}^t \, \overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \\ & \sum_{t \in T} \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VS_{kb}^t \, M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell kb}^{\tilde{t}} + \\ & \sum_{t \in T} \sum_{b \in B} \sum_{k \in K} \sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} VH_{kb}^t \, x_{pib}^t + \\ & \alpha_1 \sum_{t \in T} \sum_{b \in B} \sum_{k \in K} \theta_{kb}^t - \alpha_2 \sum_{d \in FD} \xi_d^{|T|} \end{aligned} \tag{5.39}$$

The economic objective function (5.39) aims to identify the supply chain configuration with the least total operating cost expressed in m.u. It accounts for the cost of supporting served charities (first term), and the costs of operating storage areas (second and third terms) and handling products at the warehouses (fourth term) throughout the planning horizon. Notice that the second and third terms express running costs resulting from the total available storage capacity, regardless of its use. Consequently, these terms act as a financial incentive not to install storage areas unless they are economically viable. These first four terms correspond to the most representative fixed and variable costs supported by the operational budget. Notice however that such budget is not included in the model - budget O^t pertains solely to investment capital expenditures.

Transport capacity is addressed by the fifth term of the objective function. This term penalizes by factor α_1 economic inefficiencies due to unused transport capacity, which are conveyed by slack variables θ^t_{kb} (see constraints (5.15) and (5.16)). Considering that unitary transport acquisition costs may increase from period to period, in a situation where transport capacity is necessary sometime during the planning horizon, it could be meaningful to purchase it in earlier periods. However, the vehicle fleet would only be parked for periods before actual use. With this term untimely spendings on transport capacity are avoided.

The sixth and final term rewards by factor α_2 unspent financial donations at the end of the planning horizon. As discussed in Section 4.2, financial donations are meant to buy products that can fill supply gaps, rather than replace in-kind donations. This policy is enforced by rewarding financial donations savings in the economic objective function (see constraints (5.3)). Otherwise, given that these donations do not demand transport from donors, its use could risk being distorted. Although not included in the model, the institution could also channel financial donations unspent by the last planning period to other ends, e.g. to alleviate the effort of raising investment capital, or to reinforce the operational budget, which are further reasons to promote these savings.

Environmental objective

$$\begin{aligned}\text{Min } z_2 = \alpha_3 \sum_{t\in T}\sum_{p\in P}\varphi^t \left[\sum_{d\in DD}\left(Q^t_{pd} - \sum_{b\in B_d} x^t_{pdb}\right) + \sum_{d\in CD}\left(Q^t_{pd} - \sum_{b\in B} x^t_{pdb}\right)\right] + \\ \alpha_4 \sum_{t\in T}\sum_{b\in B}\sum_{i\in CD\cup B\setminus\{b\}} \omega^t\, U_{ib}\,(2\,\mu + \sum_{p\in P} x^t_{pib}) \qquad (5.40)\end{aligned}$$

The environmental objective function (5.40) minimizes the total value of food waste (first term), and of CO_2 emitted as result of transport activities carried out by the food banks (second term). The total quantity of food waste corresponds to the difference between the amount of food products made available for donation by product donors $DD \cup CD$, and the volume actually redistributed by the food banks to the charities. Food waste is disposed of at unit cost φ^t in each period.

CO_2 emissions are associated with the trips travelled by food bank vehicles to pick-up food items from collection donors CD, and from other food banks. According to the model assumptions, in these trips vehicles travel empty on the outward journey, and only carry a load on the return journey. Hence, the second term of the environmental objective function accounts for the cost of

CO_2 emissions that results from a journey on empty, plus a journey with cargo. In addition to the weight circulated, the distance travelled and the unit cost per tonne-d.u. are also factored in. Observe that the fixed component of the second term, only involving parameters ω^t, U_{ib}, and $2\,\mu$, while not determining the solutions obtained, influences the value of the environmental objective. This fixed component is meant to correspond to a valuation of the number of trips required to transport the products, which is not determined by the model. It is taken as a simplification of the actual value of distance travelled, which would require the introduction of another set of variables to indicate which legs, or segments of the whole network are indeed travelled by the vehicles. Parameters α_3 and α_4 are pre-specified positive scaling factors designed to weight the two terms of the objective function in accordance with the preferences of the decision-maker. The environmental objective function is expressed in k€.

Social objective

$$\begin{aligned}\operatorname{Max} z_3 = {} & \alpha_5 \sum_{t\in T}\sum_{b\in B}\sum_{c\in HC} z^t_{bc} + \alpha_6 \sum_{t\in T}\gamma^t + \\ & \alpha_7 \sum_{t\in T}\psi^t \left[\sum_{b\in OB}\sum_{k\in K}\overline{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) + \sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} M_{lk}\sum_{\tilde{t}=1}^{t} w^{\tilde{t}}_{\ell kb}\right] \\ & - \alpha_8 \sum_{t\in T}\varepsilon^t - \alpha_9 \sum_{t\in T}\delta^t \end{aligned} \tag{5.41}$$

The social objective function (5.41) comprises five terms, each addressing a social concern of the institution that manages the network of food banks.

The first term represents the total number of charities that start to receive food assistance from the institution during the planning horizon. The maximization of this term corresponds to the provision by the institution of the most inclusive service possible.

The second term measures the total deviation from the reference budget for network redesign (see constraints (5.12)). It takes a significant effort to raise investment capital to support the redesign of the existing supply chain network. This effort falls not only upon the food bank institution, but also upon the social partners that support its operation such as regional and national public entities, and private patrons. As such, performance of the supply chain activities with the least investment capital needs is also a social concern of the institution. Therefore, it is incorporated into the model by the maximization of the second term of (5.41).

The third term represents the value of the social work created by the operation of food banks. It reflects the importance of engaging volunteers in the activities of the institution. It also relates to the target of increasing the number of paid jobs, which is present in most articles reviewed in Chapter 3. Recall from Section 4.1 that, while volunteers are the majority of human resources of the food bank network, employees and workers under social contract are also involved. Available storage capacity (the term inside the square brackets) is used as a surrogate for the business activities of food banks. Parameters ψ^t correspond to the monetary value of work per unit of storage capacity in each time period. Therefore, their product stands for the value of social work created by the food bank network configuration. Notice that this term expresses the net value of social work created, i.e. it considers the end result of increasing (as a consequence of establishing new food banks and of expanding the installed capacity) and decreasing (resulting from the closing of food banks) the number of volunteer positions and paid jobs generated by the supply chain.

The last two terms in (5.41) concern the proximity of charities to the assigned food banks, and the equitable distribution of products by the served charities, respectively. As discussed in the presentation of constraints (5.22), the minimization of thresholds ε^t corresponds to reducing the largest distance between any served agency and its assigned food bank. Similarly, the minimization of thresholds δ^t involved in constraints (5.26) promotes the balanced distribution of products by reducing the highest level of unsatisfied demand registered by any served charity. Hence, the last two *minmax* terms of the social objective function formalize equity concerns of the institution with regard, respectively, to distance and product distribution.

Since the five individual social terms have different units of measurement, scalars α_5 through α_9 act simultaneously as weighting and normalizing factors.

Before discussing the optimization conflicts between the objective functions in Section 5.6, it is proven that the FBNR problem is classified as NP-hard.

5.5 Computational complexity

In this section it is proven that the FBNR problem defined by constraints (5.1) to (5.38) and objective functions (5.39) to (5.41) belongs to the class of NP-hard problems.

Cornuéjols et al. (1990) present the following definition for the Uncapacitated Facility Location (UFL) problem: considering a set of clients I with a given demand for a single product, and a set of sites J where facilities that can satisfy the demand can be located, the objective of the UFL problem is to minimize the total cost (or maximize the total profit) of satisfying the total demand of all clients.

Let c_{ij} be the cost of satisfying all the demand of client $i \in I$ from facility $j \in J$, and f_j the fixed cost of opening a facility in location $j \in J$. Let also y_j represent the decision to open facility j, and z_{ij} the decision of assigning client i to facility j. Both decisions are expressed by binary variables.

Therefore, $y_j = 1$ if facility j is deployed, and $y_j = 0$ otherwise. Moreover, $z_{ij} = 1$ if client i is supplied by facility j, and $z_{ij} = 0$ otherwise.

The integer linear programming model is written as follows.

$$\text{Min}\, z = \sum_{i\in I}\sum_{j\in J} c_{ij}\, z_{ij} + \sum_{j\in J} f_j\, y_j \tag{5.42}$$

$$s.t. \sum_{j\in J} z_{ij} = 1 \qquad i \in I \tag{5.43}$$

$$z_{ij} \leq y_j \qquad i \in I,\ j \in J \tag{5.44}$$

$$y_j,\, z_{ij} \in \{0,1\} \qquad i \in I,\ j \in J \tag{5.45}$$

Single-assignment constraints (5.43) ensure that the demand of every client i is fully and strictly satisfied by one of the facilities j. Constrains (5.44) guarantee that only open facilities j can satisfy the demand of clients i. Based on the node cover problem, and assuming, among others, $f_j = 1$ for all $j \in J$, Cornuéjols et al. (1990) prove that the UFL is NP-hard.

Next, it is proven that the UFL problem with $f_j = 1$ for all $j \in J$ can be reduced to the FBNR problem as modelled by expressions (5.1) through (5.41) including only the economic objective function (single objective MILP problem denoted as FBNR-Eco).

Lemma 5.1. *The FBNR-Eco problem is NP-hard.*

Proof. Given the FBNR problem as modelled by constraints (5.1) through (5.38) and objective functions (5.39) through (5.41), consider that there are no charities waiting to be included in the supply chain, such that $HC = \emptyset$ and $C = SC$. Consider also that there are no potential sites for the location of additional facilities, such that $PB = \emptyset$ and $B = OB$. Further assume that the storage and transport capacity in place at each initial food bank $b \in OB$ (or $b \in B$, following the previous assumption) is large enough to enable the satisfaction of the demand of all served charities $c \in SC$ (or $c \in C$). In this case, capacity expansion is not necessary in any situation.

Based on these assumptions, institution-related constraints (5.6), (5.8) through (5.10), (5.13), and (5.15), and operating constraints (5.27) and (5.29) of the FBNR problem, concerning potential food bank sites, can be discarded. Moreover, charities-related constraints pertaining to awaiting charities (5.18), (5.19), and (5.24) can also be abandoned. Since additional storage or transport capacity is not required, institution-related constraints (5.7) and (5.11) can equally be set aside. Similarly, considering that the initial capacity is large enough to satisfy all demand, institution-related capacity utilization constraints (5.14) and (5.16) are no longer meaningful. Given that storage and transport capacity decisions are not in play, variables $w^t_{\ell kb}$, $v^t_{\ell kb}$, and θ^t_{kb} can be excluded from the problem. The same applies to the respective domain constraints (5.33) and (5.36).

Furthermore, assuming that only one product, from any given family of products, is demanded ($|P| = 1$ and $|K| = 1$), and that this product is made available by every in-kind supplier, or can be purchased with the donations of every financial donor, in sufficient quantity to meet the demand of all charities, then all donors-related constraints (5.1) to (5.3) can be ignored. Additionally, variables ξ^t_d and respective domain constraints (5.35) can also be dropped. Under these conditions, it is enough to consider a single product donor $\mathring{d} \in CD$, that is $|DD \cup CD| = 1$, and $FD = \emptyset$. Moreover, following the assumptions made regarding storage and transport capacity, and the quantity of available donations, flows between food banks become meaningless. Hence, the set of all admissible origin-destination pairs of nodes in the network can exclude arcs $(b, b') : b, b' \in B, b \neq b'$. The revised set of admissible arcs is denoted $\mathring{A}$. Lastly, assuming that the available budget is large enough to support all investment expenses, and that all decisions are to be made for a single period ($|T| = 1$), aiming exclusively at the economic objective, then the FBNR-Eco problem for the above particular situation can be revised (rev) as follows.

$$\text{Min } z_1 = \sum_{b\in B}\sum_{c\in C} FC_{bc}\, z_{bc} + \sum_{b\in B} VS_b\, \overline{M}_b\, (1 - y_b) + \sum_{b\in B} VH_b\, x_{\mathring{d}b} \qquad (5.39\text{ rev})$$

$$s.t. \quad \sum_{b\in B} y_b \le \lceil \beta_1 |B| \rceil \qquad (5.5\text{ rev})$$

$$\sum_{b\in B} z_{bc} = 1 \qquad c \in C \qquad (5.17\text{ rev})$$

$$\sum_{c\in C_b} z_{bc} \le 0 \qquad b \in B \qquad (5.21\text{ rev})$$

$$\sum_{b\in B} x_{bc} \ge \beta_2\, X^0_c \qquad c \in C \qquad (5.23\text{ rev})$$

$$x_{bc} \le R_c\, z_{bc} \qquad b \in B,\ c \in C \qquad (5.25\text{ rev})$$

$$\sum_{c\in C} z_{bc} \ge 1 - y_b \qquad b \in B \qquad (5.28\text{ rev})$$

$$z_{bc} \le 1 - y_b \qquad b \in B,\ c \in C \qquad (5.30\text{ rev})$$

$$x_{\mathring{d}b} = \sum_{c\in C} x_{bc} \qquad b \in B \qquad (5.31\text{ rev})$$

$$y_b,\ z_{bc} \in \{0, 1\} \qquad b \in B,\ c \in C \qquad (5.32\text{ rev})$$

$$x_{ij} \ge 0 \qquad (i, j) \in \mathring{A} \qquad (5.34\text{ rev})$$

Note that, under the assumption of single period decisions, institution-related constraints (5.4), and charities-related constraints (5.20) are no longer applicable, and are therefore excluded from the formulation. Likewise, charities-related constraints (5.22) and (5.26) that establish conditions addressing, respectively, suppressed social objectives "distance" and "equity" become irrelevant, and are therefore discarded. Consequently, domain constraints (5.37) pertaining to variables ε^t and δ^t are also disregarded. Slack variables γ^t and respective domain constraints (5.38) are also not present in the above formulation of the particular FBNR-Eco problem given the budget assumption, and the fact that only the economic objective function is being considered. Naturally, budget constraints (5.12) also become irrelevant.

Assuming that all changes in the network configuration can occur in the same (single) period, i.e. $\beta_1 = 1$, then revised constraints (5.5) are no longer required. Considering that charities can be assigned to any food bank regardless of the distance in-between, i.e. the service area of each food bank covers the location of every charity, then set $C_b = \emptyset$, and revised constraints (5.21) become insubstantial.

Regarding product flows x_{bc}, establishing that $\beta_2 \, X_c^0 = R_c$ signifies that all demand R_c of every charity $c \in C$ must be fully satisfied. Moreover, setting the product handling costs of all facilities at zero ($VH_b = 0$) makes the third term of the revised objective function (5.39) meaningless. Following the above mentioned parameter assumptions, the ensuing particularization of the FBNR-Eco problem is presented below, observing a different sequence of constraints.

$$\text{Min}\, z_1 = \sum_{b \in B} \sum_{c \in C} FC_{bc} \, z_{bc} + \sum_{b \in B} VS_b \, \overline{M}_b \, (1 - y_b) \qquad \text{(5.39 rev')}$$

$$s.t. \quad \sum_{b \in B} z_{bc} = 1 \qquad c \in C \qquad \text{(5.17 rev)}$$

$$z_{bc} \leq 1 - y_b \qquad b \in B,\ c \in C, \qquad \text{(5.30 rev)}$$

$$\sum_{c \in C} z_{bc} \geq 1 - y_b \qquad b \in B \qquad \text{(5.28 rev)}$$

$$x_{bc} \leq R_c \, z_{bc} \qquad b \in B,\ c \in C \qquad \text{(5.25 rev)}$$

$$\sum_{b \in B} x_{bc} \geq R_c \qquad c \in C \qquad \text{(5.23 rev')}$$

$$x_{\mathring{d}b} = \sum_{c \in C} x_{bc} \qquad b \in B \qquad \text{(5.31 rev)}$$

$$y_b,\ z_{bc} \in \{0, 1\} \qquad b \in B,\ c \in C \qquad \text{(5.32 rev)}$$

$$x_{ij} \geq 0 \qquad (i, j) \in \mathring{A} \qquad \text{(5.34 rev)}$$

In addition to the previous assumptions, costs $VS_b\,\overline{M}_b$ are set equal to one. In that situation, in optimal solutions food banks are opened (remain open) only if they are necessary in order to supply charities. Accordingly, revised constraints (5.28) can be removed because they are always satisfied in the optimum in view of the revised objective function (5.39 rev").

Finally, variables y_b are redefined. Recalling that for $b \in OB$, which in this case became equivalent to $b \in B$, $y_b = 1$ signifies that initial food bank b changes status (i.e. closes), and $y_b = 0$ in the opposite case, variables y'_b are defined as follows: $y'_b = 1 - y_b$. Thus, $y'_b = 1$ if food bank b is open, and $y'_b = 0$ otherwise.

In conclusion, following the assumptions presented, the particular FBNR-Eco problem is formulated as follows.

$$\text{Min}\, z_1 = \sum_{b\in B}\sum_{c\in C} FC_{bc}\, z_{bc} + \sum_{b\in B} y'_b \qquad \text{(5.39 rev")}$$

$$s.t. \quad \sum_{b\in B} z_{bc} = 1 \qquad c \in C \qquad \text{(5.17 rev)}$$

$$z_{bc} \leq y'_b \qquad b \in B,\ c \in C, \qquad \text{(5.30 rev')}$$

$$x_{bc} \leq R_c\, z_{bc} \qquad b \in B,\ c \in C \qquad \text{(5.25 rev)}$$

$$\sum_{b\in B} x_{bc} \geq R_c \qquad c \in C \qquad \text{(5.23 rev')}$$

$$x_{\mathring{d}b} = \sum_{c\in C} x_{bc} \qquad b \in B \qquad \text{(5.31 rev)}$$

$$y'_b,\ z_{bc} \in \{0,1\} \qquad b \in B,\ c \in C \qquad \text{(5.32 rev')}$$

$$x_{ij} \geq 0 \qquad (i,j) \in \mathring{A} \qquad \text{(5.34 rev)}$$

Note that, on the one hand, the first two sets of constraints, (5.17 rev) and (5.30 rev'), pertain exclusively to (single period) variables y'_b and z_{bc}. On the other hand, constraints (5.23 rev') and (5.31 rev) only concern (single period) variables x_{ij}, for $(i,j) \in \mathring{A}$. Constraints (5.25 rev) involve both x_{ij}, in reference to product flows from food banks to charities, and assignment variables z_{bc}.

This particular FBNR-Eco problem with regard to variables y'_b and z_{bc} corresponds to the UFL problem with $f_j = 1$ and additional constraints (5.25 rev), (5.23 rev'), (5.31 rev) and (5.34 rev). These constraints do not influence the optimal solving of variables y'_b and z_{bc} based on constrains (5.17 rev), (5.30 rev') and (5.32 rev'), and objective function (5.39 rev"), which formulate the UFL problem with unitary f_j costs. In fact, solving the particular FBNR-Eco with regard to variables x_{ij} is trivial for any solution value of variables z_{bc}. If $z_{bc} = 1$, then, given that demand is fully satisfied,

$x_{bc} = R_c$. Otherwise, if $z_{bc} = 0$, then $x_{bc} = 0$. Once variables x_{bc} are determined for all $b \in B$ and $c \in C$, settling variables $x_{\mathring{d}b}$ for all $b \in B$ is also straightforward on the basis of equalities (5.31 rev).

Therefore, if there is a polynomial solving algorithm for the FBNR-Eco problem, then that algorithm is also able to solve the UFL problem with $f_j = 1$ in polynomial time. Considering that the UFL problem with $f_j = 1$ is classified as an NP-hard problem (Cornuéjols et al., 1990), then the FBNR-Eco problem is also an NP-hard problem. □

Besides the economic objective function (5.39), the FBNR problem comprises also the environmental objective function (5.40), and the social objective function (5.41).

Lemma 5.2. *The FBNR problem is NP-hard.*

Proof. A multi-objective problem (FBNR) that includes an NP-hard single objective problem (FBNR-Eco) is also NP-hard (Ehrgott, 2005). □

5.6 Conflicts of the objectives

The economic, environmental and social objective functions (5.39) to (5.41) reflect the conflicts faced by the management of the food bank supply chain, namely:

(i) to be efficient (by identifying the supply chain configuration with least economic cost),

(ii) to contribute to environmental goals (by reducing food waste and CO_2 emissions),

(iii) and to promote social sustainability (by, among others, being inclusive, fair, and near).

The summary presented in Tables 5.6 to 5.8 explicits some of the major conflicts between the terms of each objective function and the other objectives of the problem. In some cases, positive impacts among the various TBL terms are also identified.

The support provided by the institution to each charity included in the supply chain originates costs that are expressed by the first term of the economic objective function (5.39). As these costs depend on the number of charities supported, they conflict with the objective of increasing the level of food assistance provided to the disadvantaged population, represented by the first term of the social objective function (5.41). Moreover, considering that the increase of the number of charities assisted creates new channels to distribute food products, the minimization of the first term of (5.39) is potentially also in conflict with the environmental objective of reducing food waste.

Economic term (cost)		Environmental impact		Social impact	
		Positive	Negative	Positive	Negative
⇓	Support charities	-	Food waste	-	Food assistance
⇓	Storage areas maintenance	-	Food waste	Investment needs	Social work value Food assistance
⇓	Handling products	-	Food waste	-	Food assistance
⇓	Transport capacity inefficiencies	-	CO_2 emissions	-	Investment needs
⇑	Financial donations savings	Food waste	-	-	Food assistance

Table 5.6: Impacts: economic objective

The second and third terms of (5.39) aim to minimize costs supported by the operation of storage areas. These terms have a positive impact in the second term of the social objective function related to the effort to secure the necessary investment capital, but are in conflict with two other social terms. As storage areas costs depend on the storage capacity available, the minimization of the former leads to fewer storage resources, which restricts both the level of food assistance that can be provided to charities, and the social work value created by the supply chain (see third term of social objective function (5.41)). Furthermore, by impacting negatively the level of food assistance that can be provided to charities, it curbs the environmental objective of food waste reduction.

Likewise, the minimization of costs derived from handling products at the food bank warehouses, expressed by the fourth term in (5.39), conflicts directly with the social objective of increasing food assistance, and with the environmental objective of food waste reduction.

The fifth term of the economic objective function penalizes inefficiencies associated with the transport capacity available at the institution. In contrast to the case of storage capacity (cf. second and third terms of (5.39)), the model does not account for operational costs per transport capacity available. Given that transport acquisition costs may increase every passing period, it would be meaningful, strictly from an investment perspective, to purchase all capacity required throughout the planning horizon in the first period(s). As previously discussed, this term addresses this issue. It can therefore have a negative impact on the investment social term if acquisition of transport capacity occurs at larger costs (in later periods) than possible (in earlier periods). It may also negatively impact the environmental objective of minimizing CO_2 emissions. By penalizing unused transport capacity, this term in fact promotes the use of available transport resources, namely to collect products from donors $c \in CD$ (see constraints (5.15) and (5.16)). This means that it is fitting, in order to maximize the use of the available transport capacity, to collect products at the locations of the donors. Consequently, it contributes to increase the environmental cost of CO_2 emissions generated.

The last term rewards savings obtained from financial donations not spent. Recall from the previous section that its purpose is to favour the redistributing of in-kind donations over the acquisition of products. Therefore, on the one hand, the minimization of this term can impact positively the volume of food waste. But, on the other hand, it prevents achieving higher levels of food assistance that could otherwise be provided to charities if financial donations were to be used freely.

The minimization of food waste, expressed by the first term of the environmental objective function (5.40), has both positive and negative consequences regarding the other two objectives of the FBNR problem. With respect to the social objective, the minimization of food waste contributes directly to a higher level of food assistance. Indirectly, it may also positively influence the social work value created by the supply chain to the extent that it may require larger storage areas. However, if larger storage, and possibly also transport capacity are indeed needed, then that will require an additional effort to raise investment capital. On the economic side, the negative consequences of minimizing food waste are the ensuing higher costs of handling a greater quantity of products, and of possibly operating larger storage areas. These consequences are partially compensated if the reduction of food waste is located at collection donors. In that case, it may originate a greater use of the transport resources, i.e. less transport capacity inefficiencies, which have a positive economic impact.

Environmental term (cost)		Economic impact		Social impact	
		Positive	Negative	Positive	Negative
$\Downarrow$	Food waste at donors $d \in DD$	-	Storage areas Handling products	Food assistance Social work value	Investment needs
$\Downarrow$	Food waste at donors $d \in CD$	Transport capacity inefficiencies	Storage areas Handling products	Food assistance Social work value	Investment needs
$\Downarrow$	CO_2 emissions	-	Transport capacity inefficiencies	-	Food assistance

Table 5.7: Impacts: environmental objective

By opposition, restricting the use of vehicles in order to reduce CO_2 emissions may lead to greater economic inefficiencies related to the transport fleet. Additionally, avoiding the collection of products for the sake of minimizing CO_2 emissions caps the volume of products redistributed, which negatively impacts the level of food assistance that may be provided by the supply chain.

Note also that the two terms of the environmental objective function are in direct conflict with each other. The minimization of food waste encompasses the use of transport capacity to collect products from collection donors that results in larger CO_2 emissions. Reversely, minimizing the emissions implies that products are left uncollected, and therefore, according to the assumptions of the model, wasted.

Social term (benefit)		Economic impact		Environmental impact	
		Positive	Negative	Positive	Negative
⇑	Inclusion of charities $c \in HC$	Transport capacity inefficiencies	Support charities Storage areas Handling products	Food waste	CO_2 emissions
⇓	Investment needs	Storage areas Transport capacity inefficiencies	-	CO_2 emissions	Food waste
⇑	Social work value	-	Storage areas	Food waste	-

Table 5.8: Impacts: social objective

Objective function (5.41) comprises five terms that target different social concerns. The first term envisages the inclusion of the largest number of charities waiting to be served by the supply chain. Their inclusion is in direct conflict with the first term of the economic objective function. Additionally, increasing the population benefiting from food assistance may involve additional costs related to larger storage areas, and to the handling of a greater quantity of products. It will likely have a positive effect on the reduction of food waste as more products will be needed to provide assistance. But, that may also result in increased CO_2 emissions if transport by vehicles of the food banks is required. In this case, on the positive side, it may also increase the transport capacity economic efficiency.

Reducing the effort to raise investment capital weights favorably on the economic objective by restricting storage areas and transport capacity available at the food banks. If less transport capacity is acquired, then it can also help limiting the volume of CO_2 emissions. However, one of the most immediate consequences will be the curtailing of the volume of products that can be redistributed by the supply chain, i.e. the environmental objective of reducing food waste is negatively impacted. In that sense, this term is also in conflict with the first term of the social objective function because any investment limitation will presumably restrict the possibility of including new charities in the food supply chain.

Barring the effects related to the transport capacity, the third social term has effects that are opposite to the impacts of the second term. This term expresses the value of social work created by the supply chain, and is directly related to the available storage capacity. Thus, maximizing this term implies additional economic costs of operating storage areas. But if larger capacity to store products is in place, then that potentially favors the reduction of food waste, which will in turn generate larger costs of handling food products (not included in Table 5.8). Similar to the first social term, this term is also in conflict with the social objective of limiting the effort to raise investment capital.

The direct and indirect impacts of the last two social terms are not straightforward. For this reason they are not included in Table 5.8. Achieving greater equity in product redistribution concerns the fairness with which charities are served, which is not necessarily dependent upon the volume of products supplied, or the number of charities included in the supply chain. Similarly, striving to reduce the distance travelled by charities to collect products from the assigned food banks is certainly influenced by the number and location of both the operational food banks, and the charities served, but the impact depends significantly upon the specific network configuration.

The objective of the previous discussion is to highlight some of the major effects that the terms included in the three objective functions can exercise over the others. As discussed, these impacts can be registered between objective functions, or among the terms of the same objective, and reveal the complexity of the decisions involved in the FBNR problem.

Summary Chapter 5

This chapter presented the proposed MO-MILP model for the FBNR problem. Based on the assumptions presented in Chapter 4, the dynamic, capacitated and multi-objective mathematical programming model represents a multi-product, and multi-layer forward-oriented food supply chain with product flows in vertical and horizontal directions.

Section 5.1 introduced the notation used in the formulation. Index sets identify the stakeholders, food products and respective families, storage and transport capacity sizes, and planning periods. Parameters concerning financial aspects, supply, demand, and capacity were individually presented. Specific assumptions related to some parameters were further detailed.

Section 5.2 described the variables associated with the main decisions of the problem. These include facility location, capacity acquisition, and single-assignment binary variables. Continuous variables express the product flows across the supply chain network. A set of continuous auxiliary variables was also introduced.

Besides the domain constraints, the model comprises 31 sets of constraints discussed in Section 5.3 following the stakeholders that they mainly pertain to.

Finally, the three objective functions of the model were described in Section 5.4, and the conflicts between their terms discussed in Section 5.6.

The environmental and social objective functions incorporate some of the most frequently used metrics relevant to the decision problem. This is the case, for example, of the minimization of CO_2 emissions regarding the former, and the number (value) of job creation regarding the latter. Social criteria integrating regional differences in the model are conveyed by distinct cost structures expressed in selected financial parameters. Moreover, tailored economic, environmental, and social metrics were developed and factored in the model. These include, among others, the cost for inefficient use of transport capacity, the food waste disposal cost, and the balanced distribution of products by charities included in the food bank supply chain.

The model does not account for some factors that could also be considered relevant to evaluate the performance of the supply chain. For instance, the cost of carbon footprint generated by vehicles of delivery donors and charities is not accounted for. Likewise, the positive impact on CO_2 emissions that derives from rescuing food products from waste is also not included in the model. Nevertheless, the criteria selected provide a comprehensive assessment of the most significant economic, environmental, and social impacts of redesigning a food bank supply chain.

In Section 5.5, it was proven that the FBNR problem is NP-hard given that it includes the single objective FBNR-Eco problem, which was also proven to be NP-hard.
In the next chapter, the methodology developed to obtain test instances for the FBNR problem based on the FPBA case is presented.

Keywords: Supply chain; Network redesign; Multi-objective MILP model; Triple bottom line; NP-hard

Chapter 6

Generation of instances

The FBNR problem presented in Chapter 4 is heavily inspired by the FPBA case. However, it is not meant to strictly depict its supply chain. Assumptions, and corresponding mathematical formulation made with regard to aspects like supply and demand conditions, or capacity installation policy deviate partly from the current operational and managerial practices of the FPBA. The objective is for the FBNR model to be as relevant for the specific case of the FPBA, as for other food aid supply chains with similar settings. Moreover, it is also intended that insights drawn from the computational study carried out can be meaningful for supply chains other than the FPBA. Accordingly, it is appropriate to perform the computational experiment over a set of instances that sustain the generalization purposes of the study.

This chapter presents the methodology followed to generate all parameters that define the instances for the FBNR. Instances comprise a considerable number of parameters, most of them interrelated. In order to obtain results relevant for the management of food bank supply chains, a testing environment that can represent real-life cases is required. Based on Martins et al. (2017), the methodology appeals to data obtained from FPBA to uphold the definition of instances simulating realistic situations. Information reporting to the period 2010-2015 was collected at the FPBA, and at the Lisbon food bank during several months of 2016. This information is instrumental to set the values, or to establish ranges of admissible values for key parameters of the model. Data profiling and classification are employed to overcome missing information. User-defined values, and data from official sources are engaged when necessary.

The methodology is applied to obtain instances for regional and national food bank supply chains. In both cases, instances reflect different supply chain configurations that, while retaining core features of the FPBA supply chain, create a diversity of situations that uphold the generalization objectives.

First, parameters relating to the supply chain stakeholders are presented in Section 6.1. This section also concerns parameters that define the index sets. Section 6.2 is dedicated to the presentation of parameters related to the food products considered in the instances, including their prices. Storage and transport capacity parameters are presented in Section 6.3. With the exception of food products prices, all financial parameters are included in Section 6.4. Sections 6.5 and 6.6 describe the procedures followed to determine supply (donations) and demand parameters. Finally, scaling factors of the objective functions, and their combinations into eight different input scenarios are presented in Sections 6.7 and 6.8, respectively.

6.1 Stakeholders parameters

As presented in Chapter 5, the FPBA coordinates a network of 18 operating food banks spread across the mainland territory of Portugal. Each facility is characterized essentially by its location and by the yearly volume of food products redistributed. Based on the average volume of food products processed at each FPBA food bank in the years 2014 and 2015, it is possible to identify three types of food banks. Small food banks are accountable for less than 2% of the total quantity, in tonnes, of food products managed by the FPBA supply chain. This is the largest group of facilities in terms of size (size S), comprising nine food banks: Abrantes (located in Santarém district), Beja, Castelo Branco, Coimbra, Cova da Beira, Évora, Leira-Fátima, Portalegre, and Santarém. The set of facilities that redistribute more than 2% but less than 10% of the total quantity of products each are denoted medium food banks. This set of size M facilities consists of six facilities located in Algarve, Aveiro, Braga, Oeste (located in Leiria district), Viana do Castelo, and Viseu. The three remaining food banks are individually responsible for more than 10% of the annual volume of products processed by the FPBA supply chain. These are denoted as large food banks (size L), and are located in Lisboa, Porto, and Setúbal.

The national supply chain instances are comprised of 15 food banks that are operational prior to the beginning of the planning period, and three sites for potential set-up of new facilities. The decrease from the 18 operational facilities of the FPBA supply chain to the 15 included in the national instances is achieved by excluding one medium size and two small size facilities. These correspond to the FPBA food banks operating in Viana do Castelo, Castelo Branco, and Abrantes. The first was the latest of the medium size food banks to initiate operations, in 2009, and also one of the smallest of its group size. Similarly, the food bank of Castelo Branco was the last addition to the FPBA supply chain, and accounts for the smallest volume of products handled among all food banks. The option to exclude the small size FPBA food bank located in Abrantes is related to the fact that this facility is located in a service area that can be covered by nearby facilities, like the food banks located in Leira-Fátima, Oeste, or Santarém.

In Figure 6.1 (a) the 18 FPBA food banks are directly mapped in a rectangle of $[0,\ 500] \times [0,\ 1000]$ d.u. respecting their actual geographical dispersal in the continental territory. The rectangle is intended to be a geometrical representation of mainland Portugal, and is divided in eight numbered squares of $[0,\ 250] \times [0,\ 250]$ d.u. each. Figure 6.1 (a) also identifies the three FPBA food banks excluded from the national instances. The mapping is rotated (Figure 6.1 (b)), and then some locations are adjusted for proper fitting into the squares (Figure 6.1 (c)). Although not fully perceptible in last figure, food banks located in Évora and Beja are placed on squares six and eight, respectively. In this final map, food banks are depicted according to their size.

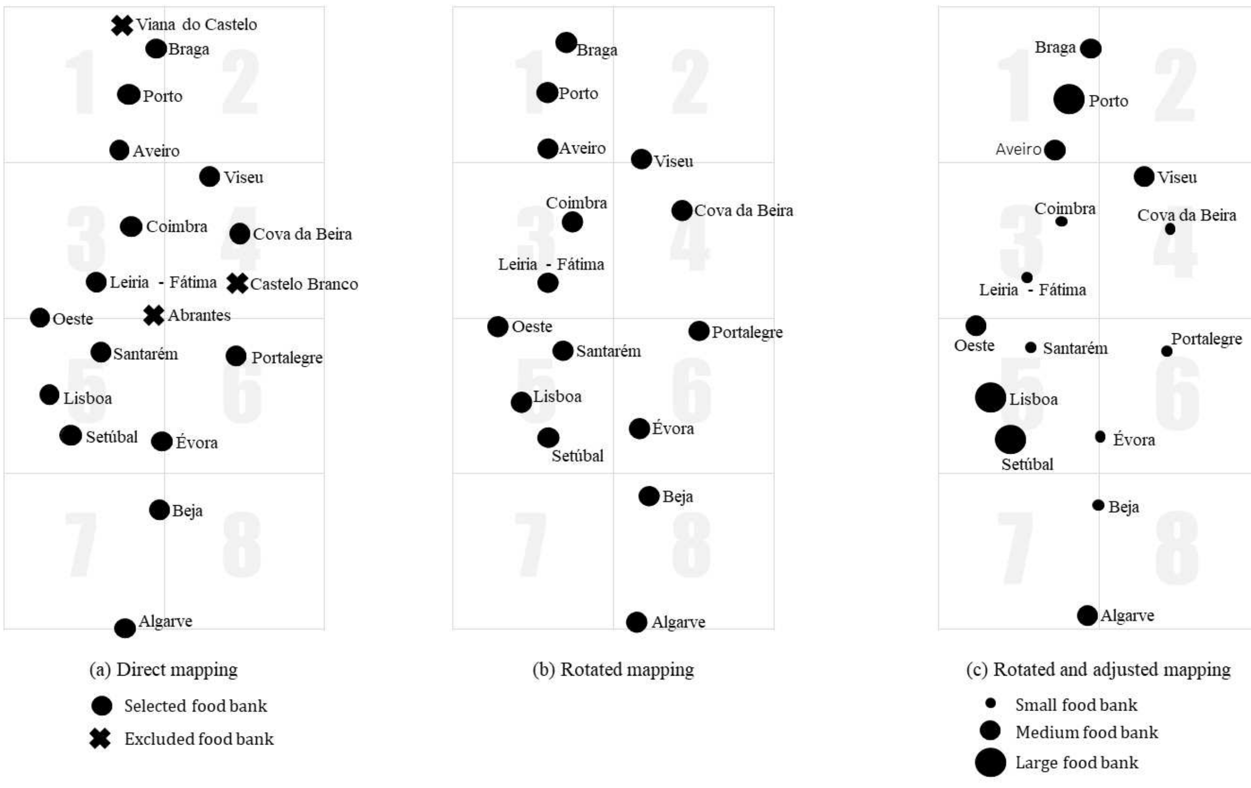


Figure 6.1: FPBA food bank network mapping

Subsequent to this mapping process, the number and respective sizes of the food banks located within each square S are retained as follows: $S1 = \{M,\ M,\ L\}$, $S2 = \emptyset$, $S3 = \{S,\ S\}$, $S4 = \{S,\ M\}$, $S5 = \{S,\ M,\ L,\ L\}$, $S6 = \{S,\ S\}$, $S7 = \{M\}$, and $S8 = \{S\}$. Next, the location of existing facilities in the national instances is determined on the basis of this geographical distribution profile. Bearing in mind the generalization purposes of the computational experiment, the coordinates of the initial facilities in the instances are randomly generated within each square observing the FPBA profile. For the purposes of this chapter, all random generated data follows a uniform distribution.

Similarly, the location of the potential food banks is randomly decided within selected squares. To that end, squares two, six, and eight are chosen, motivated by the inferior level of available food assistance in the corresponding regions of the Portuguese territory in comparison with other regions.

Figure 6.2 displays the locations of initial and potential food banks used in all test instances, national or regional. The area framed by the dotted line corresponds to the service area of the regional instances. This area comprises squares seven and eight, and the lower third of squares five and six, representing the southern region of Portugal.

Notice that, considering the geometrical area as a representation of the rectangular shape of mainland Portugal measuring 561 × 218 kms, each distance unit represents approximately 0.5 kilometers. The area featured in the regional instances accounts for 34% of the total area, and represents around $41,875\ km^2$. This area is initially served by one large, one medium and two small food banks. Moreover, it also includes one location for the installation of a potential new facility. Accordingly, in the national instances $|OB| = 15$, and $|PB| = 3$, while in the regional instances $|OB| = 4$, and $|PB| = 1$ as presented in Table 6.1 on page 106.

The largest number of food banks that can change status in a planning period is defined by parameter β_1 (cf. constraints (5.5) in Section 5.3). It corresponds to the fraction of the total number of food banks $|B|$ that can simultaneously close or open in the same period. In order not to cause excessive service disturbances arising from multiple network redesign decisions taking place in a single period, β_1 is set at 0.25 for the national instances. This figure provides enough reconfiguration flexibility to enable, for example, the closure of four food banks and the deployment of one new facility in a single period. Or to set-up two new food banks, while shutting-down three other. Regarding the regional instances, the same value for β_1 is considered too restrictive. Therefore, full flexibility is permitted in these instances by establishing $\beta_1 = 1.0$. Note that in this last case constraints (5.5) are redundant.

Based on FPBA data reporting to the years 2013 and 2105, it is estimated that a network of 15 food banks with the sizes defined for the national instances would be supplied by approximately 1,240 individual product donors, and would serve around 2,000 charities. Donors $d \in DD \cup CD$, and charities $c \in SC$ represent the estimated total number of product donors and served charities at a scale of 1:20. Thus, in the national instances $|DD| \cup |CD| = 62$, and $|SC| = 100$.

Product donors include donors $d \in DD$ that deliver goods to predetermined food banks, and

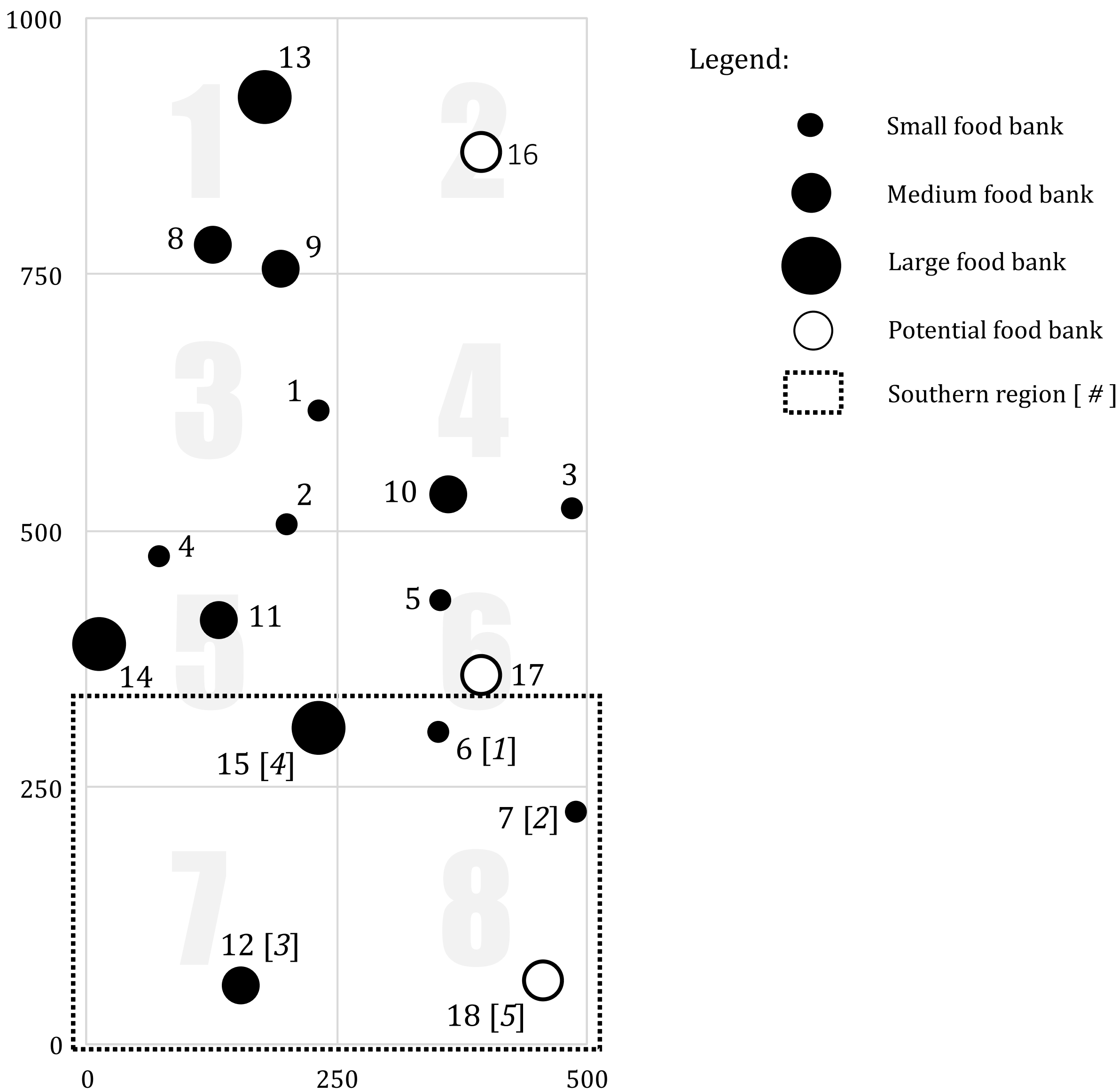


Figure 6.2: National and regional network of food banks

donors $d \in CD$ that require the collection of food donations at their location by vehicles under the food banks' responsibility. Historic records of the Lisbon food bank show that 85% of the total quantity of products managed by this facility were received from delivery donors, while 15% were collected at the location of the donor. The former includes products that were collect using the donated transport services of the partner cargo operator. Accordingly, those products are accounted

Index set	National instances	Regional instances	Source
$\|DD\|$	53	8	based on FPBA
$\|CD\|$	9	2	based on FPBA
$\|FD\|$	5	1	based on FPBA
$\|OB\|$	15	4	based on FPBA
$\|PB\|$	3	1	based on FPBA
B_d	$B_d = \{b \in OB \cup PB : U_{bd} \leq 250$ or $sel(b) = 1\}$, for $sel(b) \in \{0, 1\}$		user-defined
$\|SC\|$	100	16	based on FPBA
$\|HC\|$	20	3	based on FPBA
C_b	$C_b = \{c \in HC \cup SC : U_{bc} \geq 250\}$		user-defined
$\|K\|$	3	3	based on FPBA
$\|L\|$	3	3	user-defined
$\|T\|$	5	5	user-defined

Table 6.1: Stakeholders and other index sets

for in the share attributed to the delivery donors. This distribution is adopted to establish the number of each type of donors used in the test instances. Hence, in the national instances $|DD| = 53$ and $|CD| = 9$.

Regarding the regional instances, the total number of donors is set taking into account that approximately 16% of the population of mainland Portugal inhabits the southern region. Therefore, the number of delivery and collection donors in these instances is $|DD| = 8$ and $|CD| = 2$, respectively. Likewise, the number of served charities in the regional instances is $|SC| = 16$.

For national and regional instances these assumptions yield a ratio of served charities to product donor of 1.6, a value that is within the range of values verified at the FPBA (1.47 in 2013 and 1.85 in 2015).

According to the information available at the Lisbon food bank, for every five served charities, one other is waiting to be included in the supply chain. Hence, national instances account for $|HC| = 20$, while in the regional instances the number is $|HC| = 3$.

It is established that charities cannot be assigned to food banks located more than 250 d.u. away, which defines the set C_b. In line with the characterization of delivery donors set forth in Section 4.2, this distance is accepted also to define the local distribution area of delivery donors, required to define set B_d. In addition, food banks located outside the local distribution area are randomly selected to integrate and define the national distribution of each $d \in DD$. These assumptions are valid for the national, as well as for the regional instances.

The location of donors and charities is randomly established for every instance. The southern region of the national instances observes the density of product donors and charities set forth for the regional instances. This is accomplished by determining first, for each instance, the coordinates of the ten regional product donors and the 19 charities within the area defined by [0, 500] × [0, 335]. Following, the coordinates of the remaining number of donors and charities foreseen in the national instances are randomly established within the range [0, 500] × [336, 1000]. Location of charities observes that for each initially served charity $c \in SC$, there is at least one initially open food bank $b \in OB$ that is located at most 250 d.u. away. Distance U_{ij} between origin i and destination j corresponds to the Euclidean distance for $(i, j) \in A$.

Unlike product donors, financial donors are characterized by not having a physical location. Essentially, financial donors correspond to the monetary value of their donations, which may be used to buy food products by any of the food banks in the network. It can therefore be argued that the number of financial donors is not relevant, and that all financial donors could be aggregated into a single donor standing for the sum of donations of all financial donors. This option is taken for the regional instances where $|FD| = 1$. For the national instances, the number is set at five ($|FD| = 5$).

Food banks can opt to expand their storage and transport capacity by acquiring new resources, whenever required and allowed throughout the planning period. Three different types of capacity are defined ($|K| = 3$), depending upon the storage temperature requirements of products; dry, fresh, or frozen. Additional capacity resources can be chosen in small, medium or large sizes for both national and regional instances ($|L| = 3$). The actual capacity in tonnes for each case is presented in Section 6.3 pertaining to the values established for capacity parameters. Also applying to national and regional instances alike are the five periods comprising the planning horizon ($|T| = 5$). Considering that each time period represents one year, a timespan of five years is deemed appropriate for the strategic network redesign decisions addressed by FBNR problem.

6.2 Products parameters

FPBA records acknowledge around 170 individual products. For management purposes, these products are aggregated and classified into 33 groups as presented in Table 6.2 on page 109. Based on the further aggregation observed in the Activity Report of the Lisbon facility (Lisbon food bank, 2018), the national instances account for the 18 categories of products described in Table 6.2. Notation wise, each of the 18 categories is understood as a product $p \in P$. Products are classified either as dry, fresh, or frozen depending on storage temperature requirements ($|K| = 3$). Each set P_k is described in Table 6.3 on page 110.

While national instances deal with the complete array of products ($|P| = 18$), five products covering around 70% of all FPBA donations are selected for the regional instances ($|P| = 5$). These correspond to the two largest volume dry products (milk, and rice, pasta, flours and purée), the two largest fresh products (fresh fruit, and fresh vegetables), and the largest frozen product (frozen desserts and ice cream).

6.3 Capacity parameters

Fixing the values pertaining to storage and transport capacity parameters calls for the classification of food banks according to their size. All large facilities of the FPBA network have dedicated storage capacity for the three families of products, but the same does not apply to medium or small size facilities. Dry storage is available in all six medium size facilities, yet only four can store fresh products, and just two food banks of this size are able to store frozen products. All nine small size food banks store dry products, while fresh and frozen storage resources exists in four and two of these facilities, respectively. Respecting this profile, storage capacity per type of product family $k \in K$ is randomly assigned to the 15 initially open food banks $b \in OB$ of the national instances. The food banks of the regional instances have the same type of storage resources that are assigned to the corresponding food banks in the national instances.

Once it has been determined what type of storage capacity is held at each operating facility, the actual capacity in tonnes must be determined. The maximum capacity, per family of products $k \in K$, varies significantly among FPBA facilities of the same size. This does not allow the identification of a standard storage capacity, per size of the food bank and family of products, which can be attributed to the facilities of the instances. Hence, initial storage capacity of the operating facilities of the instances $\overline{M}_{kb}$ is randomly generated within the capacity intervals defined by the minimum and maximum values registered at the FPBA facilities of the same size as presented in Table 6.4 on page 111.

The reference capacity values of the intervals are obtained by converting the area of the FPBA facilities into weight (tonnes). With regard to dry storage, previous studies of the Lisbon food bank based on the volumetric features of a number of chief dry products suggest a conversion ratio of 0.4737 square meters to one tonne per day. On the assumption that a period $t \in T$ corresponds to a year, a bimonthly rotation frequency of these products yields a conversion ratio of 2.8421 tonnes per

FPBA		Instances		
#	Designation	$p[N]$	$p[R]$	Designation
1	Bakery and pastry	1		Bread, crackers, biscuits and snacks
2	Biscuits, crackers and snacks			
3	Coffee, chicory and tea	2		Coffee, tea, cereals, and pastry
4	Breakfasts and cereals			
5	Chocolates and pastry			
6	Assorted desserts			
7	Milk	3	1	Milk
8	Flours and purées	4	2	Rice, pasta, flours and purée
9	Rice and pasta			
10	Soups	5		Soups, seasonings, dressings and fats
11	Seasoning and dressings			
12	Vegetable and animal fats			
13	Sugar	6		Sugar and sweets
14	Sweets and canned fruit			
15	Canned legumes	7		Dry and canned legumes
16	Dry legumes			
17	Canned fish	8		Canned meat and canned fish
18	Canned meat			
19	Drinks	9		Water and sodas
20	Baby food products	10		Baby food products
21	Pre-prepared meals	11		Other dry products
22	Chips			
23	Others			
24	Cheese, dairy and eggs	12		Cheese, dairy and eggs
25	Fresh fruit	13	3	Fresh fruit
26	Fresh vegetables	14	4	Fresh vegetables
27	Meat, poultry, sausages and cold meats	15		Other fresh products
28	Fish, seafood and codfish			
29	Frozen vegetables	16		Frozen vegetables
30	Frozen fish, crustaceans and seafood	17		Frozen meat and frozen fish
31	Frozen meat, poultry and cold meats			
32	Frozen meals			
33	Ice creams, frozen desserts and cakes	18	5	Frozen desserts and ice cream

$p[N]$: index of product p in national instances; $p[R]$: index of product p in regional instances

Table 6.2: Products designation

Index set	National	Regional	Source
$\|P\|$	18	5	based on FPBA
$\|K\|$	3 (1: dry, 2: fresh, 3: frozen)		based on FPBA
P_k	$P_1 = \{1, \ldots, 11\}$	$P_1 = \{1, 2\}$	based on FPBA
	$P_2 = \{12, \ldots, 15\}$	$P_2 = \{3, 4\}$	
	$P_3 = \{16, \ldots, 18\}$	$P_3 = \{5\}$	

Table 6.3: Products cardinality

square meter in each planning period. Fresh and frozen products are stored in pallets with 1.2 m^3 $(1 \times 1 \times 1.2)$ of volume, and 200 kg of maximum weight. In these cases, the conversion ratio adopts a weekly cycle for fresh products, and a monthly cycle for frozen products. Accordingly, the ratios from cubic meters to capacity are 8.666(7) for fresh products, and 2.0 for frozen products in each planning period $t \in T$.

Concerning initial transport capacity $\overline{N}_{kb}$, a similar methodology is followed to define the capacity intervals. Conversion ratios are based on the characteristics of vehicles of the Lisbon food bank assuming one daily trip every work day. It is further assumed that, for each food bank, transport capacity is available only for the same type of products that can be stored at the facility. Similar to the case of storage capacity, the exact transport capacity is randomly selected within the intervals defined on the basis of FPBA data.

The capacities presented in Table 6.4 are adjusted for the regional instances to account for the fact that these instances do not involve all 18 products included in the national instances. Thus, given that the five products of the regional instances represent 67.4% of the total quantity of products managed in the national instances, the capacities of the southern region food banks are adjusted by this proportion for the regional instances.

Table 6.5 presents the sizes of the different capacity levels for storage ($M_{\ell k}$), and transport ($N_{\ell k}$) of food products that can be installed at existing and new food banks for the national instances. These values are defined in reference to the minimum and maximum capacity sizes at the existing food banks, and assumed to be the same in all planning periods $t \in T$. Regarding regional instances, capacities are proportionally decreased to 67.4% of the values presented in Table 6.5.

Finally, relating to the issue of transport capacity, parameter μ requires the definition of the average tare weight of vehicles used in the transport of food products, and the average number of round trips performed by a vehicle in one period. The latter figure pertains to routing decisions that

Parameters	Food bank	Product family					
	($b \in B$)	Dry ($k = 1$)		Fresh ($k = 2$)		Frozen ($k = 3$)	
		Min.	Max.	Min.	Max.	Min.	Max.
$\overline{M}_{kb}$	Small	400.0	2275.0	35.0	310.0	5.0	15.0
	Medium	1380.0	3410.0	130.0	3665.0	30.0	65.0
	Large	5400.0	7105.0	1665.0	6065.0	140.0	320.0
$\overline{N}_{kb}$	Small	0.00	960.0	0.00	960.0	0.00	135.0
	Medium	0.00	1925.0	0.00	1925.0	0.00	135.0
	Large	2885.0	3850.0	0.00	1925.0	0.00	135.0

Table 6.4: Storage and transport capacity at existing food banks (tonnes): national instances

Parameters	Capacity	Product family		
	level ($\ell in L$)	Dry ($k = 1$)	Fresh ($k = 2$)	Frozen ($k = 3$)
$M_{\ell k}$	Small ($\ell = 1$)	1500.0	250.0	10.0
	Medium ($\ell = 2$)	3000.0	2000.0	50.0
	Large ($\ell = 3$)	6000.0	4000.0	200.0
$N_{\ell k}$	Small ($\ell = 1$)	250.0	200.0	25.0
	Medium ($\ell = 2$)	500.0	400.0	50.0
	Large ($\ell = 3$)	1250.0	750.0	100.0

Table 6.5: Storage and transport capacity levels available (tonnes): national instances

are not within the scope of the FBNR problem. Therefore, rather than estimating these parameters based on FPBA data, a unitary value is used. In order to compensate the resulting under evaluation of the affected environmental objective function term, the accompanying ω^t parameter that expresses the unitary cost for CO_2 emissions is set at a purposely high value, as presented in the following section.

6.4 Financial parameters

The information necessary to estimate the value of the set of financial parameters related to investment or operating costs included in the MO-MILP model that formulates the FBNR problem is not available at the FPBA. Traditionally, network investments are determined, not by a managerial decision to acquire storage or transportation with a given capacity at a certain unitary cost, but rather by the opportunity to benefit from casual capacity resources donations. When renting is involved, it occurs at preferred financial conditions. Therefore, it is not considered appropriate to appeal to the commercial market rates of those parameters.

This limitation is overcome with the introduction of m.u. concept, and the adoption of a top-down approach that ensures the necessary coherence between the values assigned to the missing financial parameters. According to this approach, the first parameter fixed is the annual budget available for expenditures on facility location and capacity acquisition. The reference budget value in period 0 (O^0) is set at 10,000 m.u. for national instances, and at 2,500 m.u. for the regional instances. Following, the values of all investment and operating costs parameters are established in reference to the total budget. Moreover, they apply equally to both national, and regional instances.

Hence, as presented in Table 6.6 on page 115, the fixed cost of opening a new facility in period 0 FI^0 is set at 1,000 m.u., and the fixed cost of closing an operating food bank in the same period FU^0 is 500 m.u. Unitary costs of installing storage and transport capacity depend on size $\ell \in L$, and product family $k \in K$ for which they are meant to. The actual capacity in tonnes of each size is set as described in the previous section. Unitary costs are established accounting for economies of scale. This results in smaller unitary costs for larger capacity sizes. Also observed are differences in costs resulting from distinct preservation requirements of dry (least expensive), fresh, and frozen products (most expensive). According to the followed top-down approach, the values established for parameters $VSI^0_{\ell k}$ and $VTI^0_{\ell k}$ are presented in Table 6.7 on page 115. In case of facility shut-down, dismantling costs VU^0_k vary according to the type of storage capacity $k \in K$ available, and are also presented in Table 6.7.

The initial costs of operating storage areas VS^0_{kb}, and handling food products VH^0_{kb} are presented in Table 6.8 on page 116. They are both influenced by the family of products $k \in K$, and the location of food banks $b \in B$ to which they apply to. Cost structures, namely those associated with labor costs, are usually not the same in all the regions of a country. This is particularly relevant considering that most of the operations performed at the food banks are labor intensive activities. Observing the eight square areas that define the national service area of the institution (cf. Section 6.1), three regions are conceived for costing purposes. The inshore region comprises squares one, three, and five, and corresponds to the most densely populated part of the country. As the level of availability of resources influences its value, it is considered that labor costs in this region are more favorable than anywhere else in the country. On the contrary, the inland region formed by squares two, four, and six corresponds to the most scarcely populated area. It is estimated that obtaining human resources in this region, particularly volunteer workers that are the majority of the labor force of food banks, is more expensive than in the other regions. The food banks located in the region consisting of squares seven, and eight benefit from in-between costs. Observe that this last region (south region) should be not mistaken for the southern region included in the regional instances. In fact, it should be noted that all three regional costs also apply to the regional instances: food bank 1 is located in the national inland cost area, food bank 4 is located in the national inshore cost area, and facilities 2, 3, and 5 are situated in the south region (see Figure 6.2 on page 105).

The last financial parameter established following the top-down approach concerns the operational cost of serving one charity in each period. For period 0 cost FC^0_{bc} is set at 10 m.u. for all pairs of charities and food banks, as presented in Table 6.6.

All previous values are established in reference to period 0, and expected to grow at a 2% rate per period $p \in P$ throughout the planning horizon. Rescaling factors can be used to ensure consistency with the remaining financial parameters that are expressed in thousands of euros.

Based on FPBA data for the year 2015, Table 6.9 on page 117, presents the unit costs of purchasing food products in period 0, τ^0_p. Price of product $p \in P$ is defined as the weighted sum of the prices of the corresponding products appearing in the FPBA list of 33 individual products. Volatility in the prices of products over the planning period is accounted for by allowing a price variation between -2% and +5% over the price of period 0. Therefore, in each period $t \in T$, the unit price of product $p \in P$ is equal to the base value τ^0_p multiplied by a randomly generated number in the interval [0.98, 1.05] following a uniform distribution.

The cost of disposal of food products that are made available by donors $d \in DD \cup CD$, but not redistributed to charities is bore by the respective donors. Food disposal costs include the remuneration of public or private entities responsible for the destruction service, and applicable municipal taxes. Both these values vary from municipality to municipality. Based on Zacarias

(2014), the disposal cost of period 0 φ^0 is fixed at 0.055 k€/tonne. This figure is consistent with value estimated by the staff interviewed at the Lisbon food bank. In order to convey the commitment of the institution to environmental goals, it is associated with a growth rate of 5% per period $t \in T$.

The reference cost for the CO_2 emissions is a figure of much debate. The carbon market price, set either according to an Emissions Trading System (ETS), or as a carbon tax, has varied substantially by geography and over time. Ongoing debate about its expected evolution (World Bank et al., 2016) leads to the adoption of an admittedly high value of 20 k€/tonne (recall from Section 6.3 that this value is also intended to compensate the value attributed to parameter μ). Additionally, the report from the European Environmental Agency (EEA, 2015) proposes the value of 75 grams of CO_2 emissions per tonne-kilometer of road freight. This yields a cost of 0.0015 k€/tkm. Considering that each d.u. corresponds approximately to 0.5 km, parameter ω^t is fixed at 0.00075 k€/tonne-d.u. for period 0. Similar to the case of waste disposal, the growth rate associated with CO_2 emissions is set at 5% per planning period $t \in T$.

Parameters ψ^t define the value of social work created by the supply chain per tonne of storage capacity available at the network of food banks. The value assumed for period 0 is based on the FPBA network configuration of 2015, and is determined accounting for: *i*) the available storage capacity in the network of 18 mainland food banks for all product families $k \in K$, expressed in tonnes; *ii*) the human resources involved in their operation and management, expressed in number of monthly full-time workers; and *iii*) the national average monthly salary (Pordata, 2015) expressed in k€. The three terms are factored in, rendering $\psi^0 = 0.00376$ k€/tonne, the social work value generated by one unit of available storage capacity in period 0. Finally, a growth rate of 2% per period $t \in T$ is foreseen for this cost.

6.5 Supply parameters

As discussed in Section 4.2, FPBA records do not provide information pertaining to the quantity of products made available by product donors $d \in DD \cup CD$, or the value offered by financial donors $d \in FD$ to purchase food items. Therefore, the procedure presented in Algorithm 6.1 on page 119 is adopted to obtain parameters Q^t_{pd} and $\widetilde{Q}^t_d$, benefiting from the available FPBA data whenever possible.

Step 1 of the procedure determines the total quantity of food products available at donors $d \in DD \cup CD$ in period 0 ($TotalQ$). FPBA figures for the period 2010-2017 show that in 2016 approximately $23,400$ tonnes of food products were redistributed to the charities. This is the small-

Parameters	Value ($t = 0$)	Growth rate / t	Unit
FI^t	1,000	2%	m.u.
FU^t	500	2%	m.u.
FC^t_{bc}	10	2%	m.u.
O^t National	10,000	2%	m.u.
O^t Regional	2,500	2%	m.u.
φ^t	0.05500	5%	k€/tonne
ω^t	0.00075	5%	k€/tonne-d.u.
ψ^t	0.03759	2%	k€/tonne

Table 6.6: Values of assorted financial parameters

Parameters	Capacity	Product family		
	level ($\ell \in L$)	Dry ($k = 1$)	Fresh ($k = 2$)	Frozen ($k = 3$)
$VSI^0_{\ell k}$	Small ($\ell = 1$)	1.00	5.00	10.00
	Medium ($\ell = 2$)	0.75	1.50	5.00
	Large ($\ell = 3$)	0.50	1.00	2.50
$VTI^0_{\ell k}$	Small ($\ell = 1$)	2.00	7.50	10.00
	Medium ($\ell = 2$)	1.50	5.00	6.00
	Large ($\ell = 3$)	1.00	3.50	4.00
VU^0_k		0.25	0.50	1.25

Table 6.7: Capacity acquisition and capacity dismantling costs (m.u./tonne) in period 0

Parameters	Region	Food bank ($b \in B$)	Product family		
			Dry ($k=1$)	Fresh ($k=2$)	Frozen ($k=3$)
VS^0_{kb}	Inshore	$b = 1, 2, 4, 8, 9, 11, 13, 14, 15$	0.0250	0.0500	0.1250
	Inland	$b = 3, 5, 6, 10, 16, 17$	0.0500	0.1000	0.2500
	South	$b = 7, 12, 18$	0.0375	0.0750	0.1875
VH^0_{kb}	Inshore	$b = 1, 2, 4, 8, 9, 11, 13, 14, 15$	0.1250	0.2500	0.6250
	Inland	$b = 3, 5, 6, 10, 16, 17$	0.2500	0.5000	1.2500
	South	$b = 7, 12, 18$	0.1875	0.3750	0.9375

Table 6.8: Operating and handling costs (m.u./tonne) in period 0

est volume registered in any year of that period. The largest annual volume was registered in 2011, when the redistributed quantity of products surpassed 29,000 tonnes. Considering that these volumes report to the 21 food bank network, they are used as surrogates for the reference volume of products available for donation at the 15 food bank network of the national instances. Accordingly, Table 6.10 on page 120 sets $\underline{TotalQ} = 25,000$ and $\overline{TotalQ} = 30,000$ as the limits of the interval within which the value for $TotalQ$ is randomly selected in each instance.

In terms of the regional instances, values are adjusted to $\underline{TotalQ} = 3,750$ and $\overline{TotalQ} = 4,500$ to account for the smaller dimension of the supply chain. Notice that the FPBA reference values concern the total volume of product delivered to charities, of which approximately 9% were purchased with financial donations. Thus, the value of $TotalQ$ is determined by excluding this proportion, expressed by $ratiofp$.

The total volume of each product $p \in P$ donated in period 0 ($TotalQ_p$) is obtained in *Step 2*, observing the range of contributions of each product p to the total volume in the FPBA network between 2011 and 2015. To that end, a percent value is randomly chosen within the intervals $\left[\underline{quant}_p, \overline{quant}_p\right]$ defined by the extreme values presented in Table 6.10 for every product p. Naturally, for national instances $p \in [1, 18]$, and for regional instances $p \in [1, 5]$. Next, the value of $TotalQ$ is updated accordingly in *Step 3*.

Step 4 of the procedure assigns one product family $k \in K$ to every donor $d \in DD \cup CD$. In 2015, 54.2% of the donors of the Lisbon food bank supplied dry products, 40.5% donated fresh products, and 5.3% offered frozen products. Although some suppliers, namely supermarkets and grocery chains, provide products of more than one family, most of the donors provide items of a single product

Parameters	Product ($p \in P$)			
	Designation	National	Regional	Price ($t = 0$)
τ_p^t	Bread, crackers, biscuits and snacks	$p = 1$		2.6113
	Coffee, tea, cereals, and pastry	$p = 2$		5.3735
	Milk	$p = 3$	$p = 1$	0.4740
	Rice, pasta, flours and purées	$p = 4$	$p = 2$	0.8213
	Soups, seasonings, dressings and fats	$p = 5$		2.1755
	Sugar and sweets	$p = 6$		1.2559
	Dry and canned legumes	$p = 7$		0.8387
	Canned meat and canned fish	$p = 8$		2.2811
	Water and sodas	$p = 9$		0.6765
	Baby food products	$p = 10$		7.3973
	Other dry products	$p = 11$		3.6018
	Cheese, dairy and eggs	$p = 12$		1.7194
	Fresh fruit	$p = 13$	$p = 3$	0.7899
	Fresh vegetables	$p = 14$	$p = 4$	0.8406
	Other fresh products	$p = 15$		5.9737
	Frozen vegetables	$p = 16$		1.5215
	Frozen meat and frozen fish	$p = 17$		2.6432
	Frozen desserts and ice cream	$p = 18$	$p = 5$	4.4345

Table 6.9: Prices of food products (k€/tonne) in period 0

family. The latter case is followed in *Step 4* by randomly selecting a percent value from the interval $[\underline{share}_k, \overline{share}_k]$, for each of the three product families $k \in K$. Parameters $donorsk_k$ indicate the total number of donors of product family $k \in K$, and are also obtained at *Step 4*. Assignment is made on the condition that all products of family $k \in K$ are supplied by $donorsk_k$ donors, and that all donors $d \in DD \cup CD$ are assigned exactly one family of products. Note that semi-randomly selecting the values, for every instance, from intervals that include the reference values obtained from the Lisbon food bank records allows for greater diversity of instances.

Next, *Step 5* determines which individual products $p \in P$ are donated by each donor. Considering which family of products $k \in K$ is donated by donor $d \in DD \cup CD$, a random binary decision is made for each product $p \in P_k$ in the national instances. Due to the smaller number of products considered in the regional instances, in this case it is assumed that each donor supplies all products of the family. Following, the total number of donors of product p ($donorsp_p$) is identified in *Step 6*.

The actual quantity of product $p \in P$ donated by donor $d \in DD \cup CD$ in period 0 is determined in *Step 7*. The reference values for these quantities are obtained by the ratio of the total quantity of product p, obtained in *Step 2*, to the total number of donors of product p, obtained in *Step 7*. A random deviation of ± 50% over the reference value for every product p determines the value of Q^0_{pd}, and is intended to create different supplier profiles. Furthermore, it also contributes to the diversity of supply chain configuration portrayed in the instances.

After updating $TotalQ$ in *Step 8*, parameters Q^t_{pd} are fixed in *Step 9*. For that, it is considered that the quantity of product $p \in P$ donated by donor $d \in DD \cup CD$ in period $t \in T$ varies randomly between -20% and +20% of the respective value in period 0.

The remaining steps of the procedure are devoted to determining the value of financial donations $\widetilde{Q}^t_d$ for every donor $d \in FD$ in each period $t \in T$. Although regional instances only account for one such donor, the procedure applies equally to national and regional instances. *Step 10* proceeds by identifying the total value of product donations ($TotalV^t$) according to the prices of products in each period given by parameters τ^t_p. Values are calculated for $t \in T \cup \{0\}$.

Step 11 makes use of $TotalV^0$ to obtain the total value of financial donations in period 0 ($TotalF^0$) based on $ratiofp$ (see *Step 1*). In *Step 12*, the corresponding values for every period $t \in T$ ($TotalF^t$) are also set. The reference value for financial donations of period t is determined similarly to the value of period 0. Afterwards, $TotalF^t$ of the period is fixed within an interval of ± 10% of the reference value.

Finally, parameters $\widetilde{Q}^t_d$ are determined in *Step 13* by dividing the total value of period $t \in T$ by the number of financial donors $|FD|$.

1. Determine $TotalQ$, the total quantity of food made available for donation in period $t = 0$, according to $TotalQ = U\left[\underline{TotalQ}, \overline{TotalQ}\right] \times \dfrac{1}{1 + ratiofp}$
2. For each product $p \in P$, determine total quantity made available for donation in period $t = 0$, $TotalQ_p = U\left[\underline{quant}_p, \overline{quant}_p\right] \times TotalQ$
3. Update $TotalQ$, as $TotalQ = \sum_{p \in P} TotalQ_p$
4. For each product family $k \in K$, assign one product family k to each donor $d \in DD \cup CD$, and determine $donorsk_k$, the total number of donors of product family k, such that $donorsk_k$ donors provide all donations of family k and $\sum_{k \in K} donorsk_k = |DD| + |DC|$, as follows: $donorsk_k = U\left[\underline{share}_k, \overline{share}_k\right] \times (|DD| + |CD|)$
5. For each product family, $k \in K$, assign food products $p \in P_k$ to each donor of product family k
6. Calculate $donorsp_p$, the total number of donors of product p
7. Determine Q^0_{pd}, the total quantity of product $p \in P$ made available by donor $d \in DD \cup CD$ in period $t = 0$, according to $Q^0_{pd} = U[0.5, 1.5] \times \dfrac{TotalQ_p}{donorsp_p}$
8. Update $TotalQ$, as $TotalQ = \sum_{p \in P} \sum_{d \in DD \cup CD} Q^0_{pd}$
9. Obtain parameters Q^t_{pd}, the total quantity of food product $p \in P$ made available by donor $d \in DD \cup CD$ in period $t \in T$, as follows: $Q^t_{pd} = U[0.8, 1.2] \times Q^0_{pd}$
10. Calculate $TotalV^t$, the value of total available food donations (in k€) in period $t \in T \cup \{0\}$, according to the price of food product τ^t_p: $TotalV^t = \sum_{p \in P} \tau^t_p \sum_{d \in DD \cup CD} Q^t_{pd}$
11. Calculate $TotalF^0$, the total value of available financial donations in period $t = 0$, according to $TotalF^0 = ratiofp \times TotalV^0$
12. Determine $TotalF^t$, the total value of available financial donations in each period t, according to $TotalF^t = U[0.9, 1.1] \times ratiofp \times TotalV^t$, for $t \in T$
13. Obtain parameters $\widetilde{Q}^t_d$, the value of financial donations made available by donor $d \in FD$ in each period t, as follows: $\widetilde{Q}^t_d = \dfrac{TotalF^t}{|FD|}$, for $t \in T \cup \{0\}$

Algorithm 6.1: Procedure *supply* to determine the values of parameters Q^t_{pd} and $\widetilde{Q}^t_d$

Parameters	Step	National	Regional
$ratiofp$	1	0.09	0.09
$\{\underline{TotalQ}, \overline{TotalQ}\}$	1	$\{25000, 30000\}$	$\{3750, 4500\}$
$\{\underline{quant}_1, \overline{quant}_1\}$	2	$\{0.029, 0.063\}$	$\{0.120, 0.230\}$
$\{\underline{quant}_2, \overline{quant}_2\}$	2	$\{0.015, 0.059\}$	$\{0.100, 0.320\}$
$\{\underline{quant}_3, \overline{quant}_3\}$	2	$\{0.083, 0.116\}$	$\{0.270, 0.540\}$
$\{\underline{quant}_4, \overline{quant}_4\}$	2	$\{0.066, 0.187\}$	$\{0.130, 0.240\}$
$\{\underline{quant}_5, \overline{quant}_5\}$	2	$\{0.028, 0.056\}$	$\{0.002, 0.020\}$
$\{\underline{quant}_6, \overline{quant}_6\}$	2	$\{0.006, 0.023\}$	
$\{\underline{quant}_7, \overline{quant}_7\}$	2	$\{0.017, 0.062\}$	
$\{\underline{quant}_8, \overline{quant}_8\}$	2	$\{0.017, 0.045\}$	
$\{\underline{quant}_9, \overline{quant}_9\}$	2	$\{0.025, 0.059\}$	
$\{\underline{quant}_{10}, \overline{quant}_{10}\}$	2	$\{0.001, 0.015\}$	
$\{\underline{quant}_{11}, \overline{quant}_{11}\}$	2	$\{0.018, 0.035\}$	
$\{\underline{quant}_{12}, \overline{quant}_{12}\}$	2	$\{0.073, 0.160\}$	
$\{\underline{quant}_{13}, \overline{quant}_{13}\}$	2	$\{0.145, 0.357\}$	
$\{\underline{quant}_{14}, \overline{quant}_{14}\}$	2	$\{0.075, 0.158\}$	
$\{\underline{quant}_{15}, \overline{quant}_{15}\}$	2	$\{0.002, 0.010\}$	
$\{\underline{quant}_{16}, \overline{quant}_{16}\}$	2	$\{0.002, 0.020\}$	
$\{\underline{quant}_{17}, \overline{quant}_{17}\}$	2	$\{0.002, 0.020\}$	
$\{\underline{quant}_{18}, \overline{quant}_{18}\}$	2	$\{0.002, 0.020\}$	
$\{\underline{share}_1, \overline{share}_1\}$	4	$\{0.500, 0.600\}$	$\{0.500, 0.600\}$
$\{\underline{share}_2, \overline{share}_2\}$	4	$\{0.350, 0.450\}$	$\{0.350, 0.450\}$
$\{\underline{share}_3, \overline{share}_3\}$	4	$\{0.025, 0.075\}$	$\{0.025, 0.075\}$

Table 6.10: Minimum and maximum values of auxiliary parameters for procedure supply

6.6 Demand parameters

The FPBA incorporates the demand requirements of charities on the basis of the demographic characteristics of the population assisted, and the type of food aid provided (see Section 4.1). While accounting for some fluctuation in volume, it is expected that the demand profile of each charity is maintained throughout the planning period. With the purpose of generating parameters R^t_{pc} that express the demand of charities $c \in C$ for products $p \in P$ in each period $t \in T$, a distinction is made between demand of served charities $c \in SC$, and demand of charities on hold $c \in HC$. Regarding the former, the supply of period 0 X^0_{pc} provides the demand profile for the following planing periods. Afterwards, the average profile of this group of charities is assumed as a reference to establish the demand profile of the waiting charities. In both cases, consistency with the supply volume available in each period must be ensured. Procedure *demand* presented in Algorithm 6.2 on page 123 details the steps followed to obtain parameters X^0_{pc} and R^t_{pc}.

Step 1 of the procedure appeals to auxiliary parameter $TotalF^0$ obtained in *Step 11* of Procedure *supply* to identify the total amount of financial donations available in period 0. The quantity of food items of product p bought with financial donations in that period ($Total\widetilde{Q}_p$) is obtained based on the share of the total amount that is spent with purchases of product p, and on the price of product p in the period τ^0_p. The range of contributions used in *Step 2* of Procedure *supply* is valid for semi-randomly determining the share of financial spendings per product.

The total quantity of food items of product p available in period 0 ($Prod_p$) is determined in *Step 2* by accounting for the quantity received from in-kind donations $TotalQ_p$ and the quantity bought with financial donations $Total\widetilde{Q}_p$.

The distribution of the available quantities in period 0 by the served charities in performed in *Step 3* to obtain parameters X^0_{pc}. For each product p, the first $|SC| - 1$ charities receive a fraction of the total quantity available in period 0 that does not exceed a maximum share expressed by $\frac{2}{|SC|}$. This share corresponds to 2% per charity in the national instances, and to 12.5% in the regional instances. The last charity $|SC|$ is assigned the remaining quantity that was not distributed to the other agencies, or zero if the available quantity $Prod_p$ was already distributed by the remaining. This process ensures that all product available in period 0 is assigned to the served charities. It may result that the quantities supplied to charities exceeds the reference value for the quantity available in period 0: $\sum_{c=1}^{|SC|} X^0_{pc} > Prod_p$. However, it does not conflict with supply parameters Q^t_{pd} and $\widetilde{Q}^t_d$ obtained in Procedure *supply*, and, most important, it establishes the necessary coherence between those parameters and the ones determined in Procedure *demand*.

Parameters R^t_{pc} expressing the product demand by served charities $c \in SC$ over the planning horizon are identified in *Step 4*, and assumed to vary between 90% and 110% of the quantities received in period 0. A correction factor of 0.05 (1.00) is added to the lower (upper) value of the range of variation $[0.90, 1.10]$ to rectify code errors arising from cases in which $X_{pc}^0 = 0$.

The demand requirements of the waiting charities $c \in HC$ are set in *Step 7* based on the average demand per product of the served charities ($AvgR_p^t$) assessed in *Step 5*, and enforcing the assumption that demand by charities exceeds donations of product donors (see Section 4.2).

Auxiliary parameters $Rest_p^t$ are calculated in *Step 6* to identify the quantity of available product p that is not absorbed by the demand of all served charities $c \in SC$. If this quantity is positive for any product $p \in P$, then it must be ensured by the demand of charities on hold that overall demand surpasses available in-kind supply. Accordingly, *Step 7* (a) establishes that the demand of the first $|HC| - 1$ charities can be at most twice the average demand of the initially served charities $c \in SC$. Concerning the last charity on hold, *Step 7* (b) establishes that if all available in-kind donations are already covered by the demand of served charities and of previous charities on hold, i.e. if $Rest_p^t - \sum_{c=1}^{|HC|-1} R_{pc}^t \leq 0$ holds, then its demand is set similarly to the first $|HC| - 1$ charities. However, if it is not guaranteed by the demand of the $|SC| \cup |HC| - 1$ charities that overall demand is larger that available in-kind donations, then this assumption is verified by the demand assigned to the last charity on hold. In this case, demand of charity $|HC|$ is randomly set at a value that is at least equal to the not yet covered available supply, and at most to twice that quantity. Thus, parameters R_{pc}^t are also set for all charities on hold $c \in HC$.

Finally, two demand-related parameters that are not included in Procedure *demand* are established as follows.

Parameter β_2 is fixed at 0.7 for both national and regional instances, meaning that, according to constraints (5.23), at least 70% of the product $p \in P$ supplied to served institution $c \in SC$ in period 0 is delivered in all planning periods $t \in T$. Notice that *Step 4* of Procedure *demand* guarantees that $R_{pc}^t \geq \beta_2 X_{pc}^0$.

Parameter β_3 concerns the minimum level of supply that initially waiting charities can expect if they are included in the supply chain (see constraints (5.24)). For both national and regional instances this level is set at 50% ($\beta_3 = 0.5$) of their demand for every product $p \in P$ in each period $t \in T$.

1. For each product $p \in P$, determine $Total\widetilde{Q}_p$, the total quantity of product purchased with financial donations in period $t = 0$, according to $Total\widetilde{Q}_p = U\left[\underline{quant}_p, \overline{quant}_p\right] \times \frac{TotalF^0}{\tau_p^0}$, with $\underline{quant}_p$ and $\overline{quant}_p$ (Table 6.10 on page 120)
2. For each food product $p \in P$, calculate the total quantity of product available from in-kind and financial donations in period $t = 0$ as follows: $Prod_p = TotalQ_p + Total\widetilde{Q}_p$ with $TotalQ_p$ obtained in ***Step 2*** of Procedure ***supply*** (Section 6.5)
3. Obtain parameters X_{pc}^0, the total quantity of food product $p \in P$ received by charity $c \in SC$ in period $t = 0$, as follows:
   (a) $X_{pc}^0 = U\left[0, \frac{2}{|SC|}\right] \times Prod_p$ for $c = 1, \ldots, |SC| - 1$, and
   (b) $X_{p|SC|}^0 = \max\left\{0, Prod_p - \sum_{c=1}^{|SC|-1} X_{pc}^0\right\}$
4. Obtain parameters R_{pc}^t, the demand of charity $c \in SC$ for product $p \in P$ in period $t \in T$, as follows: $R_{pc}^t = U[0.90, 1.10] \times X_{pc}^0$
5. Calculate $AvgR_p^t$, the average quantity of product $p \in P$ demand by each charity $c \in SC$ in period $t \in T$, according to $AvgR_p^t = \frac{\sum_{c \in SC} R_{pc}^t}{|SC|}$
6. Calculate $Rest_p^t$, the quantity of product $p \in P$ available at donors $DD \cup CD$ in excess of demand by charities $c \in SC$ in each period $t \in T$, according to $Rest_p^t = max\left\{0, \sum_{d \in DD \cup CD} Q_{pd}^t - \sum_{c \in SC} R_{pc}^t\right\}$
7. Obtain parameters R_{pc}^t, the demand of charity $c \in HC$ for product $p \in P$ in period $t \in T$, as follows:
   (a) $R_{pc}^t = U[0, 2] \times AvgR_p^t$ for $c = \{1, \ldots, |HC| - 1\}$, and
   (b) $R_{p|HC|}^t = \begin{cases} U[0, 2] \times AvgR_p^t, & \text{if } Rest_p^t - \sum_{c=1}^{|HC|-1} R_{pc}^t \leq 0 \\ U[1, 2] \times Rest_p^t - \sum_{c=1}^{|HC|-1} R_{pc}^t, & \text{otherwise} \end{cases}$

Algorithm 6.2: Procedure *demand* to determine the values of parameters X_{pc}^0 and R_{pc}^t

6.7 Scaling parameters

The final set of parameters concern the scaling factors involved in the objective functions of the MO-MILP model. These parameters are used to penalize, weight, or normalize the affected terms of the objective functions. Table 6.11 presents the values, or respective expressions that apply equally to national and regional instances.

Parameters	Value	Source
α_1, α_2	0.0001	user-defined
α_3, α_4	$\{0.25, 0.50, 0.75\} \quad \sum_{i=3,4} \alpha_i = 1$	user-defined
α_5	$w_5 \times \frac{1}{\lvert HC\rvert \times \lvert T\rvert} \times 1000$	user-defined
α_6	$w_6 \times \frac{1}{\sum_{t\in T} O^t} \times 1000$	user-defined
α_7	$w_7 \times \frac{1}{(\sum_{b\in OB}\sum_{k\in K} \overline{M}_{kb} + \lvert B\rvert \sum_{k\in K} M_{3k}) \times \lvert T\rvert} \times 1000$	user-defined
α_8	$w_8 \times \frac{1}{max\{U_{bc}: b\in B, c\in C\} \times \lvert T\rvert} \times 1000$	user-defined
α_9	$w_9 \times \frac{1}{\lvert P\rvert \times \lvert T\rvert} \times 1000$	user-defined
w_i	$\{0.15, 0.20, 0.40\} \quad \sum_{i=5,\ldots,9} w_i = 1$	user-defined

Table 6.11: Scaling factors

Parameters α_1 and α_2 are used in the economic objective function (5.39) to penalize unused transport capacity, and to promote savings from financial donations not spent by the last planning period (positive penalty), respectively. In both cases, parameters can also be called upon to convert the units of these two terms into the unit of the other components of the objective function (m.u.). However, in the present study their main purpose is to act as penalty factors, and so they are both assigned the value 0.0001.

Environmental objective function (5.40) involves parameters α_3 and α_4. The first is associated with the term accounting for food waste disposal costs, while the second affects the term expressing the cost of carbon footprint from transport activities. These parameters are used as weight factors to assert the preferences of the decision maker. Three preference options are foreseen: if the decision maker is neutral with regard to the two factors, then $\alpha_3 = \alpha_4 = 0.5$; if greater importance is assigned to the minimization of food waste, then $\alpha_3 = 0.75$ and $\alpha_4 = 0.25$; if, on the contrary, the decision maker favors the minimization of CO_2 emissions cost, then $\alpha_3 = 0.25$ and $\alpha_4 = 0.75$.

The inclusion of parameters α_5 through α_9 in the social objective function (5.41) has a twofold purpose. They are required to normalize the components of this objective function, and also to convey the preferences of the decision maker in a similar way as the factors used in the environmental objective function. For the latter, the expressions of parameters α_5 - α_9 presented in Table 6.11 identify the associated weight factors w_5 - w_9. These can take values 0.15, 0.20, or 0.40 to express the level of importance assigned to the respective terms by the decision maker. A neutral positioning with regard to the five social terms translates into attributing the value 0.20 to all factors w_5 - w_9. If, for example, the decision maker favors the inclusion of new charities in the supply chain, then the weight associated with the first term is set at $w_5 = 0.40$, and all the other weights take the value 0.15. The combination of the weight factors introduced in the environmental and social objective functions allows the formulation of eight different positioning alternatives by the decision maker. These cases are presented in the next section.

The other purpose of parameters α_5 to α_9 is to address the fact that each term of the social objective function is represented in a different measurement unit. Factoring all terms in the same objective function requires that each is included in proportion to its largest possible value. As discussed in Chapter 3, some authors opt to normalize the terms in proportion to the difference between the largest and the smallest values they can assume. In this case that option is not feasible because variables γ^t are not bounded by a lower value. Therefore, the largest value that each of the five social criteria can assume is given by the terms multiplying the weight factors w_5 to w_9 in the expressions of parameters α_5 to α_9 presented in Table 6.11.

The largest value of the first term of the social objective function corresponds to accounting for number of charities on hold $|HC|$ in each planing period $t \in T$. The second term is upper bounded by the value of the reference budget O^t in all periods t. Creation of social work value is limited by the largest possible storage capacity that can be available in the supply chain. It corresponds to installing, in addition to the initial capacity $\left(\sum_{b\in OB}\sum_{k\in K}\overline{M}_{kb}\right)$, the largest storage capacity size for all product families in all food banks, existing and potential $\left(|B|\sum_{\ell=3}\sum_{k\in K}M_{\ell k}\right)$, since the first planning period. The fourth social term is normalized by the maximum distance between any food bank $b \in B$ and any charity $c \in C$. This maximum distance varies from instance to instance, and is dependent upon the semi-randomly generated location coordinates of the charities and the food banks. It should not be misinterpreted as the largest admissible distance between a charity and its assigned food bank defined by set C_b in Section 6.1. The last social term concerns the highest level of unsatisfied demand registered at any served charity. According to constraints (5.26), if a given product p demanded by a served charity c is not supplied in period t, then $\sum_{b\in B}\frac{R^t_{pc}\,z^t_{bc}-x^t_{pbc}}{R^t_{pc}} = 1$. Noting that the largest possible value of δ^t is dependent upon the number of products $p \in P$ included in the instances, the term is normalized by the largest number of products ($|P| = 18$ for the national instances, and $|P| = 5$ for the regional instances) accounted for in each period t. It should be remarked that actually the value one for variables δ^t is never met in the presence of constraints (5.23) and (5.24). However, as the largest possible value of δ^t considering constraints (5.23) and (5.24) is dependent upon the inclusion of new charities $c \in HC$ in the supply chain, and thus not known upfront, it cannot be used as the normalizing factor of the last social objective function component. For that reason the total number of products is used in its stead. Finally, all parameters used in the social objective function are multiplied by 1,000 for scaling purposes.

6.8 Input scenarios

Table 6.12 presents the eight cases of combinations of weight factors considered for the computational study. The values of parameters α_3 - α_4 and w_5 - w_9 in the first case C1 carry a neutral positioning of the decision maker with regard to each environmental and social criteria accounted for in the respective objective functions. This case is denoted "Neutral" and corresponds to the default scenario. Cases C2 and C3 maintain a neutral social policy but express distinct preferences concerning the two environmental factors. In the first case, designated "Food waste", priority is assigned to the minimization of food waste disposal cost, while in the second ("CO_2 emissions") minimizing carbon footprint cost is preferred. The other five cases report exclusively to preferences affecting the social terms. In each case one of the social terms deserves the highest priority, and the remaining are valued equally among them. These cases are named "Inclusion" for prefering the introduction of new charities in the supply chain, "Investment" for favoring the least effort to raise capital, "Work value" when employment or volunteer work creation is promoted, "Proximity" if greater attention is given to the distances travelled by charities to collect food items, and finally "Equity" if fairness in product redistribution is the chief social goal.

The upper and lower bounds of the social objective function are not easily determined. This is due to the fact that some terms are not bounded, and some are in conflict with others. Consider for example cases C1 to C3 that convey a neutral positioning of the decision maker with regard to the five social criteria, i.e. each social term contributes with 20% of the total value. The largest social value is obtained when the first three terms of the social objective function reach their highest values, and the last two have the smallest values possible. That would correspond to solutions where all new charities are included from the first period, investment capital is never required, yet social work is created to its largest possible value. In such hypothetical solutions, the total value of the first three terms would be +600. However, that value is not attainable because the second (investment)

Case	Priority	α_3	α_4	w_5	w_6	w_7	w_8	w_9
C1	Neutral	0.50	0.50	0.20	0.20	0.20	0.20	0.20
C2	Food waste	0.75	0.25	0.20	0.20	0.20	0.20	0.20
C3	$C0_2$ emissions	0.25	0.75	0.20	0.20	0.20	0.20	0.20
C4	Inclusion	0.50	0.50	0.40	0.15	0.15	0.15	0.15
C5	Investment	0.50	0.50	0.15	0.40	0.15	0.15	0.15
C6	Work value	0.50	0.50	0.15	0.15	0.40	0.15	0.15
C7	Proximity	0.50	0.50	0.15	0.15	0.15	0.40	0.15
C8	Equity	0.50	0.50	0.15	0.15	0.15	0.15	0.40

Table 6.12: Cases of strategic priorities

and third (social work) terms are in mutual conflict. It is not possible to install the largest storage capacity possible on top of the initial capacity without investment capital spendings. Accordingly, the upper bound for these two terms would have to be determined jointly, corresponding to the largest creation of social value with the least investment effort. Moreover, the upper bound of the objective function also requires that each of the last two terms is factored in at its smallest value possible. That value would be zero if demand of served charities (all, according to the first term) is fully satisfied by food banks that share the same location as the assigned charities.

The hypothetical lower bound for the social objective function value is even less straightforward, particularly due to the fact that investment expenditures can freely exceed the reference budget by any value ($\gamma^t \in \mathbb{R}$). By opposition to the upper bound case, obtaining the lowest social values would involve creating the smallest social work value, while spending the largest possible amount in opening and closing of facilities, and capacity installation. Concurrently, it would require not serving new charities, and ensuring that served charities would be assigned to the farthest food bank possible. Moreover, variables δ_t measuring the maximum level of unsatisfied demand would be determined by the minimum quantity of products that has to be supplied to initial charities. Considering that the smallest theoretical values of the first and third terms is zero, and that the second, fourth and fifth terms can reach negative values, the lower bound of the social objective function certainly has a negative value, however it not easily determined.

Although the range of values achievable by the social objective function is not clearly bounded, the above discussion provides some insight regarding the social results obtained in the computational experiment presented in the following chapters.

Summary Chapter 6

Chapter 6 was dedicated to the methodology developed to obtain instances for the FBNP problem. Instances illustrate both national and regional food bank supply chains. Based on the FPBA geographical dispersion of facilities, as well as their respective size, coordinates identifying the location of existing food banks, and potential sites for the installation of new facilities are semi-randomly generated in an area of $[0,\ 500] \times [0,\ 1000]$ for the national instances, and $[0,\ 500] \times [0,\ 335]$ for the regional instances. The purpose is to obtain instances conform but not limited to the FPBA case. This will allow the usefulness of the problem to other food bank supply chains with similar features, and the generalization of results and insights obtained from the computational experiment to other situations.

The national (regional) instances comprise 15 (four) food banks operating in period 0, and three (one) sites for potential food bank set-up. In the national instances, food banks are supplied by 62 product donors and five financial donors. The regional cases comprise 10 product donors and one financial donor. 100 (16) served charities, plus 20 (three) on hold for food assistance constitute the target population of the national (regional) instances.

While location of food banks is the same in all instances, coordinates for donors and charities locations change from instance to instance. Both types of instances foresee three families of food products (dry, fresh, and frozen), three storage and transport capacity sizes (small, medium and large), and five planning periods. National instances consider 18 individual food products whereas regional instances consider the five products that represent around 70% of all redistributed items. All three families of products are represented by one or more of the five products selected for the regional instances.

Initial storage and transport capacity of food banks operating in period 0 are set based on the range of values observed in the FPBA facilities. The size of the food banks is taken into account to define the type, and capacity of storage and transport for each of the product families initially available in every operating facility. Afterwards, capacity of each size $\ell \in L$ of additional storage and transport resources is defined in reference to the initial capacities.

Similar to the distance unit introduced to express distances between the stakeholders locations, a monetary unit is used to measure most financial parameters. Supported by a top-down approach starting from the value of budget O^t in each period, values are set for all parameters pertaining to investment and operating costs. Unitary capacity costs depend on size (featuring economies of scale), product families (considering distinct technical requirements), and/or

regional location of facilities.

Financial parameters expressed in k€ are derived from FPBA data (price of products), relevant references (waste disposal cost), or official sources (CO_2 emissions cost and national average salary). All costs are set for period 0. Different assumptions are made regarding their annual growth rates throughout the planning horizon.

Sections 6.5 and 6.6 presented two procedures developed to determine supply and demand parameters required by the MO-MILP model and not fully supported by FPBA data. The procedures ensure the necessary coherency between supply and demand quantities. Furthermore, they guarantee that relevant model assumptions, e.g. relating to insufficiency of donations, are observed by the instances. Based on ranges of volumes set in accordance with the overall level of activity of the FPBA supply chain, instances are characterized by a diversity of supply chain situations that are required to sustain the generalization objectives mentioned above.

Sections 6.7 described the intention of the scaling parameters involved in the three objective functions. These parameters are used as penalty factors in the economic objective function, as weight factors to convey the decision maker preferences with regard to the two environmental terms, and both as weight and normalizing factors associated with the five social criteria. Eight combinations of weights describe the different input scenarios developed for the computational experiment. As presented in the final section, these scenarios correspond to different environmental and social policies by the decision maker. A neutral environmental positioning is defined by adopting identical weights for the environmental terms. Similarly, a neutral social policy does not differentiate among the weights associated with the five social criteria. Policies that favor either one of the environmental, or the social goals are defined by valuing more the coefficient of the term that expresses that goal. Accordingly, combinations define cases denoted as "Food waste", "$C0_2$ emissions", "Inclusion", "Investment", "Work value", "Proximity", and "Equity". This chapter ends with a discussion about the lower and upper bounds of the social objective value.

The following chapters are dedicated to the results of the computational experiment performed on the regional and national instances. First, results obtained for the regional instances are presented next in Chapter 7.

Keywords: FPBA; Semi-random generation of instances; National and regional supply chains; Decision-maker positioning

Chapter 7

Regional supply chain

The content of this chapter is partially included in Martins et al. (2019).

A typical regional supply chain set-up is depicted in Figure 7.1 on page 132. On the basis of the procedure established to generate instances for the FBNR problem presented in the previous chapter, it comprises a network of four existing food banks ($|OB| = 4$) and one potential location for the installation of a new facility ($|PB| = 1$). Donations are provided by eight delivery donors ($|DD| = 8$), two collection donors ($|CD| = 2$) and one financial donor ($|FD| = 1$). Sixteen beneficiary agencies are initially served by the supply chain ($|SC| = 16$) and three others are on-hold to be included ($|HC| = 3$).

The computational study carried out for the regional supply chain considers a set of 20 instances. In all instances the number and location of food banks is the same, corresponding to those displayed in Figure 7.1. However, storage and transport resources available in each existing facility vary from instance to instance. The number of donors and charities is also the same in all instances but their location and respective supply and demand profiles are individual to each instance.

The regional supply chain redistributes five different products ($|P| = 5$) aggregated into three families ($|K| = 3$): dry products comprise (1) milk and (2) rice, pasta, flour and purées ($P_1 = \{1, 2\}$), (3) fresh fruit and (4) fresh vegetables are the fresh products ($P_2 = \{3, 4\}$), and the frozen product is (5) frozen desserts and ice cream ($P_3 = \{5\}$). The minimum level of supply to each initially served charity $c \in SC$ in each planning period $t \in T$ is set at 70% of deliveries made in period 0 ($\beta_2 = 0.7$). If included in the supply chain, then charities initially awaiting food supply $c \in HC$ will receive at least half of their demand in each period $p \in P$ ($\beta_3 = 0.5$). Furthermore, charities can only be assigned to food banks located within a 250 d.u. radius.

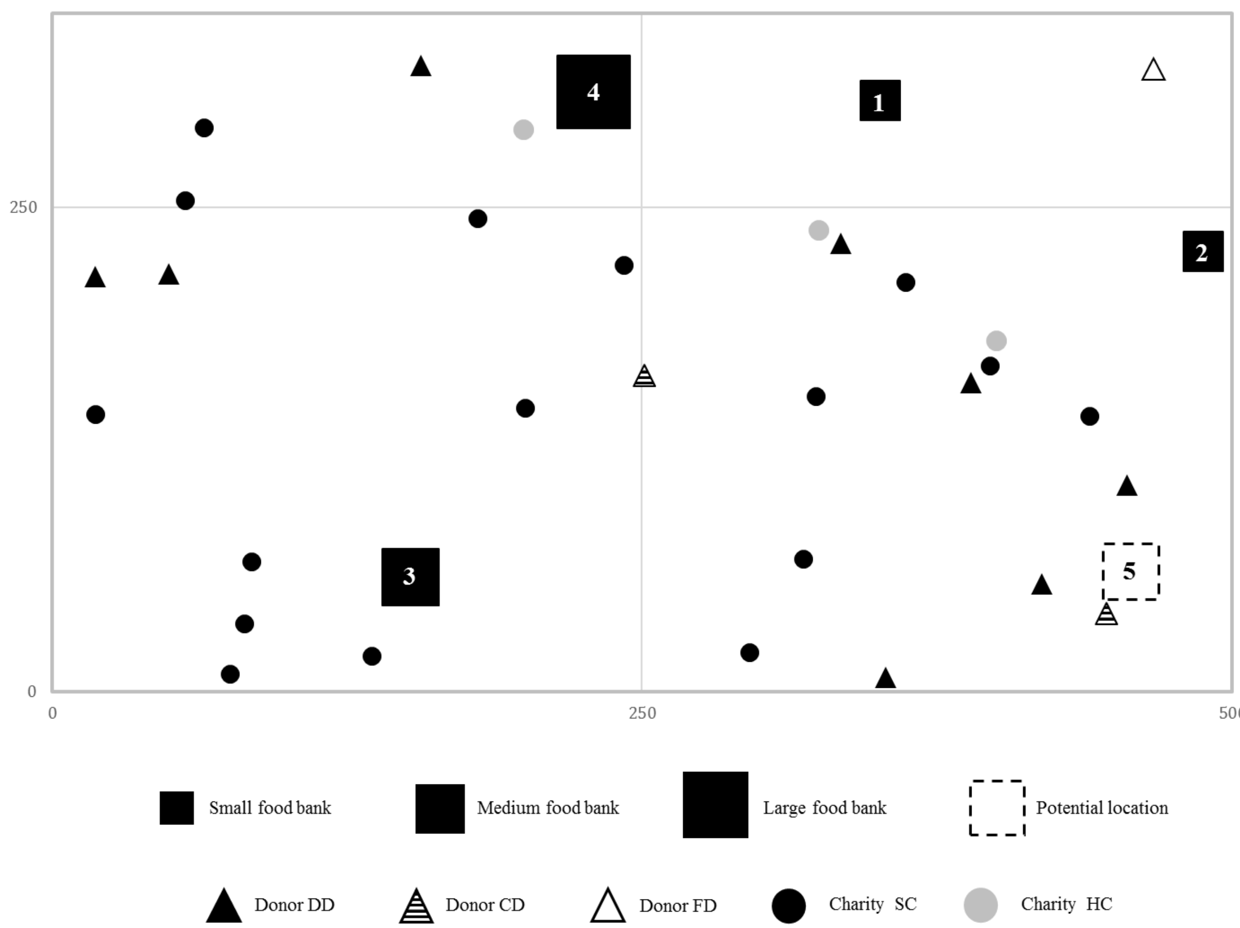


Figure 7.1: Regional supply chain

The network redesign project spans five planning periods ($|T| = 5$). In each period, there is no limit imposed regarding the maximum number of allowed changes of food banks status ($\beta_1 = 1$). To install storage and transport capacity, food banks have three option of sizes ($|L| = 3$): small, medium and large. All parameters used in the study are presented in Chapter 6.

Each test instance has 5,067 constraints and 5,420 variables, including 950 binary and 4,470 continuous variables.

Section 7.1 presents the methodology followed to obtain solutions for the decision problem. Results for a set of 20 test instances are reported in Section 7.2. One instance is selected to illustrate in detail the main features of the solutions (Section 7.2.1). Results for the case expressing a neutral policy regarding environmental and social criteria (case C1 of Section 6.8) are reported in Section 7.2.2, followed by derived managerial insights in Section 7.2.3, and the comparison with the starting supply chain configuration in Section 7.2.4. Results for priority cases C2 through C8 are discussed in Section 7.2.5. Finally, Section 7.2.6 is dedicated to the computational effort required to obtain solutions for the regional supply chain instances.

7.1 Solving methodology

Multi-objective problems differ from single objective problems because, unlike the latter, they usually do not have a unique optimal solution, or a set of alternative optimal solutions. Rather they are characterized by the optimization of multiple and conflicting objectives. Subsequently, in general, there is no single solution that simultaneously optimizes all objective functions. In these problems the concept of optimality of single objective problems is replaced with the notion of Pareto optimality or efficiency (Ehrgott and Ruzika, 2008).

A feasible solution for a multi-objective problem is Pareto optimal if improving the value obtained for one of the objective functions compels the deterioration of the value obtained for at least one of the other objective functions. The set of all non-dominated points, corresponding to Pareto optimal or efficient solutions, is denoted as Pareto set.

According to Mavrotas (2009) citing Hwang et al. (1979), multi-objective optimization methods to identify Pareto optimal solutions can be divided into three categories, depending on the moment in which the decision maker intervenes in the optimization process.

A priori methods require the decision maker to articulate preferences on the objectives before the solving process starts. Preferences are expressed by the setting of goals, or weights associated with each objective. In practice, it may be difficult for the decision maker to specify, and particularly quantify preferences beforehand. By contrast, no preferences are considered in *a posteriori*, or generation methods. These methods involve searching for all, or at least a representative set of Pareto optimal solutions, from which the decision maker then selects the most adequate alternative. The generation of many (or all) Pareto optimal solutions is often computationally prohibitive. Moreover, the usually very large number of Pareto optimal solutions can make it harder for the decision maker to select a preferred alternative. The third category is comprised of interactive methods whereby the search towards promising solutions is guided by preference information specified and refined by the decision maker during the search process. Phases of searching for solutions are interchanged with discussions with the decision maker, allowing the process to converge to the preferred solutions within a few iterations. The solutions obtained with this type of methods are conditioned by the range of preferences of the decision maker, and there is no guarantee that all efficient solutions are identified.

Lexicographic ordering (LO) is an *a posteriori* method that provides the decision maker with a concise set of Pareto optimal solutions. The complex and interrelated decisions involved in the FBNR problem advise a detailed and comprehensive analysis of the solutions obtained, and of the trade-offs that occur when economic, environmental, and social objectives are considered simultaneously. This analysis is not viable for results comprising a large number of Pareto optimal solutions. Limiting the alternative optimal (re)designs of the network of food banks to the number of lexicographic solutions allows informed decisions, and supports an aware (re)positioning of the supply chain. Lexicographic solutions correspond to the reference key points that frame the range of every efficient solution available. Moreover, lexicographic points are elemental in other *a posteriori* methods such as the AUGMECON method (Mavrotas, 2009) which, as discussed in Chapter 3, is frequently and successfully used in multi-objective problems.

Let A in expression (7.1) be the coefficients matrix on the left-hand side of all MILP model constraints (5.1) to (5.38), assuming that slack variables have been added to constraints, when necessary, to make them all equalities, and b represent the right-hand side vector. Let x be the vector with all variables. $\mathcal{X}$ describes the conditions satisfied by the variables, including their domain.

$$\mathcal{X} = \{x \in \mathbb{R}^n : Ax = b\} \tag{7.1}$$

Let also c, e and s represent the vectors with the coefficients of the economic, environmental and social objective functions, respectively.

$$z_1 = c^T x \tag{7.2}$$

$$z_2 = e^T x \tag{7.3}$$

$$z_3 = s^T x \tag{7.4}$$

The multi-objective programming (MOP) problem is written as follows:

$$(MOP) \quad \{min\,(z_1(x), z_2(x), -z_3(x) : x \in \mathcal{X})\} \tag{7.5}$$

Under these conditions, the models presented in each box of Figures 7.2 to 7.4 are single objective mathematical programming problems.

For a pre-defined ranking of the three objectives according to their relative importance, the LO method starts by optimizing the objective given the highest preference, subject to the original constraints. The expressions of the other two objectives are included as constraints subject to a large

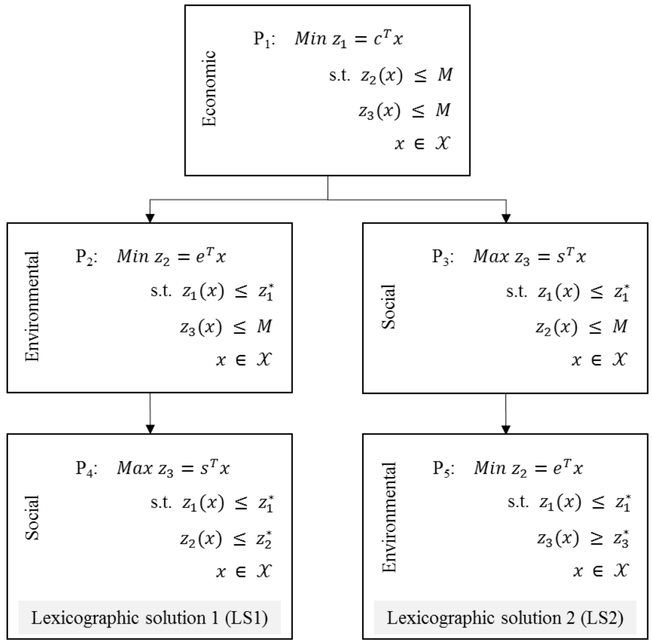


Figure 7.2: Method to obtain economic-centric solutions

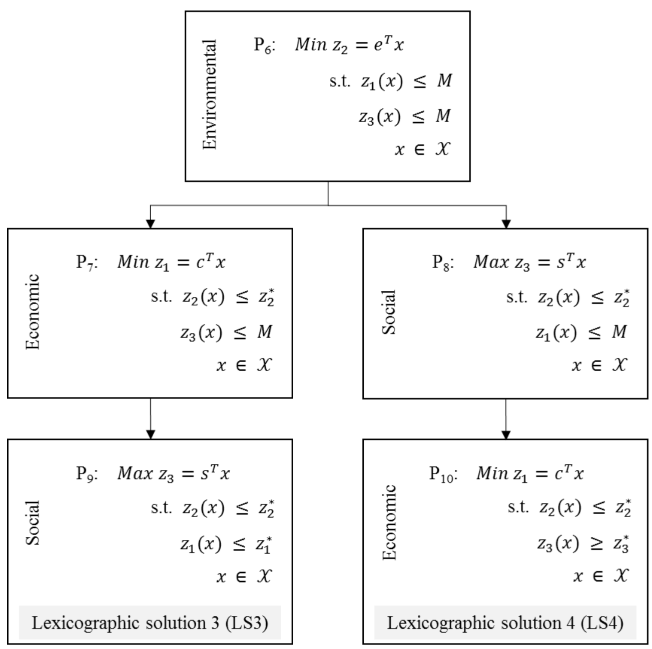


Figure 7.3: Method to obtain environmental-centric solutions

enough positive scalar M so that they do not influence the outcome of the problem. Then, the second most important objective is optimized with an additional constraint. This constraint guarantees that the first objective function preserves its optimal value, which corresponds to the solution of the previous problem. The third and final step consists of optimizing the least important objective, subject to the original constraints extended with two constraints that ensure the preservation of the optimal values of the two most important objectives. The outcome of the LO method are two Pareto optimal solutions for each objective function (Ehrgott, 2005).

Figures 7.2 to 7.4 illustrate all single objective problems involved in solving the triple objective FBNR problem according to the LO method.

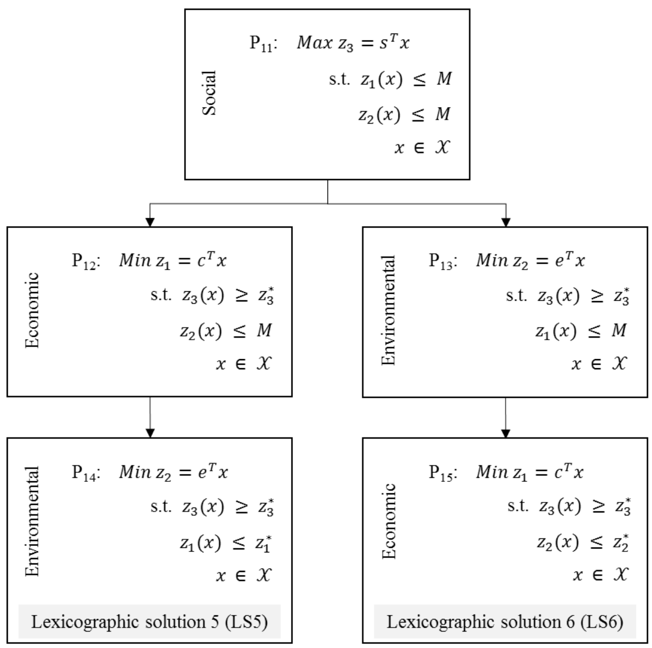


Figure 7.4: Method to obtain social-centric solutions

Lexicographic solutions LS1 and LS2 are obtained when the economic objective function (5.39) has the highest importance (see Figure 7.2). These solutions are hereinafter referred to as *economic-centric*. When the environmental objective function (5.40) is given the highest preference, the two *environmental-centric* lexicographic solutions LS3 and LS4 are identified, as displayed in Figure 7.3. Finally, Figure 7.4 shows how the two *social-centric* lexicographic solutions LS5 and LS6 are generated from assigning primary importance to the social objective function (5.41). Observe that each pair of lexicographic solutions requires solving five single objective problems. Hence, for each test instance, a total of 15 single objective MILP problems are solved to obtain the corresponding six lexicographic solutions. Observe also that the ideal vector, comprised of the best value for each objective function, is the outcome of solving problems P_1, P_6 and P_{11}.

7.2 Computational study

7.2.1 Illustrative example

Instance 15 is selected to illustrate the structure of the food bank supply chain network associated with each lexicographic solution. This instance is representative of the complete set of regional instances tested to the extent that the main features emerging from the average results over the 20 instances are largely present in the six lexicographic solutions obtained for this particular instance. The results described next refer to the neutral case of Table 6.12 on page 127, i.e. there is no particular preference for any of the two terms of the environmental objective function, nor for any of the five terms of the social objective function.

Figures 7.5 to 7.10 on pages 138 to 146 display the network configuration in the last period of the planning horizon (period 5) for the six lexicographic solutions. Table 7.1 reports the objective functions values for the solutions. Details of the individual features of these solutions are summarized in Table 7.2 on page 150. Appendix B supports the interpretation of Table 7.2, presenting the description of the features that characterize the solutions. Food banks are identified by numbers following Figure 7.1 on page 132.

Objective functions	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Economic (m.u.)	6,094.42	6,094.42	7,527.19	8,825.47	8,183.38	8,208.06
Environmental (k€)	505.57	529.95	142.14	142.14	390.08	370.39
Social	-82.61	-75.57	63.95	181.23	275.67	275.67

Table 7.1: Objective functions values of the lexicographic solutions: instance 15

The two economic-centric solutions LS1 and LS2, i.e. the solutions that are obtained when the first priority is the economic objective, share the same economic value (6,094.42 m.u.) but differ with respect to the values of the other two objectives, and also in terms of the supply chain configuration.

Figure 7.5 on page 138 shows that in LS1 there are three operating food banks. One of the small

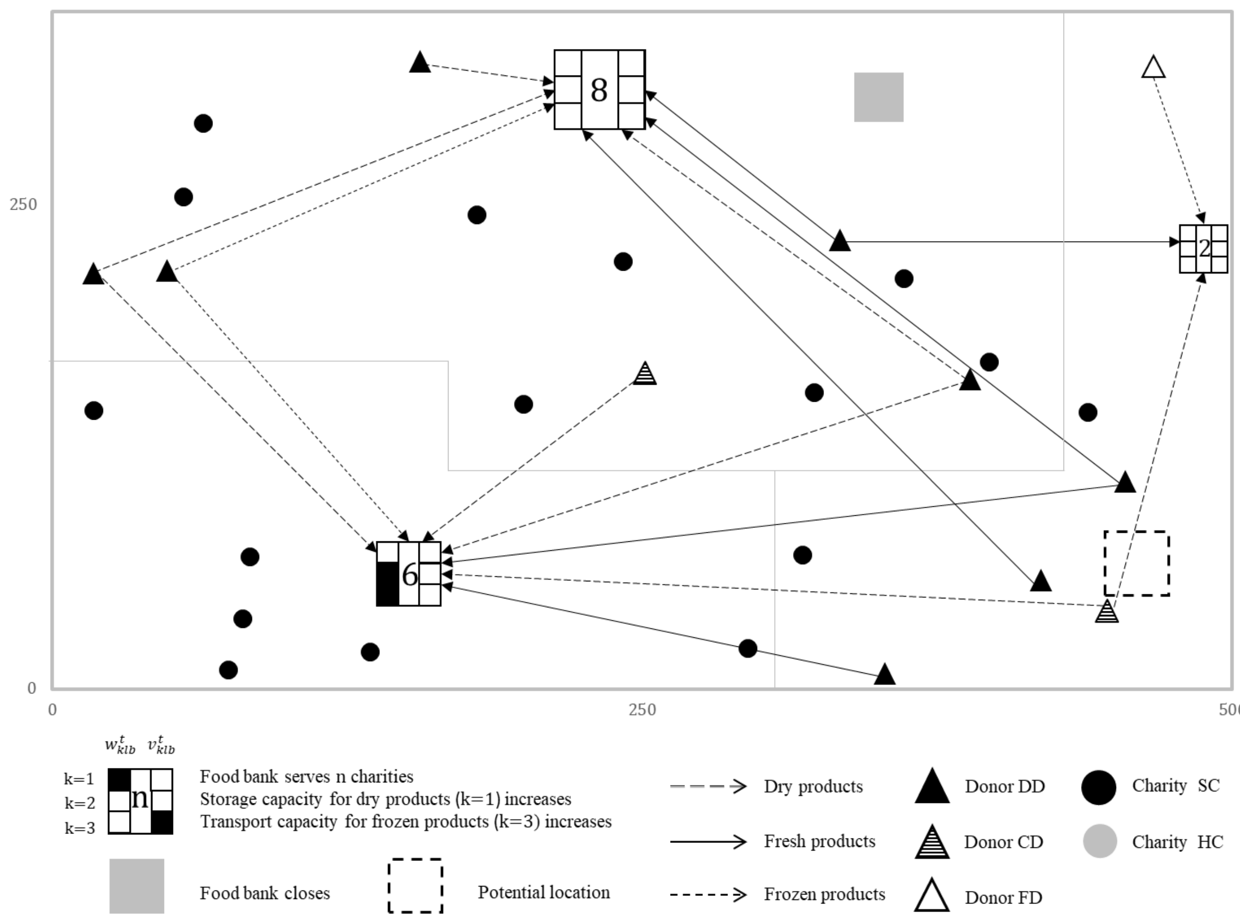


Figure 7.5: Supply chain configuration of LS1: instance 15

size facilities run by the institution prior the netwok redesign project is shut-down, and the medium size facility expands its storage capacity for fresh and frozen products by adding, in both cases, medium size capacity (see Table 7.2 on page 150). All decisions occur in the first period (not shown in the figure). The available transport capacity at the three operating facilities is kept unchanged.

The three running facilities supply the 16 initially served charities. No new charity is included in the supply chain, and the level of supply to the served charities is kept at the minimum possible, that is at 70% of the quantities received by these charities in period 0. This volume corresponds, in the case of this instance, to 70.5% of the demand by charities $c \in SC$ over the planning period (see Table 7.2). Overall, factoring in all charities, including the ones that are not included in the supply chain, the percent of demand satisfied by the supply chain of LS1 is less than 60% (59.7%) of the dietary needs of the target population. Accordingly, variables δ^t that measure the level of unsatisfied demand register in LS1 (and LS2) the highest value of all solutions.

This supply chain manages approximately 12,337.4 tonnes of food, valued at 10,122.2 k€, over the five planning periods, which is the lowest volume registered in all solutions. Donations are received mostly from delivery donors (72.7%), while products collected at donors represent 27.0% of the total. Food items bought with financial donations account for the remaining 0.3%.

Regarding the volume of products collected from donors $c \in CD$, LS1, along with LS2, registers one of the largest values of all solutions. This is due to the modeling effect involving variables θ^t_{kb} discussed in Section 5.6. Recall that these variables are maximized in the economic objective function (5.39) with the purpose of minimizing the unused transport capacity of the food banks. Besides not acquiring new transport resources, the other way by which unused transport capacity can be minimized is to actually promote the use of vehicles to collect products from donors (see constraints (5.15) and (5.16)). This results in food supply chains characterized by a proportionally higher quantity of products picked-up at collection donors than in other solutions, and subsequent small volume of food waste at these donors (only 1% of the products available for donation by donors $c \in CD$ are not collected by the food banks).

Overall, food product waste amounts to 24.7% of total products available for donation, and is registered almost exclusively at delivery donors (99.1%). In fact, 30.9% of the volume available for donation by this type of donors is not received by the food banks. The high total level of waste is a direct consequence of the decision to supply charities at the minimum level possible. The concentration of waste almost exclusively at delivery donors (99.1%) stems from the implicit preference to pick-up products from collection donors discussed before. It should also be noticed that the quantity of products bought with financial donations is very small (0.3% of the total donations). Correspondingly, the percentage of financial donations not used by the last period (85.4%) is one of the highest registered in all solutions.

In spite of the fact that the total quantity of food products processed by this supply chain is the lowest of all solutions, it generates one the highest volume of CO_2 emissions (close to 870 k tonnes-d.u., valued at 753.1 k€). This is another consequence of the decision to secure more than a quarter of the total volume of products from donors that require collection by the food banks. In this regard the results of LS1 are only surpassed by those of LS2.

LS1 is also the solution with the largest distance between a served charity and its assigned food bank (232.1 d.u.). There are no changes in assignments over the planing horizon: the large food bank serves the same eight charities in all periods, and the same occurs with the six agencies supplied by the medium size facility and the two charities served by the small food bank. Due to the few network changes, the investment capital required is only 22% of the total reference budget. Still, in the only period with investment (period 1), capital spendings exceed the reference value for the period. This feature is repeated in all solutions with the exception of the two social-centric solutions LS5 and LS6.

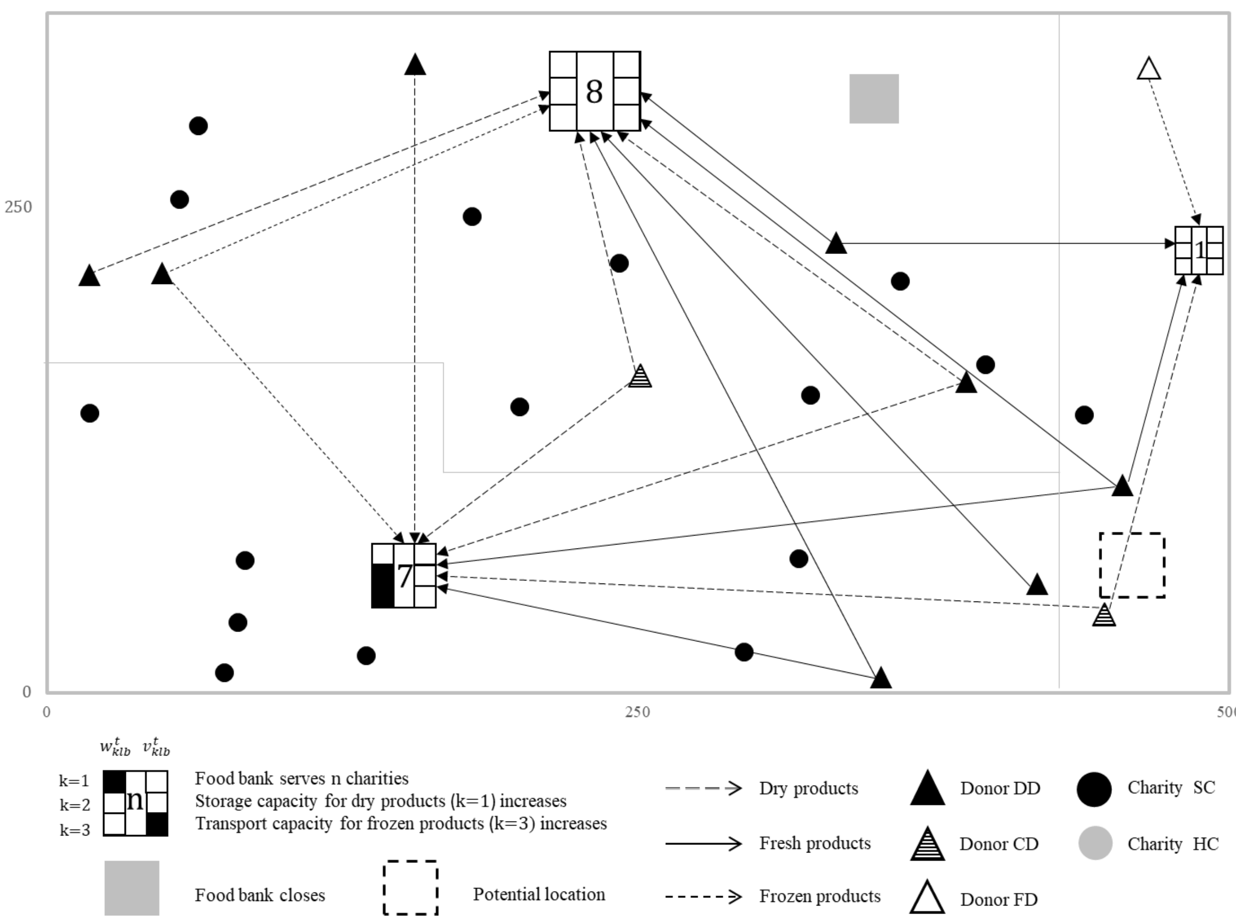


Figure 7.6: Supply chain configuration of LS2: instance 15

The profile of the second economic-centric solution LS2 is similar to that of LS1. The total volume of processed products is the same, as is the total percentage of food waste, and the supply level of the served charities. However, as displayed by Figure 7.6, the supply chain configuration is slightly different.

The supply chain of LS2 comprises a network with the same three food banks as LS1, and also has the same capacity acquisition decisions. Accordingly, the two solutions share an identical level of effort required to raise the investment capital necessary to implement network changes (22.0%).

Also in both solutions the number of charities served is 16, i.e. only the initially served front line agencies. Yet, in LS2 there is a different assignment of charities per food banks. In this solution the large food bank supplies the same eight charities that it serves in LS1, but the medium facility supplies one extra charity (seven in LS2, and six in LS1), while the small food bank only has one assigned agency in LS2 (two are assigned to this bank in LS1). The change of assignments from LS1 to LS2 lowers the maximum distance between the charities and the respective food banks to 217.9 d.u. This difference between the two solutions is justified by the fact that, in the process of obtaining LS2, the social objective has the second highest priority, whereas for LS1 it has the lowest priority.

That is, however, the only social advantage that LS2 has over LS1. All other social criteria - number of charities included in the supply chain, investment capital raising effort, value of social work created, and highest unsatisfied demand of served charities - are identical in the two economic-centric solutions.

By contrast, environmental costs are more penalized in LS2 than in LS1. Despite the same overall food waste level of the two solutions, in LS2 all waste is located at delivery donors. Concurrently, all food products available at collection donors are picked-up by vehicles of the food banks. This policy generates the highest CO_2 emissions volume of all solutions (925,322.2 tonnes-d.u., corresponding to more than 800 k€ over the planning horizon). It derives from the fact that, whereas in LS1 the environmental objective takes precedence over the social, which (marginally) limits the use of the food banks vehicle fleet to collect products, in LS2 the environmental objective has the least importance, and so the percent of products coming from collection donors is the largest of all solutions (27.31%).

The slight differences between LS1 and LS2 are reflected in the values of the objective functions. While both solutions have the same economic cost (6,094.4 m.u.), LS1 has an environmental cost (505.6 k€) that is lower than that of LS2 (530.0 k€), but also a lower (worse) social value (-82.6 vs -75.6). In general, LS1-LS2 originate the poorest environmental and social results of all solutions obtained.

Naturally, the best environmental results are obtained by the food supply chains conceived by solutions LS3 and LS4. Although revealing significantly different supply chain configurations, as depicted by Figures 7.7 (p. 142) and 7.8 (p. 143), these two solutions share that same food waste level (8.1%), and carbon emissions volume (approximately 230.3 k tonnes-d.u.), resulting in a total environmental cost of 142.1 k€ (cf. Table 7.1 on page 137). Other than this common feature, the two environmental-centric solutions diverge with respect to most of the other aspects studied.

As in solutions LS1-LS2, the supply chain of LS3 portrayed in Figure 7.7 comprises three operating facilities. However, in LS3 the changes operated in the starting network are more severe. The large food bank is kept with the same capacity resources, and the medium size bank registers the same capacity expansion observed in LS1-LS2. Simultaneously, it is decided to shut-down the two small food banks, and open a facility in a new site. The new facility installs storage capacity for all food

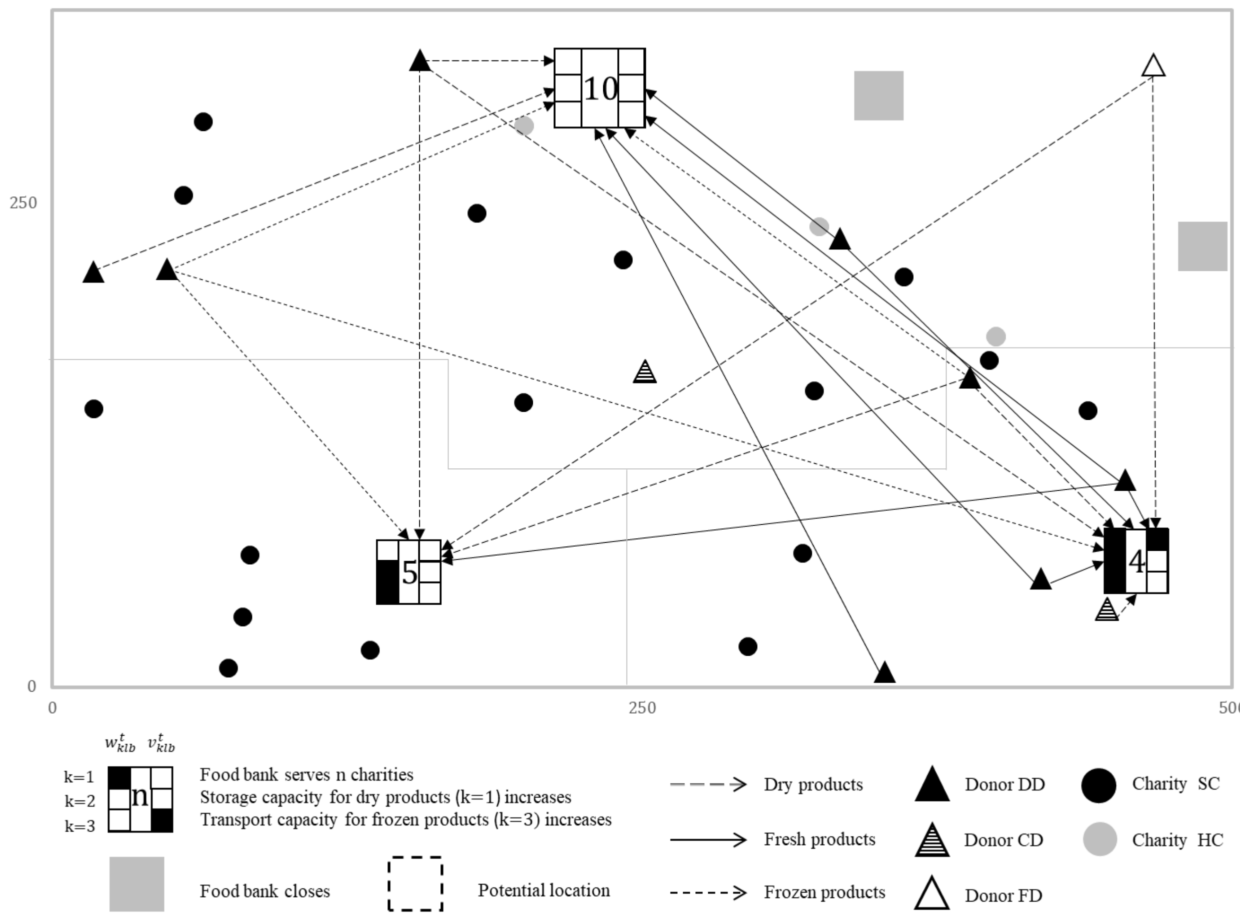


Figure 7.7: Supply chain configuration of LS3: instance 15

products (small size for dry products, and medium size for fresh and frozen products), and transport capacity for dry products. All location and capacity decisions are implemented in the first planning period.

As depicted in Figure 7.8, in the supply chain of solution LS4 all possible facilities are operational. The initial four food banks remain open, and the potential bank is deployed. In addition to the capacity decisions of LS3 regarding the large, medium and new food banks, in LS4 the two small food banks not only remain operational but actually see their storage capacity expanded. In one of the small food banks storage capacity is added for fresh products, and in the other for frozen products. In both cases the option is for the small size level of capacity. Just as in solution LS3, all these decisions are executed in the first period.

Despite the different options regarding the number and capacities of active food banks, a total of

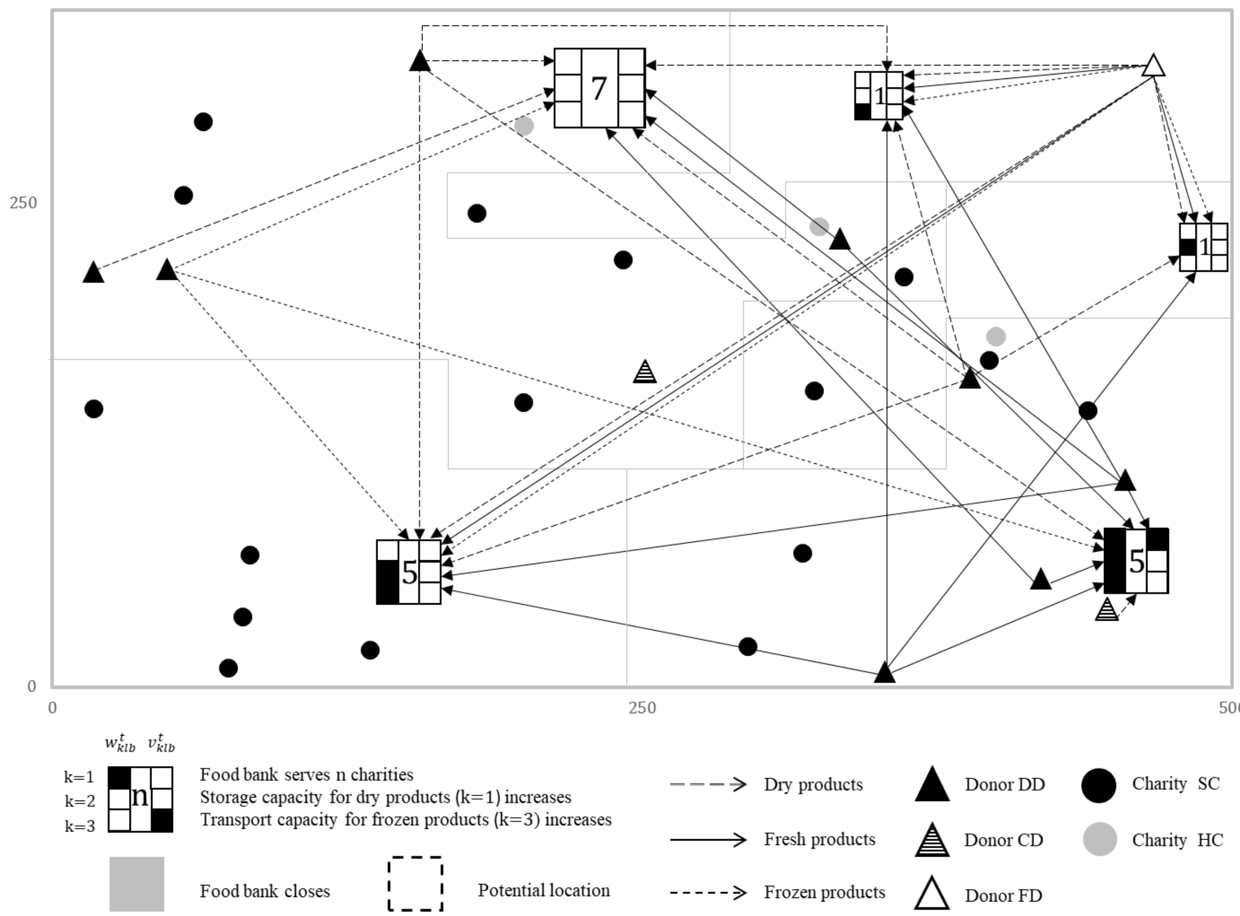


Figure 7.8: Supply chain configuration of LS4: instance 15

19 charities are served by the last planning period in both solutions.

Yet, although three (i.e. all) new charities are included in the supply chains of LS3 and LS4, the pace of inclusion is not the same in the two solutions. In LS4 the three beneficiary agencies are served from the first period, but in LS3 only two are included from the start. The third is attended only in the last period, which corresponds to a percent of inclusion over the whole planning period of 73.3% (cf. Table 7.2). Being as charities are outlets for the products available for donation, their inclusion in the supply chain enables the minimization of food waste, which is one of the main goals of this pair of solutions. Accordingly, in these two solutions not only the number of charities served is increased versus the starting status, but also the volume of product supply rises remarkably compared with solutions LS1-LS2. The level of supply to all charities, served or not, reaches 73.5% in LS3 and 81.4% in LS4, which compares for example with the level of 59.7% obtained in LS1 and LS2. The total volume of food products run by the supply chain is 15,196.7 tonnes (12,858.2 k€) in LS3 and 16,824.6 tonnes (14,022.5 k€) in LS4. This represents an increase of approximately 23% and 36%, respectively, over the volumes of LS1-LS2. Notice that, in this regard, the environmental objective (food waste reduction) acts also as a driver for the social objective (higher levels of assistance to population).

It should also be noted that, not only there is the aforementioned considerable reduction in food waste versus solutions LS1-LS2, but its composition changes fundamentally. Pursuing the objective of minimizing the environmental impact of CO_2 emissions, the use of vehicles to collect donations is discouraged. Therefore, while the totality of products made available by delivery donors are redistributed to charities, in the case of collection donors almost 40% of the available products are not picked-up.

Regarding financial donors, LS3 and LS4 convey different approaches determined by the priority given to the economic objective in each solution. In LS3 only 1.2% of the food products processed by the supply chain are bought with financial donations, which results in a high percentage of non-use of these donations by the last period (92.5%), similar to the levels registered by LS1-LS2. By opposition, in LS4 all financial donations received during the planning period are spent in the acquisition of food products. In this solution these products account for almost 11% of the total volume. Fully using the financial donations available enables the increase of quantity of products supplied to charities from 15,196.7 tonnes in LS3 to 16,824.6 in LS4.

The higher priority to the social objective in LS4 versus LS3 also translates into lower maximum distance between charities and respective food banks (182.5 d.u. vs 212.8 d.u.), higher social work value created (2,562.5 k€ vs 2,186.3 k€), and improved balance in the redistribution of products (largest value of δ^t is 1.5 in LS3 and 0.5 in LS4). In general, environmental-centric solutions improve the social results obtained by the economic-centric solutions with regard to all criteria but one. The downside resides in the higher investment capital raising effort. The network redesign determined by these solutions demand the use of 67.3% in LS3, and 62.6% in LS4 of the reference investment capital O^t. These are the largest values registered by any of the six lexicographic solutions.

Nevertheless, as seen in Table 7.1 (p. 137), solutions LS3-LS4 provide not only the best environmental cost achieved by any solution, but also a social value (circa 64.0 in LS3 and 181.2 in LS4) that largely surpasses the ones registered by LS1-LS2. However, these environmental and social results are obtained at the expense of an economic cost that, in LS3 (LS4), is 24% (45%) greater than in solutions LS1-LS2.

The two social-centric solutions LS5 and LS6 exhibit the largest similarity among all three pairs of solutions with respect to their network configurations. As depicted in Figures 7.9 and 7.10 (p. 146),

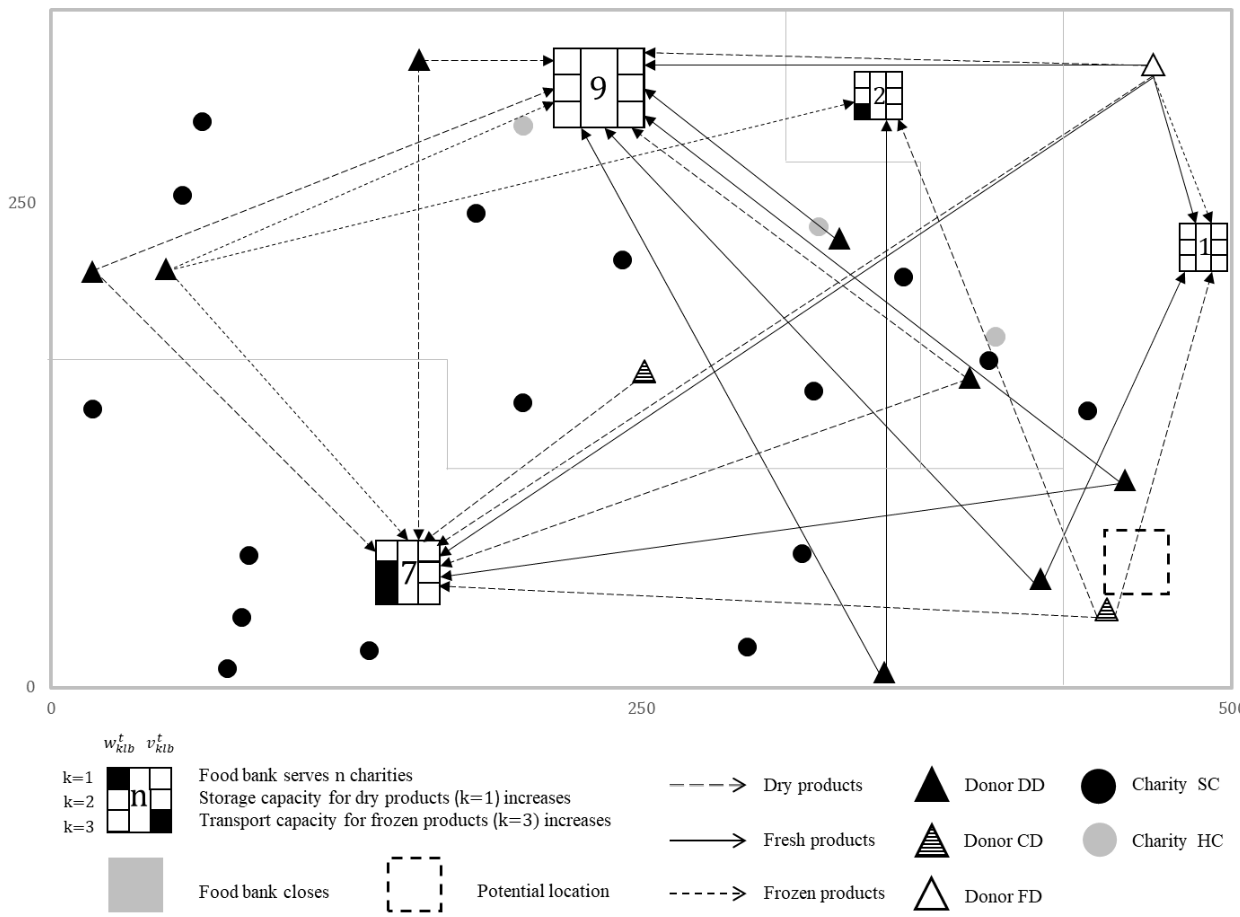


Figure 7.9: Supply chain configuration of LS5: instance 15

both solutions maintain the initially open food banks running throughout the planning horizon, and do not deploy the potential new facility. Storage capacity is expanded at the medium size facility at the same (medium) level as in all previous solutions. One of the small facilities also adds medium size capacity for frozen products. All storage expansions occur in the first period, and no transport capacity is acquired. This is the pair of solutions that introduce fewer changes to the initial network of food banks, and subsequently the one where the level of effort required to obtain the necessary investment capital is lowest (18.1%).

The maximum number of charities (19) is served from the first period, with the same assignment to food banks in LS5 and LS6. The only difference between the two solutions illustrated by Figures 7.9 and 7.10 concerns the flow of products, notably the exchange of products between food banks, which is included in Figure 7.10 but not in Figure 7.9. Actually, in solution LS5 this inter-food banks

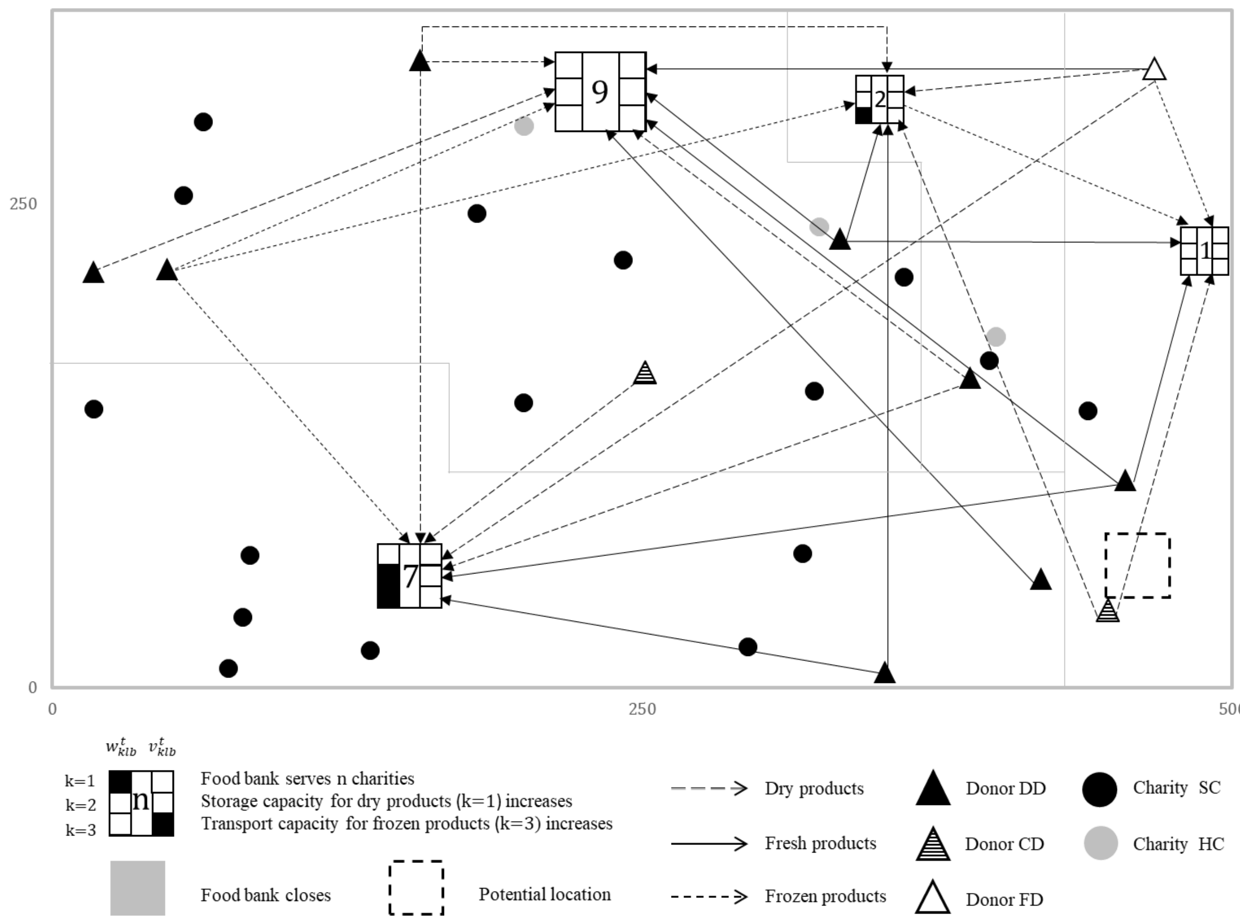


Figure 7.10: Supply chain configuration of LS6: instance 15

exchange also occurs (frozen products are delivered from the large food bank to one of the small facilities) but only in the first four periods, and therefore this product flow is not shown in Figure 7.9 that only depicts the status at period 5. By contrast, in LS6, frozen products are transported from a small food bank to another small facility in all periods. In this particular illustrative instance, the two social-centric solutions are the only ones that include exchange of products between food banks.

Figures 7.9 and 7.10 reveal other differences concerning the product flows generated in each solution. These differences lead to a minor distinction between the two solutions with regard to the total volume of food products processed in the corresponding supply chains. In LS5 this volume is of 17,824.2 tonnes, and in LS6 of 17,835.8 tonnes. These are the largest volumes registered by any lexicographic solution, exceeding, for example, the volume generated by the economic-centric solutions by almost 45%. They allow the highest level of overall demand satisfaction of all solutions

(86.2% in LS5 and 86.3% in LS6), the most balanced product distribution among charities (largest value of δ^t is 0.3), and a provision of service to the new charities at a level identical to the one offered to initially existing charities (see Table 7.2 on page 150).

More than 90% of the total quantity of products redistributed by the institution comes from in-kind donations, which results in a food waste level of less than 1% in both solutions. It is relevant that this value outperforms the results obtained in the environmental-centric solutions that register a waste level of 8.1%. Just as the reduction of food waste has a positive effect in the level of assistance provided to the population (see discussion above regarding solutions LS3-LS4), the inclusion of a larger number of charities in the supply chain from as earliest as possible, and at an higher supply level, also impacts positively the reduction of food waste, especially if this impact is not curtailed by other objectives, namely pertaining to the CO_2 emission volume. As discussed in Section 5.6, the two terms of the environmental objective function are, to some extent, conflicting. This explains why the best food waste-related results are obtained in the social-centric solutions. Naturally, the downside of this better performance by solutions LS5-LS6 is that the carbon footprint generated by LS5 (around 890 k tonnes-d.u.) and LS6 (close to 850 k tonnes-d.u.), is respectively almost 290% and 270% above the outcome of solutions LS3-LS4. As expected, the high CO_2 emissions cost offsets the waste disposal related gains of the social-centric solutions over the environmental-centric ones.

Along with the value of LS4, the maximum distance between served charities and the respective assigned food banks of solutions LS5-LS6 (182.5 d.u.) is the smallest of all solutions. However, the social work value created in the social-centric solutions (2,056.8 k€) is outperformed by solutions LS3-LS4 albeit at a much higher investment capital raising effort. Due to the few changes operated in the initial network, this social objective finds in LS5-LS6 the lowest value of all solutions, with only 18.1% of the reference investment budget over the planning horizon spent, all of it on storage capacity acquisition.

Overall, in addition to the expected absolute best social results, solutions LS5-LS6 have an environmental cost that, on average over the two solutions, improves the results obtained in the economic-centric solutions by around 26%, and an economic cost that, although approximately 35% worse than the lowest, achieved by solutions LS1-LS2, is in the middle of the range defined by the values registered in the environmental-centric solutions (see Table 7.1).

In conclusion, the results obtained for the illustrative instance reveal a similarity between the supply chains of each pair of solutions. The two environmental-centric solutions reveal a greater diversity of supply chain configurations than the other pairs of solutions, which is likely related to the fact that the environmental objective function is the only one that involves just flow (continuous) variables. Binary variables are used in the objective function of the first problems leading to solutions

LS1-LS2 (P_1, economic objective function) and LS5-LS6 (P_{11}, social objective function). In the case of LS3-LS4, their involvement in the objective function first occurs in the second problems, i.e. the problems that precede solution LS3 (P_7, economic objective function) and LS4 (P_8, social objective function). This indicates that solutions obtained for P_1 and P_{11} leading, respectively, to LS1-LS2 and to LS5-LS6, restrain the characteristics of the solutions of the following problems strongly than the solution of P_6 restricts the specific features of the supply chains of solutions LS3-LS4.

Nevertheless, the methodology allows the identification of six distinct solutions that highlight the conflicts between the three objectives defined for the problem. The analysis and discussion of the results obtained for the particular, but representative case of instance 15 also shows that regarding the environmental and social objectives, conflicts exist within each objective too, which, as pointed out in Section 5.6 adds another degree of complexity to the decision problem.

In the next section the results obtained for the set of 20 test instances are presented, and further conclusions regarding the main features of each lexicographic solution are discussed.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Food banks						
Banks closed (#)	1	1	2	-	-	-
Banks opened (#)	-	-	1	1	-	-
Operating banks (#)	3	3	3	5	4	4
Total storage capacity added (t)	1,381.7	1,381.7	3,774.4	3,949.6	1,415.4	1,415.4
dry products	-	-	1,011.0	1,011.0	-	-
fresh products	1,348.0	1,348.0	2,696.0	2,864.5	1,348.0	1,348.0
frozen products	33.7	33.7	67.4	74.1	67.4	67.4
Total transp. capacity added (t)	-	-	505.5	505.5	-	-
dry products	-	-	505.5	505.5	-	-
fresh products	-	-	-	-	-	-
frozen products	-	-	-	-	-	-
Storage capacity utilization (%)						
dry products	18.2	18.2	21.1	20.6	25.6	25.4
fresh products	43.7	43.7	39.1	36.2	57.2	57.8
frozen products	29.2	29.2	38.4	39.8	41.9	42.2
Transport capacity utilization (%)						
dry products	19.2	19.4	12.3	9.3	17.2	16.4

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
fresh products	-	-	-	-	-	-
frozen products	-	-	-	-	2.2	2.8
Flow between food banks (t)	-	-	-	-	9.9	12.7
Charities						
Included (#)	-	-	3	3	3	3
Included (%)	-	-	73.3	100.0	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	70.5	70.5	77.3	81.9	86.2	86.3
of served charities HC	-	-	76.6	78.6	86.1	86.1
of served charities C	70.5	70.5	77.2	81.4	86.2	86.3
of all charities HC	-	-	52.5	78.6	86.1	86.1
of all charities C	59.7	59.7	73.5	81.4	86.2	86.3
Max. unsatisfied demand (δ^t)	3.6	3.6	1.5	0.5	0.3	0.3
Min. assigned to a bank (#)	2	1	4	1	1	1
Max. assigned to a bank (#)	8	8	10	7	9	9
Changes in assignments (#) banks-charities	-	-	1	-	-	-
Assignments (#) to						
food bank 1	-	-	-	1	2	2
food bank 2	2	1	-	1	1	1
food bank 3	6	7	5	5	7	7
food bank 4	8	8	9	7	9	9
food bank 5	-	-	4	5	-	-
Max. distance to an assigned bank (d.u.) (ε^t)	232.1	217.9	212.8	182.5	182.5	182.5
Donations						
Total food donations (k€)	10,122.2	10,122.2	12,858.2	14,022.5	14,775.4	14,790.1
Total food donations (t)	12,337.4	12,337.4	15,196.7	16,824.6	17,824.2	17,835.8
from donors DD (%)	72.7	72.5	85.4	77.1	72.2	72.7
from donors CD (%)	27.0	27.3	13.5	12.2	18.9	18.0
from donors FD (%)	0.3	0.2	1.2	10.7	9.0	9.2
Unused financial donations (k€)	1,075.4	1,140.6	1,164.4	-	-	-

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Unused financial donations (%)	85.4	90.6	92.5	-	-	-
Network flows						
Flows donors-food banks (#)	129	126	135	202	186	185
from donors DD (%)	69.8	68.3	88.9	78.2	62.9	68.1
from donors CD (%)	26.4	27.8	7.4	5.0	19.9	18.4
from donors FD (%)	3.9	4.0	3.7	16.8	17.2	13.5
Flows between food banks (#)	-	-	-	-	2	3
Flows food banks-charities (#)	375	376	450	476	475	475
Environmental indicators						
Total food waste (k€)	258.0	257.1	84.1	84.1	7.9	10.6
Total food waste (t)	4,041.5	4,027.0	1,316.4	1,316.4	112.3	150.4
Total food waste (%)	24.7	24.7	8.1	8.1	0.7	0.9
donors DD share (%)	99.1	100.0	-	-	100.0	-
donors CD share (%)	0.9	-	100.0	100.0	-	100.0
of donors DD offer (%)	30.9	31.0	-	-	0.9	-
of donors CD offer (%)	1.0	-	39.1	39.1	-	4.5
Total CO_2 emissions (k€)	753.1	802.8	200.2	200.2	772.3	730.2
Total CO_2 emissions (t-d.u.)	869,254.3	925,322.2	230,295.9	230,295.9	890,358.0	846,229.0
Social indicators (others)						
Total social work (k€)	1,951.6	1,951.6	2,186.3	2,562.5	2,056.8	2,056.8
Total investment capital required (% of reference budget)	22.0	22.0	67.3	62.6	18.1	18.1
Periods with investment (#)	1	1	1	1	1	1
Periods over budget (#)	1	1	1	1	-	-

Table 7.2: Characteristics of the lexicographic solutions: instance 15

7.2.2 Neutral case

This section reports the results obtained for the set of 20 test instances considering the neutral case of Table 6.12 on page 127. This case is defined by the absence of preference with regard to any of the individual terms of the environmental and social objective functions. Food waste and CO_2 emissions are valued identically as ecologic objectives, and the same applies to the five social terms. Instances have in common some elements of the supply chain (e.g. number of stakeholders, products, capacity levels), and the locations of the food banks. Supply and demand parameters, location of donors and charities, among others are specific to each instance, thereby creating a diversity of starting supply chain configurations.

Results obtained for the set of 20 instances are evaluated in this section according to *i*) the gaps between the ideal vector and estimates of nadir points of each objective function, *ii*) the trade-offs between the three objectives, and *iii*) the distances between the points representing the six lexicographic solutions. Each solution is characterized based on the results obtained, particularly with respect to location decisions. Results report to the average values over the set of test instances.

7.2.2.1 Objective functions values

Table 7.3 on page 152 summarizes the average three objective functions values of the lexicographic solutions. Each lexicographic solution is characterized by the values obtained for the economic, environmental and social objectives, which constitute the lexicographic vector of the solution. Average values registered for the economic objective range from 6,690.34 m.u. - obtained for the economic-centric solutions LS1-LS2, and corresponding to the economic value of the ideal vector -, to 9,801.13 m.u. of solution LS4. The gap of 46% between best and worst values is the smallest of all objective functions.

The environmental objective is in the opposite position, with a gap of 186%. Values registered for this objective range from 166.82 k€, which is the ideal environmental value resulting from solutions LS3-LS4, to 477.20 k€, registered in solutions LS2. The social objective is, in this regard, in an intermediary position. The gap from worst (-91.73, registered in LS1) to the best value (241.49 of social-centric solutions LS5-LS6) is of 138%.

These gaps are relevant for the decision maker as they constitute a measure of the range of economic, environmental, and social valuation of the network redesign optimal choices. For example, the decision maker is aware that the array of possible supply chain positioning can lead to widely different environmental results. On the other hand, they also know that the economic cost of the prospective solutions is more tightly bounded.

The average standard deviations presented in Table 7.3 highlight the divergence of results obtained across the 20 test instances. Results for the individual instances deviate, from the respective average values and in percent of the ideal values, between 14% and 21% for the economic cost, and between 10% and 27% for the social values. The environmental cost of each individual instance varies the most from the average for any lexicographic solution, ranging from 29% in LS3 to 97% in LS6. These deviations are an expression of the diversity of supply chain configurations represented by the 20 instances tested.

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

Table 7.3: Objective function values of lexicographic solutions (lexicographic vectors)

7.2.2.2 Trade-offs between objectives

Trade-off analysis quantifies by how much one objective is penalized so that the best value for another objective is achieved. The penalty is a measure of compromise between the objectives assessed in relation to the best possible value of the penalized objective, i.e. its ideal value. The trade-offs between the three objectives of the problem are depicted in Figure 7.11.

Although the economic objective does not deteriorate as much as the other two when it is not considered as the first optimization priority (solutions LS3 through LS6), it is the one that most penalizes the others. When the economic objective is first priority, the resulting environmental cost exceeds the best environmental cost (of LS3-LS4) by 178% (LS1), or 186% (LS2). Similarly, the social value is 138% (LS1), or 137% (LS2) worse than the ideal social value obtained in LS5-LS6. These are the highest trade-offs registered in any lexicographic solution, and give evidence of the extent to which economic considerations conflict with environmental and social factors, which is another valuable insight for the decision maker.

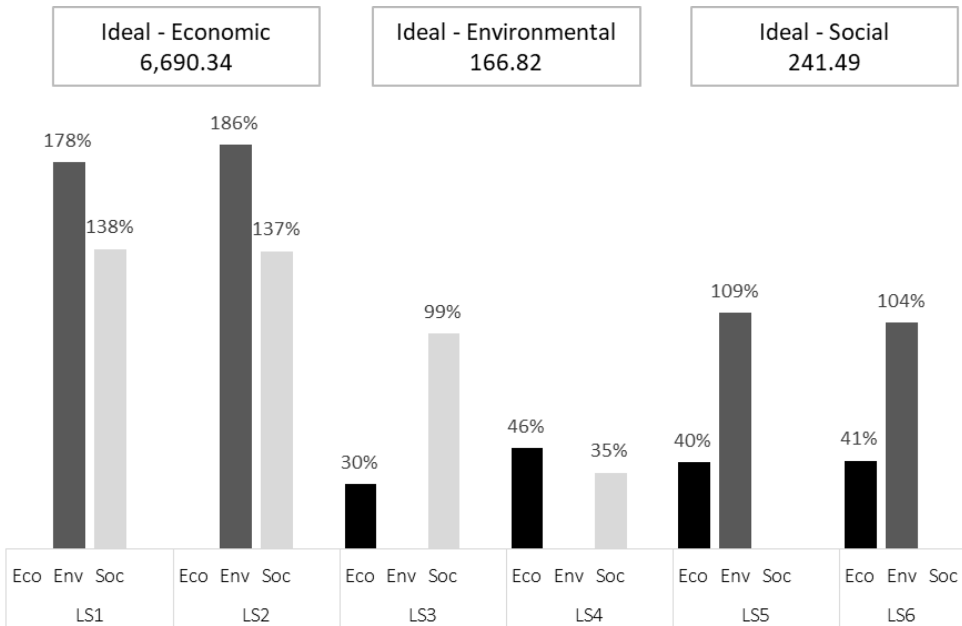


Figure 7.11: Percent deviations of lexicographic vectors from average ideal vector

The other two objectives are considerably less demanding in this respect. On average, in order to obtain the ideal environmental value, the economic value worsens from its ideal value by 30% or 46%, respectively in LS3 and LS4. In the case of the social value, the decrease is by 99% in LS3, and 35% in LS4.

The social objective shows, on average, poorer trade-offs than the environmental objective, yet it is less penalizing to the other objectives than the economic objective. When the social objective has the highest priority, the compromise imposed on the economic objective is of 40% in LS5 and 41% in LS6. Regarding the environmental objective the compromise is of 109% (LS5), or 104% (LS6).

This analysis provides another perspective on the range of possible values for each objective. In summary, economic costs can be considered more controlled as their range of possible values is more limited than the range of the other two objectives. On the other hand, small changes in the economic values of the solutions, lead to significant changes in the values of the other objectives, namely to those of the environmental objective. The opposite occurs with regard to the environmental objective. Although the environmental cost can fluctuate more than the value of the economic and social objectives, variations are the least impacting on the other objectives.

Based only on this trade-offs analysis, LS4 appear to be the most balanced solution in the sense that it is the one that, on average, and in order to obtain the ideal value for one of the objectives (environmental, in this case), imposes less total decay in value of the others. From this perspective, the other environmental-centric solution, LS3, is the next best solution.

7.2.2.3 Distances between solutions

A distance measure is employed to assess the similarities and differences between the solutions, as expressed by the distance between the respective points in the objective space. Each point is defined by the (three) objective functions values of the solution. Given the different units of measurement of each objective, the absolute distance is not an adequate measure. Thus, distances between (points identifying) lexicographic solutions are considered in relation to the point corresponding to the ideal solution, and respective values. Let X_1, X_2 and X_3 be the coordinates of point X, Y_1, Y_2 and Y_3 the coordinates of point Y, and I_1, I_2 and I_3 the coordinates of the ideal point. The relative Euclidean distance between points X and Y is given by the following expression.

$$dist = \sqrt{\left(\frac{X_1 - Y_1}{I_1}\right)^2 + \left(\frac{X_2 - Y_2}{I_2}\right)^2 + \left(\frac{X_3 - Y_3}{I_3}\right)^2} \tag{7.6}$$

As expected, and in line with the analysis of the illustrative example presented in the previous section, results reveal a greater proximity between points of the same pair of objective-centric solutions, which is synonym of similarity of the solutions. Within the three pairs of lexicographic solutions, Table 7.4 and Figure 7.12 show that the two environmental-centric solutions diverge the most among them. The distance between points of solutions LS3 and LS4 (0.659, signaled by the dotted line in the figure) is considerably larger than the distance between the lexicographic vectors corresponding to the social-centric solutions LS5-LS6 that, with 0.048 (solid line), reveal the greatest similarity. Even the distance between the points of economic-centric solutions (0.083) is significantly smaller than the distance between the vectors of solutions LS3-LS4. Although all lexicographic solutions are distinct, there is a likeness in solutions LS1-LS2, and particularly in LS5-LS6 that is not present in solutions LS3-LS4. This confirms, for the set of 20 instances, the conclusions deduced with respect to the illustrative example.

Table 7.4 and Figure 7.12 also show that, in general, the objective functions values obtained for solutions LS1 and LS2 differ the most from the others. The distance from the points of this

	Lexicographic solutions						Ideal	Nadir
	LS1	LS2	LS3	LS4	LS5	LS6		(estimate)
LS1	-	0.083	1.845	2.106	1.594	1.617	2.251	0.319
LS2	0.083	-	1.922	2.171	1.623	1.648	2.311	0.318
LS3	1.845	1.922	-	0.659	1.476	1.441	1.035	1.219
LS4	2.106	2.171	0.659	-	1.146	1.101	0.583	2.782
LS5	1.594	1.623	1.476	1.146	-	0.048	1.161	3.643
LS6	1.617	1.648	1.441	1.101	0.048	-	1.118	3.644

Table 7.4: Relative distance between lexicographic vectors and to ideal and estimated nadir vectors

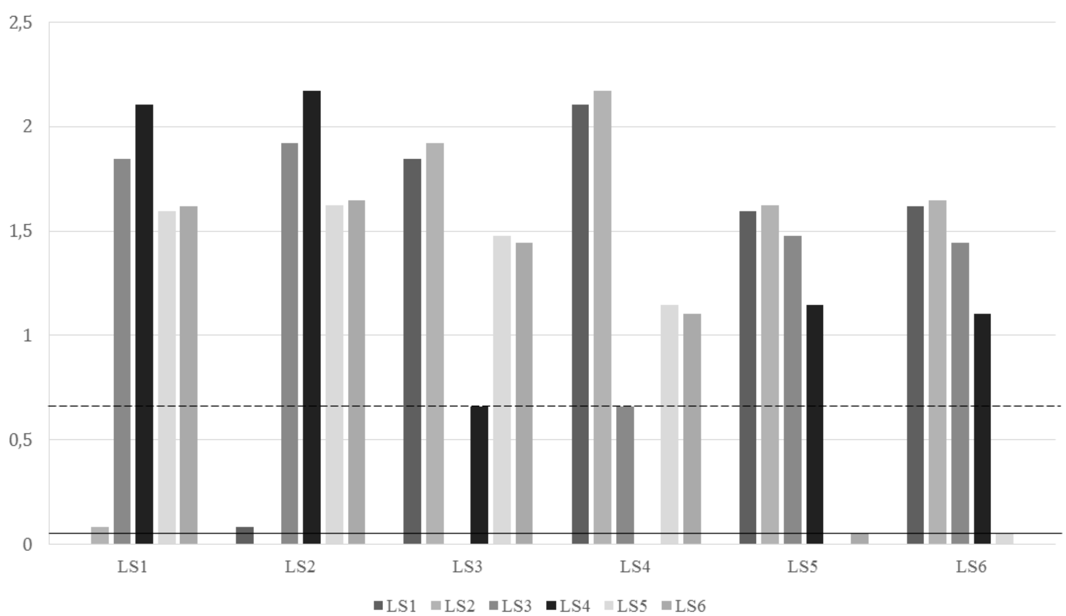


Figure 7.12: Relative distance between lexicographic vectors

pair of solutions is particularly large to the environmental-centric lexicographic vectors, meaning that they are particularly distinct with respect to their objective function values. On average over the 20 instances, solutions LS3 are closer (more similar) to social-centric solutions LS5-LS6 than to economic-centric solutions LS1-LS2. The same is verified for solutions LS4, but in this case the unbalance is larger than in the case of LS3. Points of solutions LS4 are simultaneously closer to the vectors of social-centric solutions, and more distant from the vectors of economic-centric solutions, than in the case of solutions LS3. Regarding the two social-centric solutions, not only are they the most similar, but also the ones whose points are most equidistant to the others. The range of distances between lexicographic vectors of LS5-LS6 and the remaining is the narrowest, and in this sense the social-centric display more balanced attributes than the others.

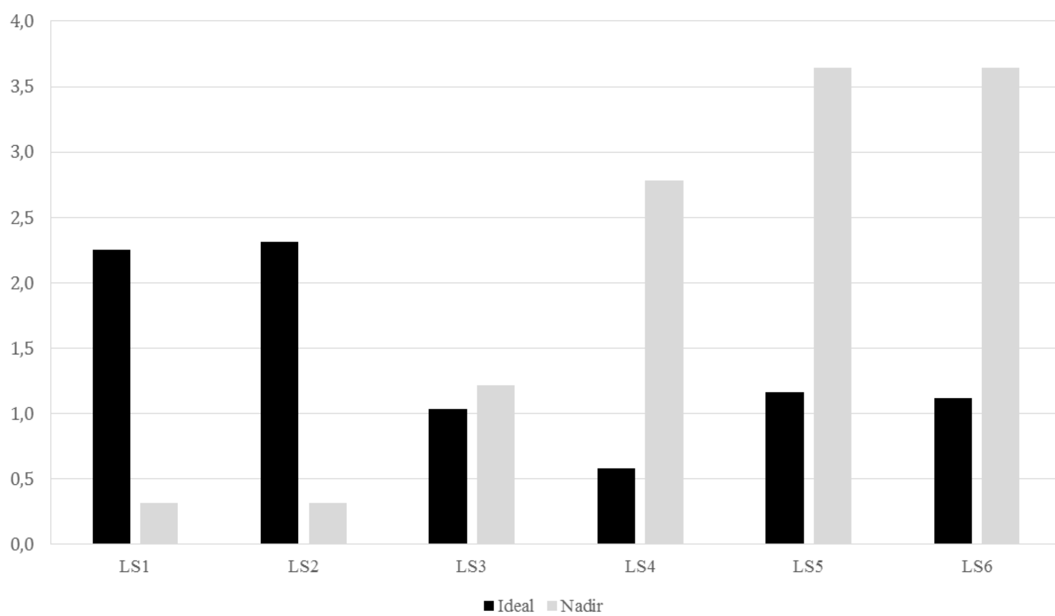


Figure 7.13: Relative distance of lexicographic vectors to ideal and estimated nadir vectors

Figure 7.13 (p. 156) illustrates the distances from the points of each solution to the points of the ideal and estimated nadir vectors (constituted by the worst value for each objective function identified in all lexicographic vectors - see Alves and Costa (2009)). It is noticeable that the points corresponding to the economic-centric solutions are farther away from the ideal vector and closer to the estimated nadir vector than any other solutions. On the contrary, the points corresponding to the social-centric solutions are the ones most distant from the estimated nadir vector, while the points of the environmental-centric solutions are closest to the ideal vector. In this sense, the vector of solution LS4, in particular, is nearest to the ideal vector. It also has one of the largest distances from the estimated nadir vector, surpassed only by the vectors of the social-centric solutions. From this perspective, LS4 once again arises as the solution that may offer the best compromise of all solutions.

In spite of all solutions being lexicographic and, by definition, efficient, this analysis allows some insights in terms of the balance between the values of the objectives functions achieved by each solution. Strictly in this regard, the environmental and social-centric solutions possess some advantages over the economic-centric solutions. These advantages are related to the fact that the economic objective is the one that declines the least when one of the other objectives are optimized as first priority, as discussed in the beginning of this section. This suggests that an environmental, or social-oriented positioning of the supply chain is expected to achieve the best environmental, or social results without compromising in excess the economic objective. By opposition, a positioning favoring the best economic results, can have quite a negative impact on the environmental and social objectives in comparison with their best possible values.

7.2.2.4 Characteristics of solutions

Tables 7.5 (p. 158) and 7.6 (p. 161) provide details on the differences and similarities between the six lexicographic solutions that complement the distance analysis. Data reports to the situation at the final planning period, or to the average over the planning horizon, as appropriate and noted in the tables. Results for the illustrative instance 15 of section 7.2.1 are signaled in italic font.

The economic-centric solutions LS1 and LS2 are characterized by several changes in the configuration of the existing food bank network over the planning horizon. These changes usually involve the closing of more than half of the three initially open food banks, and frequently (in 11 instances) the opening of the new facility. Notice that in all instances tested, a minimum of one and a maximum of three facilities are shut-down in these solutions. As a result, the initial network of food banks is reduced from four to three running facilities. No food assistance is provided to waiting charities that continue to be kept on-hold, and the demand requirements of the already served charities are met at the minimum level possible. It follows that the quantity of products processed by the supply chains of these solution is the lowest of all solutions at approximately 13.8 thousand tonnes. The impact of this strategy is also evidenced by a high percentage of unused food donations. In fact, almost one-quarter of all food items made available by donors are not redistributed. This, in turn, leads to the largest waste disposal costs of all solutions: 278.3 k€ in LS1, and 276.5 k€ in LS2. Sourcing distribution per type of donors is also unique to these solutions. LS1-LS2 exhibit the largest average collection rate of food products from collection donors (over 22%), which leads to some of the largest CO_2 emissions costs registered (between 648.7 k€ in LS1 and 677.9 k€ in LS2). Another characteristic of LS1-LS2 is that most of the financial donations are not used. On the contrary, the location policy results in a significant investment capital procuring effort. In effect, most of the capital raised is dedicated to support opening or closing of facilities, and not to acquire additional storage or transport capacity, whose values are in line with the more conservative approach followed by the social-centric solutions.

Lexicographic	Instances																			
solutions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	*15*	16	17	18	19	20
LS1																				
Food banks closed	2	2	2	1	1	1	2	1	1	1	2	1	3	3	*1*	2	1	1	2	2
Food banks opened	-	1	1	-	1	-	1	-	1	-	1	1	1	1	-	-	-	1	-	-
Charities included	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LS2																				
Food banks closed	2	2	2	1	1	1	2	1	1	1	2	1	3	3	*1*	2	1	1	2	2
Food banks opened	-	1	1	-	1	-	1	-	1	-	1	1	1	1	-	-	-	1	-	-
Charities included	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LS3																				
Food banks closed	2	1	1	1	2	2	2	1	1	1	2	2	2	2	*2*	2	1	1	3	1
Food banks opened	-	-	1	1	1	-	1	1	-	1	1	1	1	-	*1*	1	1	1	1	1
Charities included	-	-	2	2	2	1	1	3	1	2	3	3	3	1	*3*	1	1	3	2	-
LS4																				
Food banks closed	-	-	-	-	1	1	-	-	-	1	2	-	-	1	-	-	-	-	-	-
Food banks opened	-	-	1	-	1	-	-	-	-	1	1	1	-	-	*1*	1	1	1	-	1
Charities included	3	2	3	3	3	3	3	3	3	3	3	3	3	3	*3*	3	3	3	3	-
LS5																				
Food banks closed	-	1	-	-	-	-	-	1	-	-	-	-	-	1	-	-	1	-	-	1
Food banks opened	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Charities included	3	3	3	3	3	3	3	3	3	3	3	3	3	3	*3*	3	3	3	3	3
LS6																				
Food banks closed	-	1	-	-	-	-	-	1	-	-	-	-	-	1	-	-	1	-	-	1
Food banks opened	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Charities included	3	3	3	3	3	3	3	3	3	3	3	3	3	3	*3*	3	3	3	3	3

Table 7.5: Number of food banks closed and opened, and of charities included per instance and solution over the planning horizon

The low level of investment in capacity expansion is actually one of the few characteristics that applies equally to the economic and to the social-centric solutions. With respect to most of the other features these solutions convey opposite network redesign strategies. Solutions LS5-LS6 advocate very limited interventions in the initial network of food banks. In the few cases that changes are made to the initial network configuration, the option is for the closing of facilities. This results in a low investment effort, and in an average number of operating facilities closest to that of the initial network. In spite of the limited investment in storage capacity, this strategy ensures a significant social work value, which is exceeded only by LS4. As expected, the largest volume of food redistribution is achieved by these solutions. Products are secured mostly from delivery donors, and food purchases often complement in-kind donations. This is particularly the case of LS6 where all financial donations are spent. In total, the quantity of products flowed through the supply chains of solutions LS5-LS6 is upwards of 19 thousand tonnes over the five planning periods. This volume allows the highest level of assistance to charities as more than 80% of the demand of all charities is satisfied. It also results in a higher utilization of the available storage capacity, and the lowest values of product waste (maximum of 2%). However, transport resources are more engaged to collect food donations and for inter-warehouse shipments. Consequently, larger CO_2 costs are incurred (670.0 k€ in LS5, and 654.7 k€ in LS6). These costs are about 200% above the ideal value registered by the environmental-centric solutions, and clearly outweigh the low waste disposal costs of LS5-LS6. As concluded with respect to the illustrative instance, this performance is enabled by (and warrants) the inclusion of the largest number of new charities in the supply chain. This is another distinctive feature of the social-centric solutions as all three awaiting agencies are always included in the respective supply chains.

Features	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
Banks opened (#)	0.6	0.6	0.8	0.5	-	-
Operating banks (#)	3.0	3.0	3.2	4.3	3.8	3.8
Total storage capacity added (t)	1,574.5	1,574.5	3,153.0	3,002.7	1,511.4	1,511.4
dry products	556.1	556.1	909.9	657.2	-	-
fresh products	994.2	994.2	2,182.1	2,283.2	1,474.4	1,474.4
frozen products	24.3	24.3	61.0	62.3	37.1	37.1
Total transp. capacity added (t)	91.8	88.5	303.3	321.0	55.6	55.6
dry products	-	-	67.4	84.3	-	-
fresh products	87.6	85.9	232.5	232.5	50.6	50.6
frozen products	4.2	2.5	3.4	4.2	5.1	5.1
Storage capacity utilization (%)						
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 utilization (%)						
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						

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Included (#)	-	-	1.8	2.8	3.0	3.0
Included (%)	-	-	60.0	93.3	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	80.4	78.9	82.7	82.8
of served charities HC	-	-	50.2	67.8	80.8	81.1
of served charities C	69.9	69.9	79.9	78.3	82.4	82.6
of all charities HC	-	-	30.4	65.0	80.8	81.1
of all charities C	59.1	59.1	72.7	76.7	82.4	82.6
Max. unsatisfied demand (δ^t)	2.7	2.7	1.5	0.7	0.5	0.5
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	0.3	0.3	1.4	2.2	2.2	2.2
food bank 2	1.4	1.4	1.8	3.0	2.4	2.4
food bank 3	2.9	2.9	4.1	4.0	4.4	4.5
food bank 4	10.0	10.0	7.0	7.3	10.1	10.0
food bank 5	1.5	1.5	2.9	2.1	-	-
Max. distance to an assigned bank (d.u.) (ε^t)	236.8	236.1	236.3	213.8	222.1	222.1
Donations						
Total food donations (k€)	11,019.7	11,019.7	13,676.1	14,382.5	15,373.3	15,411.2
Total food donations (t)	13,774.3	13,774.3	16,940.5	17,852.8	19,131.7	19,178.1
from donors DD (%)	76.3	75.9	85.2	80.8	74.6	74.8
from donors CD (%)	22.1	22.6	11.0	10.4	16.8	16.4
from donors FD (%)	1.7	1.5	3.8	8.7	8.7	8.8
Unused financial donations (k€)	1,063.0	1,069.4	706.4	-	7.8	-
Unused financial donations (%)	79.6	80.3	54.1	-	0.5	-
Network flows						
Flows donors-food banks (#)	128.9	132.1	140.0	178.7	178.2	177.9
from donors DD (%)	72.8	73.6	84.2	78.3	66.4	67.0

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
from donors CD (%)	21.5	20.9	6.7	5.5	16.0	15.6
from donors FD (%)	5.7	5.5	9.1	16.1	17.5	17.3
Flows between food banks (#)	0.2	0.2	-	-	4.6	4.6
Flows food banks-charities (#)	387.0	388.1	434.2	468.6	478.1	475.0
Environmental indicators						
Total food waste (k€)	278.3	276.5	102.9	102.9	27.5	26.4
Total food waste (t)	4,358.0	4,330.3	1,613.0	1,612.9	427.9	409.2
Total food waste (%)	24.4	24.2	8.9	8.9	2.0	1.9
donors DD share (%)	90.2	91.9	0.2	0.2	39.0	23.4
donors CD share (%)	9.8	8.1	99.8	99.8	61.0	76.6
of donors DD offer (%)	27.9	28.3	-	-	0.9	0.5
of donors CD offer (%)	8.7	6.1	53.0	53.0	4.4	6.3
Total CO_2 emissions ((k€)	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 (others)						
Total social work (k€)	2,077.5	2,077.5	2,305.3	2,818.3	2,538.4	2,538.4
Total investment capital required (% of reference budget)	42.7	42.0	65.0	51.7	25.1	25.1
Periods with investment (#)	1.1	1.1	1.3	1.1	1.0	1.0
Periods over budget (#)	0.9	0.9	1.1	0.9	0.6	0.6

Table 7.6: Characteristics of the lexicographic solutions: average over 20 instances

Solutions LS3-LS4 have in common the results pertaining to environmental factors, but other than those each has its own specific features. Solution LS3 share some of the features of the economic-centric solutions, whereas the profile of solution LS4 exhibits more similarity to the characteristics of the social-centric solutions. Location decisions of LS3 are identical to those made in solutions LS1-LS2, albeit more favorable to the opening of the new facility, which occurs in 15 of the 20 instances. Accordingly, like the economic-centric solutions, LS3 leads to a reduction in the number of initially operating facilities, in this case at a slightly higher average of 3.2 food banks. The only solution that produces a redesigned network larger than the initial network is LS4. On average, in this solution the final set-up of the food bank network comprises 4.3 operational facilities. Solutions LS3 and LS4 are the ones that register the larger installation of storage and transport capacity, and also the ones that require higher effort to raise investment capital. Resulting from the expansion in the number of operating food banks, and the storage acquisition policy, LS4 provides the largest social work value of all solutions. In both solutions new charities are included in the supply chain. In LS3 approximately half the agencies on hold are served by the last planning period (1.8), while in LS4 almost all (2.8) are supplied. Unlike solutions LS1-LS2 that do not include any new charity, and solutions LS5-LS6 that include all charities from the first period, in solutions LS3-LS4 charities are included in multiple periods. This explains the fact that changes in assignments of charities to food banks only occur in these solutions. Although more charities are included in LS4 than in LS3, the overall level of demand satisfaction is slightly higher in LS3 (80.4%) than in LS4 (78.9%). Overall, a larger quantity of food products is supplied in solution LS4 (17,852.8 tonnes versus 16,940.5 tonnes in LS3), mainly due to the greater use of financial donations to purchase products. In LS4, similar to the social-centric solutions, all financial donations are spent by the last period, whereas in LS3 only around half the available donations are used. Otherwise, the quantity of in-kind donations managed by the supply chains of the two solutions is identical, as is the corresponding volume of food waste valued at 102.9 k€. Notice that the distribution of food waste per type of donor is also the same in LS3 and LS4, following a common policy of not engaging transport capacity in the collecting of food donations (in both cases 99.8% of food waste is located at collection donors). Notice also that, for the same reason, these are the only two solutions that do not register any volume of inter-food banks flows. This policy leads to the most distinctive feature of these solutions, which is the lowest level of CO_2 emissions cost of all solutions (230.8 k€).

Common to all lexicographic solutions is the fact that the large food bank (food bank 4) is the most used facility. In most cases this food banks serves more than half the charities. The medium size bank (food bank 3) is also operational in all solutions, and has the second largest service area. When deployed, the new facility has the profile of a small food bank in terms of installed capacity and number of served charities.

The identifying features of each lexicographic solution, according to the average results obtained for the set of instances, are summarized in Table 7.7. In the next section, key features are selected to derive relevant and succinct managerial insights.

Lexicographic solutions		
Economic-centric	Environmental-centric	Social-centric
Small network of food banks	Most changes in network design	Few changes in network design
No new charities included	Some new charities included	All new charities included
Minimum level of food assistance	High level of food assistance	Highest level of food assistance
Least use of financial donations	No inter-food banks flows	High use of financial donations
Highest level of food waste	Low level of food waste	Lowest level of food waste
Large CO_2 emission cost	Lowest CO_2 emission cost	Large CO_2 emission cost
Large investment effort	Largest investment effort	Lowest investment effort
Low social work value creation	High social work value creation	High social work value creation

Table 7.7: Main features of lexicographic solutions

7.2.3 Managerial insights

The solutions obtained for the redesign of the food bank supply chain can be characterized and evaluated according to several different criteria. Table 7.8 (p. 164) introduces and defines the Key Performance Indicators (KPIs) selected to enable a comparison between the results of each lexicographic solution. Results for a lexicographic solution, in this section like in the previous, refer to the average results over the 20 test instances for a lexicographic solution.

With the exception of KPI *%Work*, KPIs are expressed in relation to the worst (largest) value registered in all lexicographic solutions. Therefore, the value 100% features in, at least, of the six solutions, identifying the one(s) with the poorest results for that indicator. Of the eight KPIs selected, KPI *%Work* is the only associated with a maximizations objective. In order to allow the same interpretation for all KPIs, this KPI is expressed differently from the others, as described in Table 7.8. Based on that description, and unlike the other KPIs, no solution features the value 100% for KPI *%Work*. That would occur only if no storage capacity was available in the supply chain, which is an impossibility. On the contrary, at least one of the solutions will have the value 0%, corresponding to best solution for this criterion.

It should be noted that the selected KPIs are biased toward the social issues. These are represented by the last four KPIs, while economic issues are represented by the first two (*%Cost* and *%Storage*), and environmental issues by the following two KPIs (*%Waste* and *%CO2*).

Figure 7.14 (p. 165) displays the radar charts pertaining to each of the lexicographic solutions. According to the definition of the KPIs, the wider the area represented in the radar chart, the lower

KPIs	Description
%Cost:	Ratio to the largest economic objective function value
%Storage:	Ratio to the largest unused storage capacity at an operating food bank
%Waste:	Ratio to the largest quantity of unused in-kind food donations
%CO2:	Ratio to the largest cost of CO_2 emissions
%Demand:	Ratio to the largest quantity of unsatisfied demand over all charities (*SC* and *HC*).
%Distance:	Ratio to the largest distance between a charity and its designated food bank.
%Investment:	Ratio to the largest investment capital raising effort
%Work:	1 - Ratio to the largest value of the social work created

Table 7.8: Key performance indicators

the quality of the corresponding solution.

Clearly the areas of the two upper radar charts concerning the performance of solutions LS1 and LS2 in relation to the selected KPIs are wider than the areas of the remaining charts. Indeed, the economic-centric solutions exhibit the worst performances for KPIs *%Demand*, *%Distance*, and *%Work*. Moreover, solution LS1 also has the largest *%Waste*, and solution LS2 has the highest *%CO2*. This means that, individually, each of the two economic-centric solution shows the poorest performances for half the criteria analyzed, and for another two (*%Storage* and *%CO2* for LS1, and *%Storage* and *%Waste* for LS2) their results are close the worst performances registered by all solutions The only KPI for which both solutions show a clear benefit over the others is *%Cost*.

In comparison with LS1-LS2, solutions LS3-LS4 are represented by a smaller area, with some perceived advantage for LS4. The better performance LS4 evidences over LS3 in social-related indicators *%Demand*, *%Distance*, *%Investment* and *%Work* is counterbalanced by the better results of LS3 in economic-related KPIs *%Cost* and *%Storage*. Moreover, the performance of these solutions is respect to environmental KPI *%CO2* is superior to the results of all others.

The two charts at the bottom of Figure 7.14 reveal solutions with very similar performances. Solutions LS5-LS6 share the best performances for KPIs *%Storage*, *%Waste*, *%Demand*, and *%Investment*. Additionally, their results regarding *%Distance* and *%Work* are only improved marginally by solution LS4. These performances are however shadowed by economic-related KPI *%Cost*, and environmental-related KPI *%CO2*.

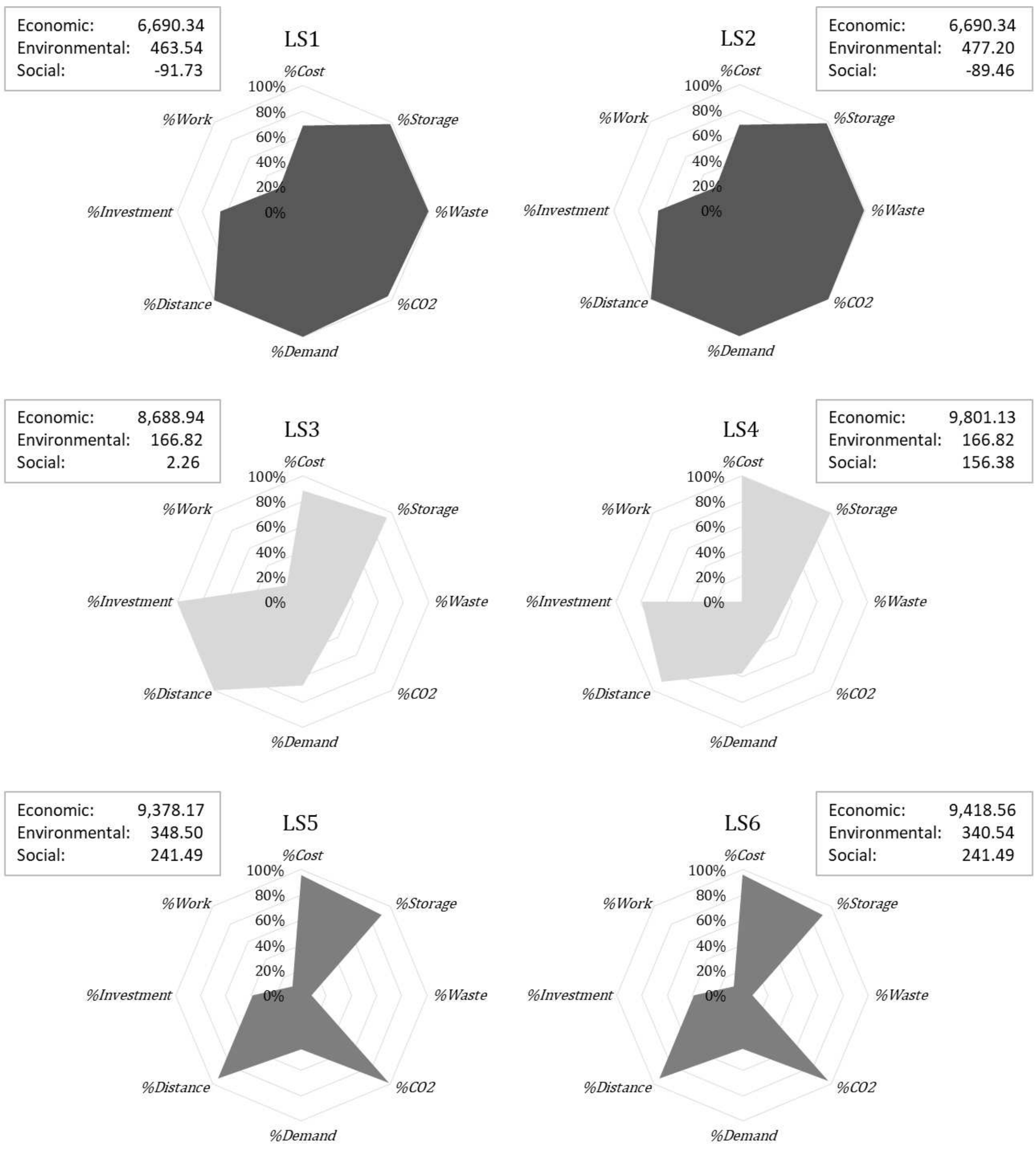


Figure 7.14: Comparison of selected KPIs per lexicographic solution

Figure 7.15 offers a complementary perspective. The radar charts in this figure display the results obtained in each solution for the selected KPIs. For each KPI, worst and best solution(s) are over and underlined, respectively. Also displayed is the maximum difference, in percent points (pp), between worst and best values recorded in all solutions, which are helpful to put into perspective the benefits some solutions hold over the others. The maximum value represented in all charts is 100%, except in the chart depicting performance in terms of KPI *%Work*, whose maximum value is 30%.

The six solutions present identical results for KPIs *%Storage* and *%Distance*. These KPIs have the narrowest range of values, with a maximum difference of 10 pp between worst and best values. Hence, although solution LS6 has the best performance in terms of *%Storage*, and solution LS4 has superior *%Distance* performance, their values are closely followed by all other solutions. More distinctive are the relative benefits revealed by solutions LS3-LS4 in relation to *%CO2*, and LS6 with respect to *%Waste*. Notice that the value of solution LS5 for *%Waste* is very similar to that of LS6. In the case of these KPIs the difference between the solutions is quite significant, reaching 66 pp for *%CO2*, and 92 pp for *%Waste*. As observed already in the analysis of each solution, LS1 is the solution that most frequently evidences the worst values of all solutions. On the contrary, LS4 is the solution that most repeatedly presents the best value, which occurs for three of the eight KPIs.

7.2.4 Comparison with existing network

The ultimate purpose of redesigning the food bank supply chain is to obtain a network configuration that is more beneficial than the starting situation.

Therefore, to evaluate the possible benefits of the six lexicographic solutions obtained in the computational experience carried out their results are compared with the estimated results of the existing network. In order to estimate the economic, environmental and social results obtainable by the initial supply chain a number of assumptions are required.

Maintaining the supply chain "as is" throughout the planning horizon means that:

(i) the four existing food banks $b \in OB$ are operated in all periods $p \in P$;

(ii) additional storage or transport capacity is not installed;

(iii) the potential facility $b \in PB$ is not deployed;

(iv) initially served charities $c \in SC$ receive in each period $t \in T$ the same quantity of product $p \in P$ supplied in the period 0 $\left(X^0_{pc}\right)$, and

(v) charities on-hold $c \in HC$ are not included in the supply chain.

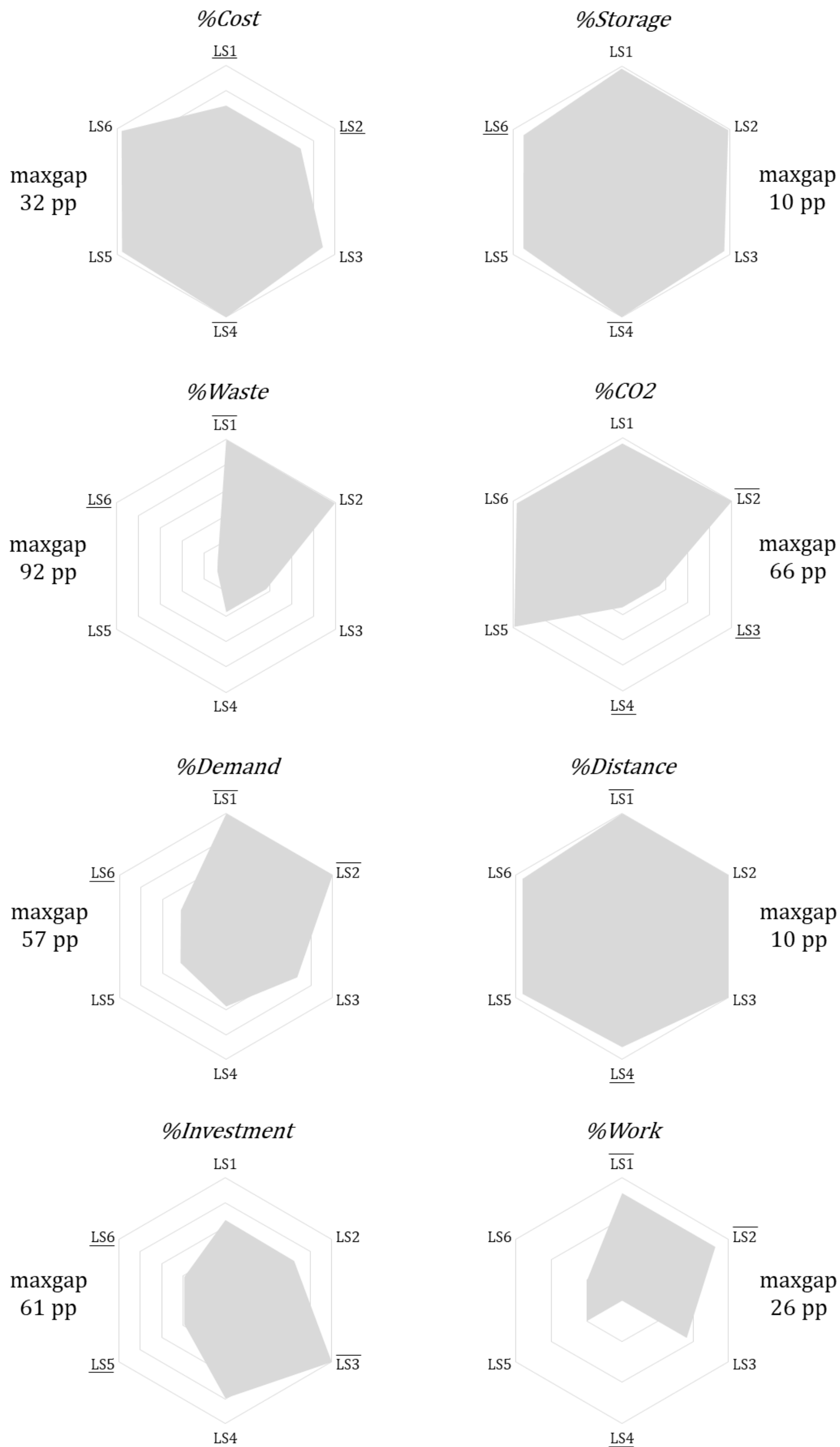


Figure 7.15: Comparison of lexicographic solutions per selected KPI

Based on these assumptions, the total volume of products distributed in each period corresponds to the average value of $\sum_{p \in P} \sum_{c \in SC} X^0_{pc}$ over the 20 instances. This value is estimated at 3,935.52 tonnes, and the total volume of the five periods at 19,677.6 tonnes. Based on the profile of the FPBA southern region supply chain, the distribution of the total volume per product is the following: 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. Also consistent with the profile of the regional FPBA supply chain, the small size facilities (food banks 1 and 2) process 2.5% of the total volume each, the medium size food bank (3) processes 30%, and the large food bank (4) handles 65% of the total redistributed products. All other estimation input data, namely supply and demand conditions, as well as the expected evolution of unit costs, are obtained by taking the corresponding averages over the test instances.

Table 7.9 presents the values estimated for the three objective functions when the existing supply chain configuration (denoted "existing network") is maintained over the planning horizon. The percent deviations to the values of the lexicographic solutions are also showed in the table.

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

Table 7.9: Comparison of lexicographic solutions with existing network configuration

The projected economic cost over the five planning periods for the configuration "as is" is 7.786,40 m.u. This value compares favorably with the economic cost of all lexicographic solutions with the exception of LS1-LS2. If the first priority is economic, solutions LS1-LS2 allow savings of 14%, albeit with losses of 41% - 45% for the environmental cost, and 282% - 286% lower social values. Due to the trade-offs between the objectives, improvements on the environmental or social results lead to poorer economic results. In fact, solutions LS3-LS4 provide environmental results that improve those estimated for the option of maintaining the existing network unchanged. In particular, solution LS4 simultaneously improve the estimated environmental cost of the supply chain "as is" by 49%, and its social value by 218%. However the economic cost increases by 26%. In solution LS3 the increase in the economic cost (12%) is not as strong, but in this case the social result worsens in comparison with the value estimated for the "as is" configuration.

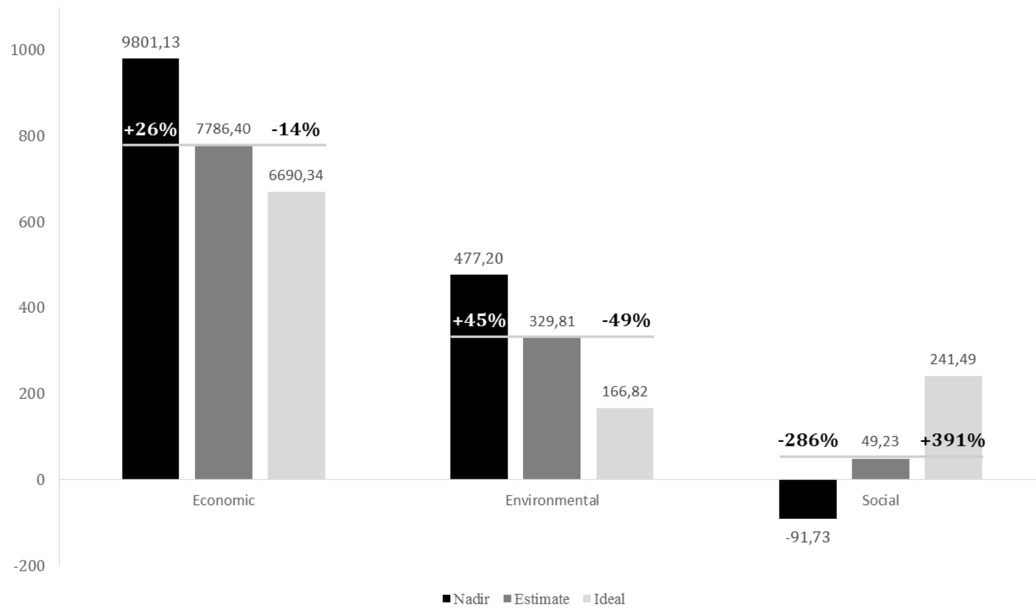


Figure 7.16: Comparison of existing network configuration with ideal and estimated nadir vectors

Finally, the greatest differences between the lexicographic solutions and the estimated values occur with regard to the social criterion. In this case, solutions LS5-LS6 (by 391%), as well as the already mentioned solution LS4 (by 218%) offer significantly better results than those estimated for the maintenance of the pre-planning network design. Solutions LS5-LS6 involve an environmental cost considered to be in line with that of the existing supply chain, but the economic cost exceeds by around 20% the “as is” option cost.

The estimate suggests that a strategy that involves keeping the number of served charities at the initial level, supplying them with the same (initial) volume of product in all periods, and not investing in changes to the network of food banks, does not have a clear inferior quality compared with the policies defined by the lexicographic solutions. However, it must be pointed out that the estimate implicitly assumes that the initial storage and transport resources available at each bank are suited to process the specific flow of products associated with the projection. This may not necessarily hold for all individual product flows, either from specific donors to the food banks, or from these to the charities, under individual supply and demand conditions.

Nevertheless, the estimate, and its comparison with the solutions obtained are instrumental to frame and evaluate the impact of policy changes towards a more economic, environmental or social oriented management of the supply chain. This is illustrated by Figure 7.16 that compares the best and worst objective function values of the lexicographic solutions with the estimated results of operating the initial food bank supply chain "as is" throughout the planing horizon.

7.2.5 Other cases

In previous sections the FBNR problem is studied on the assumption of neutral preferences on the part of the decision maker. In accordance, the two environmental terms are accounted for with equal importance, and the same applies to the five terms of the social objective function.

In this section, the results of considering different environmental and social preferences are reported and discussed. As introduced by Table 6.12 on page 127, further to case C1 that expresses indistinct preferences by the decision make, seven other cases are defined. These cases establish the following scenarios:

(a) Case C2: the decision maker is partial to the reduction of food waste; the environmental term $\sum_{t\in T}\sum_{p\in P}\varphi^t\left[\sum_{d\in DD}\left(Q^t_{pd}-\sum_{b\in B_d}x^t_{pdb}\right)+\sum_{d\in CD}\left(Q^t_{pd}-\sum_{b\in B}x^t_{pdb}\right)\right]$ is weighted at 0.75, while the CO_2 emissions term is weighted at 0.25, and the five social terms share the same weight of 0.2;

(b) Case C3: reflects the situation in which preferences lean toward the reduction of CO_2 emissions cost as expressed by $\sum_{t\in T}\sum_{b\in B}\sum_{i\in CD\cup B\setminus\{b\}}\omega^t\, U_{ib}\,(2\,\mu^t+\sum_{p\in P}x^t_{pib})$; this case differs from the previous by exchanging the weights of the two environmental terms;

(c) Case C4: the decision maker has no particular preference with regard to the environmental factors, which are weighted at 0.5 each, but looks for the largest inclusion of new charities in the supply chain; in this case, the first term of the social objective function $\left(\sum_{t\in T}\sum_{b\in B}\sum_{c\in HC}z^t_{bc}\right)$ is weighted at 0.4 and the remaining four terms are weighted at 0.15 each;

(d) Case C5: the main goal of the decision marker in this case is to limit the effort required to raise investment capital as accounted for by the term $\sum_{t\in T}\gamma^t$; accordingly, this second social term weights 0.4, while the other social terms weight 0.15 each; in this, like in the following cases, each environmental term is valued at 0.5;

(e) Case C6: if greater efforts are directed toward increasing the value of social work created by the supply chain, which is dependent upon the storage capacity available at the food banks, then the term $\sum_{t\in T}\psi^t\left[\sum_{b\in OB}\sum_{k\in K}\overline{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t}y^{\tilde{t}}_b\right)+\sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K}M_{lk}\sum_{\tilde{t}=1}^{t}w^{\tilde{t}}_{\ell kb}\right]$ is weighted at 0.4, and the other social terms are valued at 0.15 each;

(f) Case C7: in this case the chief social motivation of the decision maker is to shorten the distance that charities must travel to collect food products from their assigned food banks; the term $\sum_{t\in T} \varepsilon^t$ is weighted at 0.4 and the others at 0.15 each;

(g) Case C8: when achieving the most balanced distribution of products to charities possible, as expressed by the last social objective term $\left(\sum_{t\in T} \delta^t\right)$, is favored, then this term has more weight (0.4), and the other four terms share the remaining 0.6 weight equally.

Results reported pertain to the average over the same 20 regional supply chain instances used to study case C1. Thus, just like in the previous sections, results for a lexicographic solution are understood as the average results over the set of instances for the same lexicographic solution.

7.2.5.1 Environmental cases

Figure 7.17 on page 172 compares the cases that assign distinct importance to the components of the environmental objective function, while the components of the social objective function are identically valued among them. Comparison is made between the average performance of the three objectives in each of the six lexicographic solutions obtained for cases C2 and C3, and the respective results of case C1. Each objective is illustrated in an individual radar chart. Table 7.12 on page 179 reports the value of each objective function for these three cases, and also for the social cases. Appendices C and D present the characteristics of the lexicographic solutions obtained for case C2 and case C3, respectively.

The three radar charts that illustrate the results of cases C1, C2 and C3 share an identical shape. This indicates that the proportion among the results of respective solutions is maintained independently of the case. However, there are some noteworthy differences among them.

Regarding the economic results (chart on the left), the main differences of cases C2 and C3 in comparison with C1 are observed when the environmental objective is the first priority, that is in solutions LS3-LS4. In any of the four other solutions, the economic cost of giving preference either to the reduction of food waste, or to the decrease of CO_2 emissions is indistinct of the cost obtained in C1. Observe that in order to obtain any of those four solutions, the environmental objective is considered as second (for solutions LS1 and LS6) or third priority (for solutions LS2 and LS5). Hence, it is concluded that attributing different weights to the two environmental terms has no impact in the economic cost of these solutions.

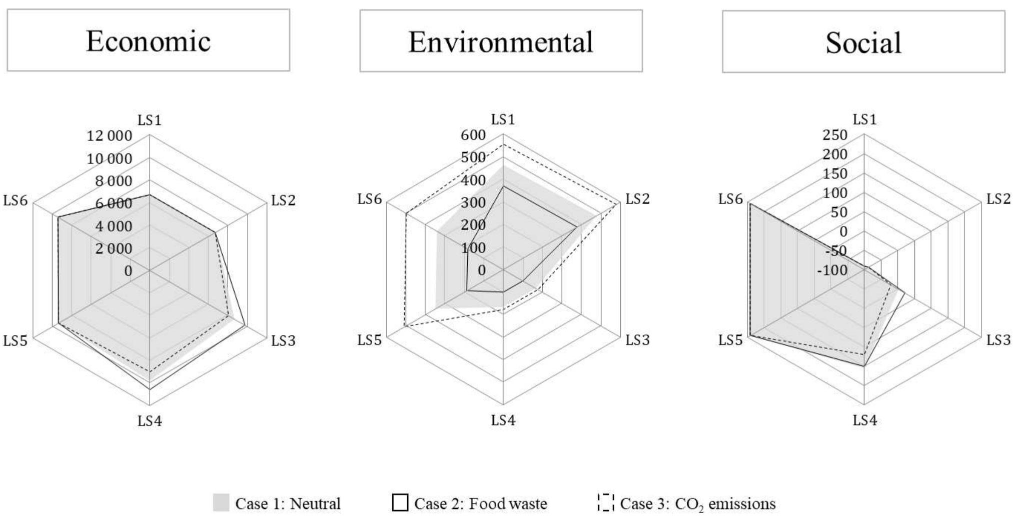


Figure 7.17: Objective functions values of the lexicographic solutions: environmental cases

That is not however the case of solutions LS3-LS4. As reported in Table 7.19 on page 180, the economic cost of these solutions is larger in case C2 (by 12.1% for LS3 and by 8.1% for LS4) than in C1. This signifies that attaching greater preference to the reduction of food waste, in opposition to being indifferent with regard to the two environmental criteria, leads to larger economic costs. The explanation resides in the fact that, in order to achieve greater food waste reduction, the level of food assistance to charities increases, often involving the inclusion of new charities in the supply chain, which has an economic cost. More meaningful is the fact that reducing food waste forcibly implies handling larger quantities of products at food banks, and plausibly involves operating larger storage areas, both of which result in higher economic costs. Table C.1 in Appendix C reveals that supply chains of solutions LS3-LS4 for C2 manage a total quantity of products of 14,525.5 tonnes and 15,663.1 tonnes, respectively. Recall that the corresponding volumes in C1 are 13,676.1 tonnes and 14,382.5 tonnes.

The opposite occurs in case C3. In this case, acting preferably toward the reduction of CO_2 emissions prompts lower economic costs than having a neutral attitude with regard to the environmental factors. The economic cost of LS3 (LS4) in C3 decreases by 7.2% (7.9%) in comparison with the economic cost registered in C1 (cf. Table 7.19). On the one hand, the use of the available transport capacity is more restrict than in case C1, which can have a negative economic impact because the penalty for unused transport capacity is higher. But, on the other hand, the level of service provided to charities is sacrificed in favor of further reducing the CO_2 emissions cost. When the chief goal is the reduction of the carbon footprint cost, fewer products are picked-up at collection donors, or exchanged with other food banks, and the total volume ready for redistribution decreases. Additionally, a smaller number of charities are included in the supply chain. Consequently, the total quantity of products managed by the supply chain is less than in case 1: 12,967.5 tonnes for LS3 and 13,377.0 for LS4 (cf. Table D.1 in Appendix D). Thus, in opposition to what is concluded above with regard to case C2, the policy of case C3 has a smaller economic cost than that of neutral case C1.

Similar to the economic impact, and as depicted by the chart on the right in Figure 7.17, the only discernible differences in the social value of the solutions between the three cases occur in solutions LS3-LS4. The reasoning for the absence of social impact in solutions LS1-LS2, and LS5-LS6 lies, just like in the economic case, in the priority assumed by the environmental objectives in the process of obtaining these solutions. The social results of solutions LS3-LS4 for cases C2 and C3 reflect the effects of policy changes from case C1 described above with regard to the economic cost impact. Favoring the reduction of food waste (case C2) significantly improves the social results of LS3 by 827.6%. With regard to LS4 the value is identical to the one registered in case C1. In fact, there is a slight deterioration by 3.3% from the value of C1 due to inferior performances in other social criteria such as the effort to raise investment capital or the distance between charities and assigned food banks (see Table D.1).

As expected, there are no social benefits in attributing higher preferences to the reduction of CO_2 emissions (case C3). It essentially corresponds to restricting the use of food banks transport capacity, which affects the ability to collect a larger quantity of products, and therefore to provide more assistance to the population. Although it permits a lower effort associated with raising investment capital to purchase transport capacity, its overall social impact is unequivocally worse than that of C1. The information reported in Table 7.12, indicates that in case C3 the social value of solution LS3 decreases by 1,025.6% compared to C1, and the values of solution LS4 recedes by 22.9%.

Naturally, more than the economic or social results, environmental costs are affected by changing the preferences with regard to the environmental criteria. The radar chart in the middle of Figure 7.17 shows that the environmental cost diverges in each of the three cases for all lexicographic solutions. Even though the shapes that represent the results of each case are identical, clearly case C3 is responsible for an weighted environmental cost larger than the cost provided by the other cases. Case C2 generates the smallest weighted cost, outperforming the results obtained for case C1.

It should be kept in mind that these costs concern the value of the environmental objective function. This function is not the same in the three cases due the changes operated in the weights associated with its terms. Given that the two environmental terms have different magnitudes of cost, instead of comparing the weighted environmental cost provided by each case, it is appropriate to compare the respective unweighted environmental results.

Unweighted results are obtained by adding for each solution the unweighted food waste disposal cost and the unweighted CO_2 emissions cost. For solutions LS3-LS4, the total unweighted environmental cost of case C1 is 333.6 k€. This cost actually increases by 67.1 k€ (approximately 20%) in solutions LS3-LS4 of case C2 to 400.7 k€. The unweighted cost of LS3-LS4 in case C3 is also larger than in C1 but not by as much (26.4 k€, i.e. around 8% more).

Along with the impact in terms of the environmental cost, cases C2 and C3 produce significant changes to the main characteristics of the supply chain designed by C1. Case C2 provides for a good example of these changes. In essence, when higher relevance is given to food waste disposal than to the generation of CO2 emissions, food aid reaches more charities and a larger quantity of food products is distributed, resulting in a lower level of food waste, and in a higher level of CO_2 emissions associated with trips to collect in-kind donations. As discussed in Sections 7.2.2 and 7.2.3 in reference to case C1, those are features typically associated with the social-centric solutions.

Table 7.10 presents a summary of the main characteristics of the environmental-centric solutions of cases C2 and C3 in comparison with features of those solutions in case C1. Further details about the results of C2 and C3 can be found in Appendices C and D, respectively.

7.2.5.2 Social cases

The comparison of the results obtained by changing the weighting factors associated with the terms of the social objective function is presented in Figure 7.18 on page 176. The objective function values for cases C4 to C8 are reported in Table 7.12 (p. 179). Appendices E through I inform on the individual features of each social case.

The economic and environmental costs of the six lexicographic solutions for any of the five cases are almost indistinct to the comparable costs observed for case C1. The shapes represented on the chart on the left for the economic cost, just as the shapes of the chart in the middle pertaining to the environmental cost, overlap for the values of solutions in which the social objective is not the first optimization priority (solutions LS1-LS4).

Even for solutions that rank the social objective function as first optimization priority (LS5-LS6), the economic and environmental results of case C1 and of each of the five social cases are very similar. As reported in Table 7.12, weighting favorably the support of new charities (case C4) or promoting the creating of social work value (C6), leads to the same economic and environmental results obtained by neutral case C1 for all lexicographic solutions. Stressing the importance of reducing the social effort required to raise investment capital (C5) can impact positively both the economic results (at most by 2.9% in LS5), and the environmental cost (by 2.8% in LS5-LS6) registered in C1.

Cases	Features	Comparison with neutral case C1
Case C2: reduction of food waste		
	Larger network	Average number of operating food banks increases from 3.2 to 4.0 in LS3, and from 4.3 to 4.4 in LS4. Additional storage capacity increases 23% (25%) in LS3 (LS4), and new transport capacity increases by almost 60% in LS3-LS4
	Greater demand satisfaction	Number of included charities increases from 1.8 to 2.5 in LS3, and from 2.8 to 3.0 in LS4. Supported by an increase of the total volume of products processed (6.2% in LS3 and 8.9% in LS4), the overall demand satisfaction of all charities $c \in C$ adds 4.5 pp in LS3, and 6.8 pp in LS4
	Less food waste	Food waste is virtually suppressed in LS3-LS4 (0.1%) - was 8.9% in case C1
	More emissions	CO_2 emissions cost rise by 73% in comparison with solutions LS3-LS4 of case C1
	Environmental cost	Total unweighted environmental cost increases 67.1 k€ (20%) from 333.6 k€ in case C1 to 400.7 k€ in Case 2 for LS3-LS4 over the five planing periods
	Social impact	LS3 and LS4 demand greater capital raising effort (around extra 20 pp in LS4); increase in social work value is more expressive in LS3 (15%)
Case C3: reduction of CO_2 emissions		
	Smaller network	Average number of operating facilities diminishes to 3 food banks in LS3, and to 4 facilities in LS4. New storage capacity diminishes 16% in LS3-LS4 and, most significantly, additional transport capacity is reduced to half the value of case C1
	Lower demand satisfaction	Decrease of 5% (LS3) to 7% (LS4) in the total volume of items handled, and decrease in the number of charities included to 1.4 in LS3, and 2.5 in LS4, leads to lower demand satisfaction levels for charities $c \in C$ (-3.9 pp in LS3 and -5.5 pp in LS4)
	More food waste	Cost of food waste disposal increases by almost 80%, from 102.9 k€ to 184.2 k€
	Less emissions	Decrease of 24% in CO_2 emissions cost in LS3-LS4
	Environmental cost	Total unweighted environmental cost of LS3-LS4 increases 26.4 k€ (8%) from 333.6 k€ (case C1) to 360.0 k€ (case C3) over five periods
	Social impact	LS3 and LS4 generate less social work value (around 6%), but also require less 10 pp of investment capital raising effort

Table 7.10: Impact analysis of environmental cases C2 and C3 compared to case C1

Environmental results of case C1 for solutions LS5-LS6 can also be improved by around 3% if the option is to foster the proximity between the charities and the assigned charities (case C7).

However economic costs obtained in C1 increase by approximately 4% in that situation. Finally, both economic and environmental costs of solutions LS5-LS6 increase versus the results of C1 if a greater balance in product redistribution is sought. Regardless, similar to all previous impacts, the deterioration is small, and in this case it does not exceed 2% of the costs obtained in C1.

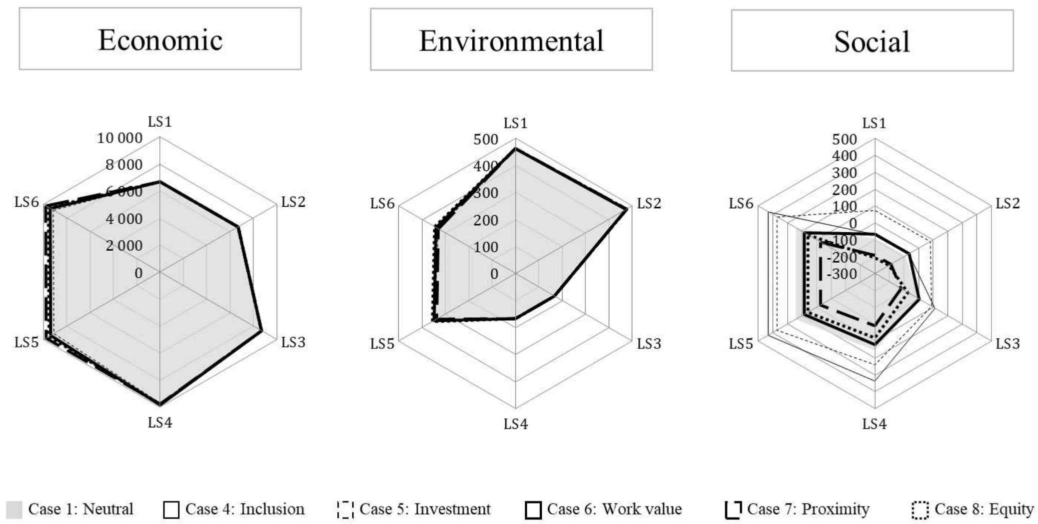


Figure 7.18: Objective functions values of the lexicographic solutions: social cases

Results of the five cases in relation to the social value obtained for the solutions of case C1 vary considerably from case to case. As depicted in the graph on the right in Figure 7.18, stimulating the inclusion of new charities in the supply chain (case C4), or valuing most the investment raising indicator (C5) improve the values registered in the neutral case for all solutions. Notably, case C5 always achieves a positive social value. In contrast, if the preferred social criterion is the proximity of charities to food banks (case C7), or the balance achieved in product distribution (C8), then the social value obtained is always worse than in the neutral case. For case C6 that endorses the creation of social work value, results improve for solutions LS1-LS3 but aggravate for solutions LS4-LS6.

Table 7.11 on page 178 summarizes the chief differences in the supply chains of social-centric solutions LS5-LS6 produced by cases C4 to C8 in light of the results of neutral case C1. As discussed before, these are the only solutions for which relevant impacts of cases C4 to C8 are identified.

The results reported in this section can play an influential role in the decision making process since they enable the evaluation of the impact of assigning higher preference to each one of the components in the environmental and social objective functions. Typically, in accordance to the existing trade-offs between the objectives, and in some cases within the same objective function (see

Section 5.6) benefits achieved on some features from specific preferences lead to a deterioration of other features. The two environmental cases clearly highlight those conflicts. Moreover, in those cases, attaching higher preferences to one of the environmental terms in detriment of the other leads to overall (unweighted) poorer environmental results. The five social cases have a more limited impact. This applies particularly to the cases pertaining to the inclusion of new charities in the supply chain, and the creation of larger social work value. In general, the results obtained for these cases are indistinct from the results of the neutral case. The other three cases offer considerably more individual alternatives to the neutral case. However, trade-offs are quite visible is these cases.

Cases	Features	Comparison with neutral case C1
Case C4: inclusion of new charities in the supply chain		
	Identical supply chain	Nondescript differences in comparison with case C1
Case C5: controlling the effort to raise investment capital		
	Fewer capacity resources	New storage capacity decreases by 15%, and addition of transport resources decreases 49%. Minor decrease in the average number of operating facilities in LS6 to 3.7.
	Similar demand satisfaction	Same final number of charities included, and moderately (-1.4%) fewer food items redistributed lead to slight decrease in the level of demand satisfaction for all charities $c \in C$ by 1 pp in LS5-LS6
	Environmental cost	Food waste increases by 50% in LS5 and by 59% in LS6, but CO_2 emissions cost is reduced by 3% in LS5 and by 5% in LS6
	Social impact	Investment raising effort decreases 2 pp. Social work value and distance from charities to food banks decrease by 2%
Case C6: creation of larger social work value		
	Identical supply chain	Nondescript differences in comparison with case C1
Case C7: improve the proximity of charities to food banks		
	Larger network capacity	Minor increase in number of operating facilities to 3.9. Added storage capacity increases by 40% (6% in transport) over values of case C1
	Similar demand satisfaction	Same number of included charities, and identical volume of products distributed to charities
	Environmental cost	Food waste cost diminishes 23% in LS5 and 19% in LS6, and CO_2 emissions cost also reduces about 2.5% in both solutions

Cases	Features	Comparison with neutral case C1
	Social impact	Maximum distance between charities and food banks decreases by 12% from 222.1 d.u. to 195.1 d.u., but is followed by higher capital raising effort (from 25.1% to 34.5%)
Case C8: more equitable redistribution of products		
	Similar network	Same average number of operating food banks with small increase of new storage (5%), but considerable increase in the added transport capacity (29%)
	Similar demand satisfaction	Overall demand satisfaction for charities $c \in C$ increases from 82.4% (LS5) and 82.6% (LS6) in case C1 to 83.1% (LS5 and LS6)
	Environmental cost	Reduction of around 30% in food waste cost is offset by increase of 3% in CO_2 emissions cost. Net increase of 2% in total environmental cost
	Social impact	Marginal changes in investment effort (+2 pp), social work (+1%), and distance from charities to food banks (-1%)

Table 7.11: Impact analysis of social cases C4 to C8 compared to case C1

Figure 7.19 (p. 180) details the results obtained for the economic, environmental and social objectives in all lexicographic solutions of the eight cases. Results of the two environmental cases and of the five social cases are also compared with the results of the neutral case.

7.2.6 Computational effort

The MO-MILP model was coded in C^{++} using IBM ILOG Concert Technology. The 15 single objective MILP models defined by the solving algorithm used, following the lexicographic ordering method, were solved with IBM ILOG CPLEX 12.6.1.0 optimizer. All experiments were conducted on a PC with a 2.6 GHz Intel® Core™ i7-6700HQ processor, 12 GB RAM (12,288 (8,192 + 4,096) MB DDR3L) and running Windows 7 (64-bit).

According to the LO method, all problems except P_1, P_6 and P_{11} involve constraints that ensure that the optimal value(s) obtained in previous problems is (are) preserved for the respective objective function(s). Early computational tests revealed that solving these problems is often met with numerical issues. Numerical issues are not uncommon when CPLEX, or other commercial software is required to solve complex MILP models (Klotz and Newman, 2013). In this case, they frequently prevented CPLEX from obtaining solutions for problems following P_1, P_6 and P_{11}. Note that optimal solutions for these problems are feasible, if not optimal solutions for the subsequent problems.

Objective functions	Lexicographic solutions											
	Economic-centric				Environmental-centric				Social-centric			
	LS1		LS2		LS3		LS4		LS5		LS6	
	Value	% C1	Value	% C1	Value	% C1	Value	% C1	Value	% C1	Value	% C1
C1: Neutral												
Economic (m.u.)	6,690.34		6,690.34		8,688.94		9,801.13		9,378.17		9,418.56	
Environmental (k€)	463.53		477.20		166.82		166.82		348.50		340.54	
Social	-91.73		-89.46		2.26		156.38		241.49		241.49	
C2: Food waste												
Economic (m.u.)	6,690.34	-	6,690.34	-	9,741.91	12.1	10,599.23	8.1	9,378.17	-	9,419.44	-
Environmental (k€)	370.30	-20.1	376.83	-21.0	100.73	-39.6	100.73	-39.6	188.10	-46.0	182.31	-46.5
Social	-91.73	-	-88.19	1.4	20.99	827.6	151.15	-3.3	241.49	-	241.49	-
C3: CO_2 emissions												
Economic (m.u.)	6,690.34	-	6,690.34	-	8,064.23	-7.2	9,023.86	-7.9	9,378.17	-	9,418.62	-
Environmental (k€)	555.30	19.8	577.49	21.0	177.90	6.6	177.90	6.6	508.78	46.0	497.60	46.1
Social	-91.73	-	-88.20	1.4	-20.94	-1,025.6	120.54	-22.9	241.49	-	241.49	-
C4: Inclusion												
Economic (m.u.)	6,690.34	-	6,690.34	-	8,688.94	-	9,800.93	-	9,373.72	-	9,414.32	-
Environmental (k€)	463.53	-	477.19	-	166.82	-	166.82	-	348.01	-0.1	340.05	-0.1
Social	-68.81	25.0	-67.10	25.0	111.72	4,838.0	336.45	115.2	431.11	78.5	431.11	78.5
C5: Investment												
Economic (m.u.)	6,690.34	-	6,690.34	-	8,694.05	0.1	9,701.28	-1.0	9,101.71	-2.9	9,159.28	-2.8
Environmental (k€)	462.98	-0.1	477.14	-	166.82	-	166.82	-	345.73	-0.8	331.07	-2.8
Social	74.44	181.2	80.43	189.9	88.95	3,831.4	239.97	53.5	370.91	53.6	370.91	53.6
C6: Work value												
Economic (m.u.)	6,690.34	-	6,690.34	-	8,694.04	0.1	9,833.03	0.3	9,377.85	-	9,418.50	-
Environmental (k€)	462.91	-0.1	474.73	-0.5	166.82	-	166.82	-	348.47	-	340.51	-
Social	-66.00	28.1	-64.62	27.8	3.99	76.2	120.37	-23.0	183.88	-23.9	183.88	-23.9
C7: Proximity												
Economic (m.u.)	6,690.34	-	6,690.34	-	8,688.94	-	9,767.53	-0.3	9,771.21	4.2	9,802.08	4.1
Environmental (k€)	463.27	-0.1	477.19	-	166.82	-	166.82	-	337.20	-3.2	330.46	-3.0
Social	-191.64	-108.9	-189.56	-111.9	-120.98	-5,447.0	8.80	-94.4	72.70	-69.9	72.70	-69.9
C8: Equity												
Economic (m.u.)	6,690.34	-	6,690.34	-	8,694.05	0.1	9,803.01	-	9,521.09	1.5	9,566.54	1.6
Environmental (k€)	462.98	-0.1	477.18	-	166.82	-	166.82	-	355.36	2.0	346.47	1.7
Social	-206.15	-124.7	-202.77	-126.7	-73.94	-3,367.9	80.45	-48.6	159.04	-34.1	159.04	-34.1

Table 7.12: Objective functions values of the lexicographic solutions and in percent of values of case C1: eight cases

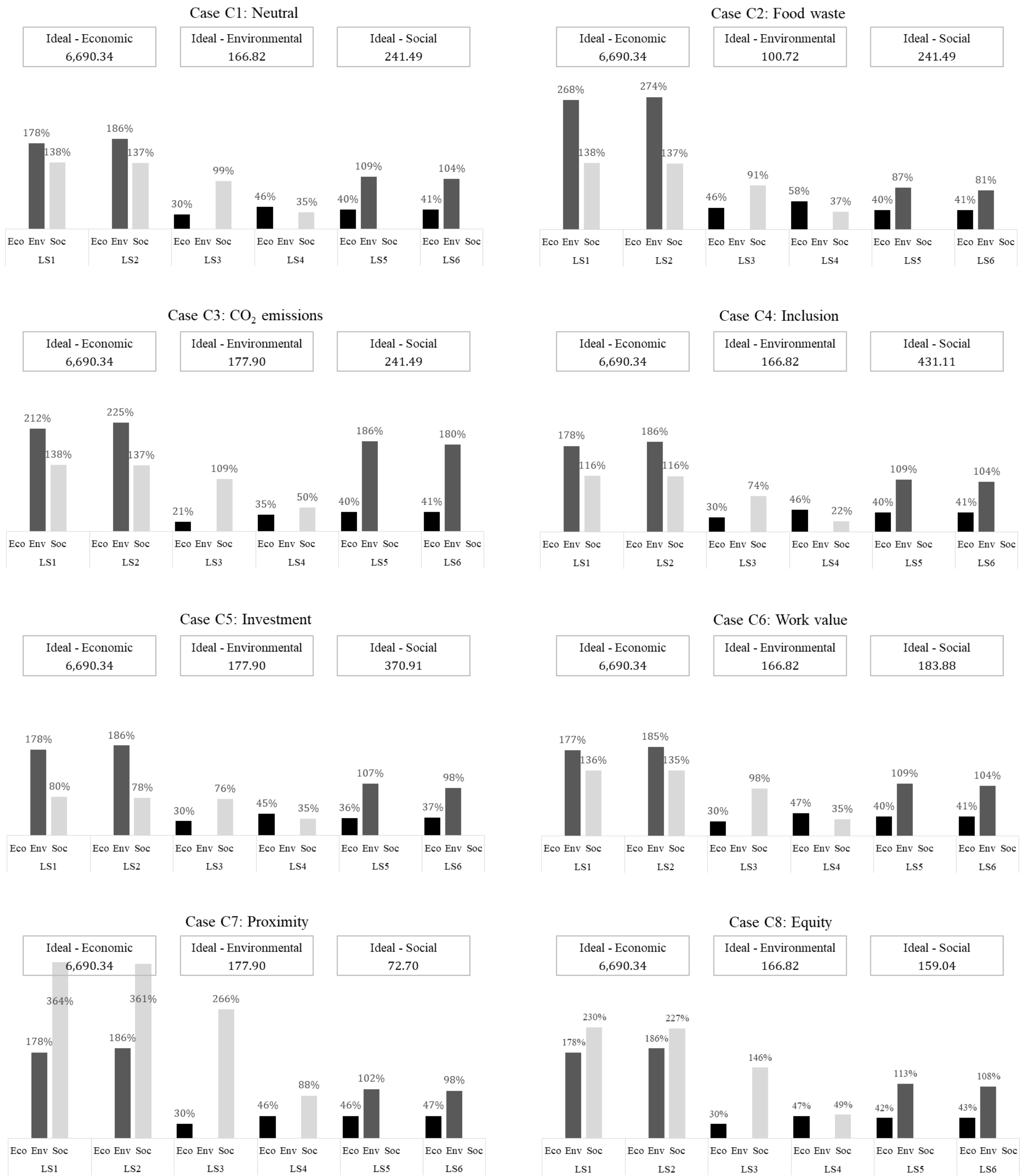


Figure 7.19: Percent deviations of lexicographic solutions from average ideal vector: eight cases

In the case of regional instances these numerical issues were addressed by the inclusion of an adjustment factor, and by changing the default CPLEX parallel optimization mode.

The adjustment factor is meant to provide some leeway to the optimization process. A small enough scalar is added to the optimal values obtained in previous problems when they are involved in the constraints of subsequent problems. Further to several tuning tests, a value of 0.001 was selected for this factor. This factor is small enough to not alter the results in any meaningful way, but proved to be effective overcoming some numerical issues.

Regarding the parallel optimization mode, CPLEX employs by default the *deterministic* mode (IBM, 2018b). This mode ensures that the optimization process always reproduces the same solution path, leading to the same results. Initial tests confirmed that several runs of the same instance in this mode originated the same output, including with respect to the computational time required to solve the problems, which registered minimal differences between runs [1]. However, this meant that if numerical issues prevented CPLEX from obtaining solutions for some instance(s), repeating runs would not solve the problem.

In *opportunistic* mode CPLEX uses all available parallelism entailing less synchronization between threads. While this mode may produce different solution paths, timings or vectors, it may also provide better performance. Tests performed with regional instances showed that, although differences were not significant, frequently the *opportunistic* mode actually took more time to obtain solutions than the *deterministic* mode. The chief benefit of selecting the *opportunistic* is that, based on the preliminary experiences performed, repeated runs for problems first unsolved are eventually successful. Usually it did not involve more than one or two re-runs before numerical problems were overcome, and an optimal solution was obtained.

The downside of using the *opportunistic* mode is that, as mentioned above, re-runs often lead to results that are not exactly equal to others possibly obtained before, or afterwards. Differences are usually negligible as reported in Table J.1 in Appendix J. This table compares the results obtained for each individual regional instance in two different runs of the solving algorithm using the *opportunistic* mode.

Hence, all results related to regional instances were obtained using an adjustment factor of 0.001, and the *opportunistic* parallel optimization mode. Unless otherwise noted, results report to the first run of Table J.1.

On average over 20 instances, the computational time required to run an instance is similar for all cases of weight factors combinations. The average time for all 8 cases is 1,634.6 CPU seconds,

[1] One run (for one instance) is understood as corresponding to one solving cycle of the MO-MILP on the basis of the solving algorithm, which involves solving 15 single objective MILP problems.

i.e. approximately 27 CPU minutes. Table 7.13 indicates that case C4, which attributes higher preference to the inclusion of new charities in the supply chain, is the most time consuming. In this case, it takes on average 34 CPU minutes to run an instance. In the opposite end is case C8. On average, running an instance with the combination of weights in the social objective function that favors the equitable distribution of food donations consumes approximately 24 CPU minutes.

Individual records (not showed in Table 7.13) varied from a minimum of just over four CPU minutes to solve instance 19 with the combination of weight factors of case C5, to over two hours and twenty CPU minutes to conclude instance 2 with the combination of case C4 as the largest time.

Problems	Case C1	Case C2	Case C3	Case C4	Case C5	Case C6	Case C7	Case C8	Avg.
Total	1,767.2	1,709.2	1,489.7	2,040.2	1,540.5	1,520.0	1,546.8	1,454.4	1,634.6
P_1	0.5	0.5	0.6	0.4	0.6	0.6	0.6	0.6	0.5
P_2	2.1	1.9	2.8	1.8	2.6	2.1	2.7	2.1	2.2
P_3	2.5	2.5	3.0	1.4	2.0	2.5	2.6	3.6	2.4
P_4	2.4	3.2	3.4	1.6	2.2	2.7	3.0	3.4	2.7
P_5	2.8	3.2	3.8	2.4	2.7	3.1	3.1	2.7	2.9
P_6	0.5	0.3	0.2	0.7	0.4	1.4	0.6	0.7	0.6
P_7	2.6	2.9	1.9	2.2	2.4	2.9	2.6	3.2	2.6
P_8	12.5	8.6	12.1	9.7	12.5	11.8	9.0	10.5	10.8
P_9	15.3	17.5	7.2	11.5	8.2	14.4	13.1	16.8	13.0
P_{10}	12.6	8.8	10.4	14.2	11.0	11.1	8.2	12.1	11.2
P_{11}	6.9	7.3	8.7	6.9	7.0	7.2	7.5	5.9	7.2
P_{12}	6.5	7.1	7.5	7.0	7.5	6.7	8.5	7.1	7.2
P_{13}	13.7	13.4	15.3	15.7	18.7	12.5	14.4	11.7	14.5
P_{14}	11.5	14.0	14.7	15.5	15.2	12.9	15.3	10.8	13.8
P_{15}	7.6	8.9	8.4	9.1	7.1	8.0	8.9	8.6	8.4

Table 7.13: Average computational time (CPU seconds) required to solve one instance per case and in percent of each problem

It is noticeable from Table 7.13 that the distribution of average time required to solve an instance is not uniformly distributed across all 15 problems involved. On average, problems P_8 - P_{10}, P_{13}, and P_{14} take longer to be solved than any of the others. Table 7.14 shows that, for any case, the group of problems involved in the process of obtaining the social-centric solution LS5-LS6, i.e. problems P_{11} though P_{15} take the longest to be concluded. On average over the eight cases, more than half of the computational time is invested in obtained these solutions, whereas only 10.8% of the total time is spent on obtaining the economic-centric solutions LS1-LS2. Identifying environmental centric-solutions LS3-LS4 takes around 38.2% of the total time.

Moreover, Table 7.14 also reveals that solving the set of problems that maximize the social objective function $z_3(x)$ requires on average more time than the others. Recall that this function not only involves binary and continuous variables but also includes two *minmax* terms. The fourth and fifth terms of the social objective function minimize the maximum distance between a charity and its assigned food bank, and the maximum unsatisfied demand by any served charity, respectively. This structure turns out to be more time consuming than the formulation of the other two objective functions, requiring on average 36.1% of the total time.

Groups of Problems	Problems	C1	C2	C3	C4	C5	C6	C7	C8	Avg.
Total		1,767.2	1,709.2	1,489.7	2,040.2	1,540.5	1,520.0	1,454.4	1,546.8	1,634.6
LS1-LS2	P_1-P_5	10.2	11.2	13.5	7.5	10.0	11.0	12.5	11.9	10.8
LS3-LS4	P_6-P_{10}	43.5	38.1	31.9	38.2	34.4	41.7	43.4	33.5	38.2
LS5-LS6	P_{11}-P_{15}	43.6	50.6	54.7	54.3	55.6	47.4	44.1	54.6	51.0
Min $z_1(x)$	P_1 P_7 P_{10} P_{12} P_{15}	29.8	28.2	28.8	33.0	28.6	29.4	28.7	31.7	29.9
Min $z_2(x)$	P_2 P_5 P_6 P_{13} P_{14}	30.6	32.7	36.9	36.0	39.6	31.9	36.1	28.1	34.0
Max $z_3(x)$	P_3 P_4 P_8 P_9 P_{11}	39.6	39.1	34.3	31.0	31.8	38.7	35.2	40.3	36.1

Table 7.14: Average computational time (CPU seconds) required to solve one instance in percent of groups of problems

Finally, Figure 7.20 (p. 184) shows the time required to solve each individual instance, on average over the eight cases of weight combinations. It is possible to observe the distinct impacts that particular parameter conditions have in terms of the computational effort. Notably, instances 2, 9, and 16 take substantially longer than the average time required by all instances. On average over the eight cases, instance 2 requires about 88 CPU minutes, instance 9 consumes 79 CPU minutes, and instance 16 takes 77 CPU minutes. In contrast, the instance that on average takes the least computational time is instance 12 with approximately 6 minutes. The instance used for illustration purposes in Section 7.2.1, pictured in gray, requires an average time of 20 CPU minutes, similar to the average for all instances (27 CPU minutes).

In Section 5.3, constraints (5.29) and (5.30) related to potential and initial food banks, respectively, were introduced as valid inequalities designed to improve the computational performance of the model. These constraints state that charities can only be assigned to operational food banks.

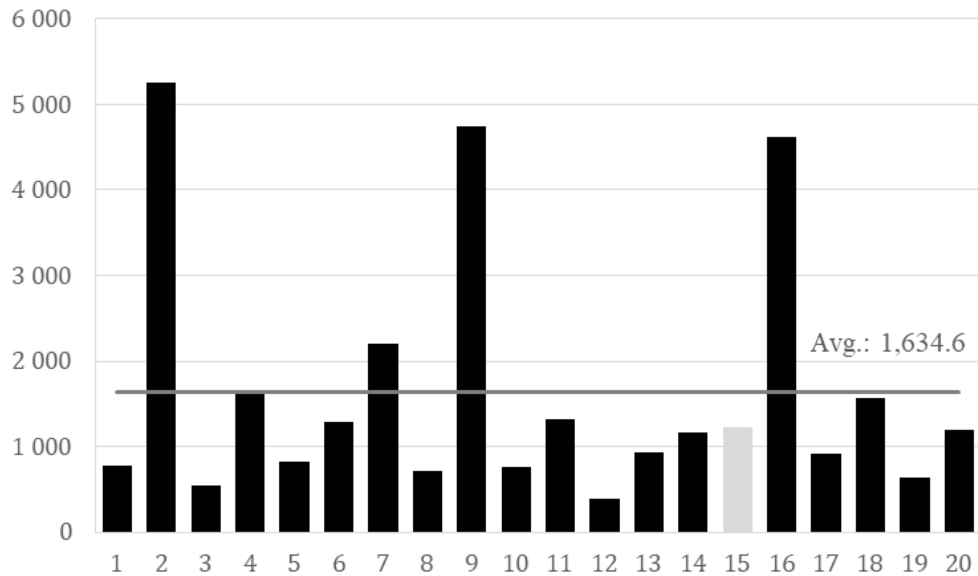


Figure 7.20: Average computational time (CPU seconds) required to solve one instance per instance

$$z_{bc}^{t} \leq \sum_{\widetilde{t}=1}^{t} y_{b}^{\widetilde{t}} \qquad b \in PB, c \in C,\ t \in T \qquad \text{(5.29 revisited)}$$

$$z_{bc}^{t} \leq 1 - \sum_{\widetilde{t}=1}^{t} y_{b}^{\widetilde{t}} \qquad b \in OB, c \in C,\ t \in T \qquad \text{(5.30 revisited)}$$

The proof that these are valid inequalities contributing to the computational performance of the MO-MILP model is made in two phases. First, it is proven that the constraints are redundant. Afterwards, it is shown that, based on tests performed, the constraints can improve the computational efficiency.

Following, the constraints involved in the redundancy proof are revisited. Regarding potential food banks $b \in PB$, constraints (5.4) state that if opened, then they can not be closed until the end of the planning horizon. Constraints (5.8) declare that storage capacity of any size, and for any type of product family may only be installed in opened potential food banks, and constraints (5.13) limit the quantity of products received by a potential bank in period t to the storage capacity installed in that facility until that period (inclusive).

Single assignment constraints (5.17), for initially served charities $c \in SC$, and (5.18), for awaiting charities $c \in HC$, limit to one (impose in case $c \in SC$) the largest number of food banks to which charities can be assigned to, in every planning period.

Minimum supply quantities are set by constraints (5.23) for charities $c \in SC$, and by constraints (5.24) for charities $c \in HC$. Moreover, constraints (5.25) state that charities can only be served (in quantities not greater than their demand) by the food bank(s) to which they are assigned to in each period t.

Lastly, constraints (5.31) determine that food banks can only (must) distribute, to charities or other food banks, a quantity of every product $p \in P$ equal to the volume received from suppliers or other food banks in each period $t \in T$. Constraints (5.32) define, concerning variables z_{bc}^t and y_b^t, that they can either assume the value zero or the value one.

If all these conditions are verified, i.e. assuming constraints (5.4), (5.8), (5.13), (5.17), (5.18), (5.23), (5.24), (5.25), (5.31), and (5.32) hold, then forcibly, in every period $t \in T$, charities $c \in C$ can only be assigned to potential food banks $b \in PB$ that have opened until that period, which is the condition established by constraints (5.29). In this case, as posited by Lemma 7.1, constraints (5.29) are rendered redundant.

The contrapositive of Lemma 7.1 states that if $z_{bc}^t \nleq \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}$ (or $z_{bc}^t > \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}$), then at least one of the constraints (5.4), (5.8), (5.13), (5.17), (5.18), (5.23), (5.24), (5.25), (5.31), and (5.32) does not hold.

The following proof appeals to the domain conditions established for parameters β_2, β_3, X_{pc}^0 and R_{pc}^t (see Table 5.3 and following comments on page 77).

Lemma 7.1. *Constraints* (5.29) *are redundant.*

Proof. Assuming domain constraints (5.32) hold for variables z_{bc}^t, then $z_{bc}^t = 0$ or $z_{bc}^t = 1$ for all $b \in PB$, $c \in C$, and $t \in T$. Hence, proof will be made separately for the two cases.

If (5.32) holds for variables z_{bc}^t and $z_{bc}^t = 0$, then (5.32) does not hold regarding variables y_b^t.

If (5.32) holds for variables z_{bc}^t and $z_{bc}^t = 1$, then (5.32) only holds regarding variables y_b^t if $\sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} = 0$, so that $1 = z_{bc}^t > \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}} = 0$. This means that in order for charity $c \in C$ to be assigned to potential food bank $b \in PB$ (henceforth denoted b') in period $t \in T$, food bank b' cannot open until that period (inclusive).

Assuming constraints (5.8) hold, then no storage capacity can be installed in that potential food bank ($\sum_{\ell \in L} w_{\ell k b'}^t \leq \sum_{\tilde{t}=1}^{t} y_{b'}^{\tilde{t}} = 0$). Subsequently, assuming constraints (5.13) also hold, no food products can be received at food bank b' from suppliers or other food banks ($\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b'\}} x_{pib'}^t \leq \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w_{\ell k b'}^{\tilde{t}} = 0$).

Further assuming that constraints (5.31) hold, i.e. the quantity of product distributed by food bank b' to charities is integrally sourced from suppliers or other food banks (no other product origins), then no products are delivered by the food bank ($\sum_{i \in D \cup B \setminus \{b'\}} x^t_{pib'} = \sum_{j \in C \cup B \setminus \{b'\}} x^t_{pb'j} = 0$).

Whether c is an initially served charity, or an awaiting charity, assumption that constraints (5.17), for $c \in SC$, and (5.18), for $c \in HC$, hold, signify that charity c cannot be served by food banks other than bank b', and therefore $z^t_{bc} = 0$ for all food banks $b \in B$ if $b \neq b'$. It also signifies that $\sum_{b \in B} z^t_{bc} = z^t_{b'c}$.

Assuming constrains (5.25) hold, then, for all food banks $b \in B$ and $b \neq b'$, no products are delivered to charity c ($x^t_{pbc} \leq R^t_{pc} z^t_{bc} = 0$). Moreover, as established earlier, no products are delivered by food bank b'. Thus, $\sum_{b \in B} x^t_{pbc} \leq 0$ for all food banks $b \in B$, including b'.

If $c \in SC$, based on the conditions over parameters β_2 and X^0_{pc}, then constraints (5.23) do not hold. Otherwise, if $c \in HC$, based on the conditions over parameters β_3 and R^t_{pc}, then constraints (5.24) do not hold (recall that $\sum_{b \in B} z^t_{bc} = z^t_{b'c}$). In both cases, it is not possible to satisfy the minimum demand volumes of served charities $c \in C$, if those charities are assigned to (can only be served by) a potential food bank b' that does not have any products to distribute because it has not yet open by period t. □

Lemma 7.2. *Constraints* (5.30) *are redundant.*

The proof of Lemma 7.2 is identical to the proof of Lemma 7.1. It involves constraints (5.4), (5.7), (5.14), (5.17), (5.18), (5.23), (5.24), (5.25), (5.31), and (5.32), and the same conditions over parameters β_2, β_3, X^0_{pc} and R^t_{pc}. The proof can be found in Appendix K.

Following it is shown that, based on instances tested, including redundant constraints (5.29) and (5.30) in the MO-MILP model contributes to improve its computational performance.

Table L.1 in Appendix L presents the results obtained for three runs of the MO-MILP model without constraints (5.29) and (5.30). As verified in multiple runs of the model including those constraints (see Table J.1), there are few differences in the value of the objective functions obtained in each run. Likewise, the average time required to solve one instance varies considerably from run to run, as a result of using the opportunistic parallel search mode.

Table 7.15 summarizes the average computational time over the 20 regional instances required by the model, with and without redundant constraints (5.29) and (5.30). Results report to two runs of the model with those constraints (with identical total average time), and three runs without the constraints (time varies between 1,895.98 CPU seconds in the second run, and 2,234.37 in the first run). Regardless of the particular runs compared, it is clear that the performance of the model improved when constraints (5.29) and (5.30) were included. On average, excluding the constraints demanded extra 16.38% CPU time. The smallest improvement was around 7%, while the largest exceeded 27%.

			With (5.29)–(5.30)		
			1st run	2nd run	Average
			1,767.20	1,748.92	1,758.06
Without (5.29)–(5.30)	1st run	2,234.37	26.44%	27.76%	27.09%
	2nd run	1,895.98	7.29%	8.41%	7.84%
	3rd run	2,007.65	13.61%	14.79%	14.20%
	Average	2,046.00	15.78%	16.99%	16.38%

Table 7.15: Average computational time (CPU seconds) required to solve 20 instances with and without constraints (5.29)–(5.30)

Detailed comparison between the results obtained in the first runs of the versions with and without the constraints is provided in Table M.1 in Appendix M for each individual instance.

Improvement of computational efficiency observed in the experiments from including redundant constraints (5.29) and (5.30) in the model derived from the reduction of the solutions search space at node zero of the branch-and-cut process. Although more constraints are included in the model, which could increase the associated computational effort, these redundant constraints for the MO-MILP model eliminate a portion of the feasible region of the corresponding linear relaxation. Consequently, they contributed to a more efficient optimization process.

The information presented in Table N.1 in Appendix N substantiates this conclusion based on data obtained during the optimization of instance 15 (selected for illustrative purposes). It can be observed that results obtained by the CPLEX optimizer at the first branch-and-cut node, corresponding to the linear relaxation solution, have consistently smaller integrality gaps when constrains (5.29) and (5.30) are involved, than when those constraints are excluded. On average over the 15 problems, the absolute integrality gap obtained when the constraints are included is 2.01, improving by approximately 5.2% the gap resulting from not including those constraints (gap of 2.12). Hence, including the redundant constraints improved the lower (upper) bounds of the minimization (maximization) problems, thereby improving the branch-and-cut efficiency.

Taking into account the relatively smaller dimensions of the regional supply chain instances in comparison with the national regional instances, the computational effort required to solve the problem plays an important part when addressing the latter. Hence, this matter is one of the main subjects of the following chapter that concerns the national instances.

Summary Chapter 7

This chapter presented the results obtained for the network redesign problem of a regional supply chain.

First, in Section 7.1, the methodological approach adopted was introduced. The lexicographic ordering method was selected because it allows the identification of a concise number of Pareto efficient solutions, which in turn enables the detailed analysis of the features of those solutions. Following this method, 15 single objective problems are solved to obtain six lexicographic solutions for each test instance. Solutions were paired according to the first optimization objective. Solutions LS1 and LS2 were denoted economic-centric, LS3 and LS4 as environmental-centric solutions, and LS5 and LS6 correspond to social-centric solutions.

The study comprised 20 regional instances generated according to the method described in the previous chapter. All instances share the same number of shareholders. There are four initially open food banks and one potential site for the deployment of a new facility, eight delivery donors, two collection donors and one financial donor, and finally 16 charities already included in the supply chain while three others are waiting to be included. The location of the food banks is fixed across all 20 instances, yet donors and charities have different locations in every instance. Supply and demand parameters are also specific to each instance, thereby creating the diversity of supply chain configurations required by the generalization purposes of the study.

In Section 7.2.1 instance 15, representative of the complete set of test instances, was chosen to illustrate the supply chain configuration at the last planning period for the six solutions. The analysis of the main features of the solutions obtained for this instance allowed their individual characterization. Later in the chapter, this characterization is confirmed for the average results over the 20 regional instances.

Although distinct, solutions LS1-LS2 reveal some similar features. The supply chains of these solutions are characterized by processing the smallest volume of food products of all lexicographic solutions. Compared with the initial network, there is a decrease in the number of operational food banks, and no new charities are served. The level of service provided to the served frontline agencies is the minimum possible, corresponding to approximately 70% of their supply in Period 0. This policy leads to the highest level of food waste of all solutions, mainly located at delivery donors. It also results in a low social work value, high investment effort, and large CO_2 costs.

On the contrary, environmental centric-solutions LS3-LS4 share the best environmental results but diverge with respect to most of the supply chain features studied. Both solutions generate a high level of food assistance, and the inclusion of new charities in the supply chain. However, while the profile of LS3 is more similar to some of the features of the economic-centric solutions, the results of LS4 are more socially oriented. In LS4, the number of operational food banks increases from the initial four to five. Reversely, LS3 reduces the number of food banks to three. Yet, both demand the largest investment costs of all solutions, while also creating the largest social work value.

The social-centric solutions LS5-LS6 are the most alike pair of solutions in terms of network configuration. They operate few changes over the initial network but manage to include all waiting charities from the first planning period. The level of supply is among the highest obtained in all solutions. Although requiring a low investment effort, and allowing the best food waste reduction results, these solutions greatly exceed the carbon footprint costs of any other solution.

Section 7.2.2 provided additional information about the features of the lexicographic solutions obtained. This section reported the average results over the 20 instances for the case in which, like in the illustrative example, the decision maker has a neutral positioning regarding the environmental and social criteria considered in the respective objective functions. Results were evaluated according to *i*) the gaps between the ideal and estimated nadir values of each objective function, *ii*) the trade-offs between the three objectives, and *iii*) the relative distances between the six lexicographic vectors.

Relevant managerial insights were derived and discussed in Section 7.2.3 based on a number of KPIs developed to enable a comparison between the results of the lexicographic solutions. The selected KPIs cover eight of the most relevant economic, environmental, and social indicators defined for the problem, and render an assessment of the performance of each solution in relation to the others. Naturally, considering that all solutions are efficient, each one of them offers distinctive benefits over the remaining with regard to some criteria. The analysis is important to allow an informed (re)positioning of the supply chain by the decision maker.

This matter was particularly addressed in Section 7.2.4. This section compared the results of the lexicographic solutions with the triple bottom line assessment of the initial network, assuming that it would not register any changes during the planning horizon. While the estimate suggested that a “no change” strategy does not have a clear inferior quality compared with the policies defined by the lexicographic solutions, it also identified potential benefits of redesigning the supply chain, which are dependent upon the decision maker preferences with regard to the three objectives.

Section 7.2.4 is also relevant to this issue. All analysis of the preceding sections concerned the neutral case, by which there is no favoring of particular environmental or social criteria. In this section, seven distinct preferences cases were presented and discussed. These cases were denoted “Food waste”, “CO_2 emissions”, “Inclusion”, “Investment”, “Work value”, “Proximity”, and “Equity”, and are defined by weighting more favorably the respective objective function element. The analysis showed the chief differences of these cases from the neutral case. Overall, weighting one of the environmental (social) terms more favorably than the other(s), results in outcomes that diverge mostly from the neutral cases with regard to the environmental-centric (social-centric) solutions. Even though the main features that characterize each lexicographic solution do not deviate substantially from the neutral case, differences are more prominent with respect to the term that is championed.

The chapter was concluded with the report on the computational effort demand by the MO-MILP model. The largest portion (51%) of the average time required to solve one instance (27 CPU minutes on average of all cases) is allocated to obtain the social-centric solutions, while economic-centric solutions take the smallest time (around 11%). When higher preference is attributed to the inclusion of new charities in the supply chain (case C4) the average time increases to 34 CPU minutes. The opposite occurs when equitable distribution of food donations is favored in case C8 (24 CPU minutes).

It was proven that constraints (5.29) and (5.30) are valid inequalities and computational experiments have shown that they can contribute to improve the computational performance of the MO-MILP model.

As remarked by the end of this chapter, based on the computational study of the regional supply chain instances, computational effort will play an important role when national instances are addressed in the next chapter.

Keywords: Regional instances; Lexicographic ordering method; Economic, environmental and social-centric solutions; Managerial insights; Valid inequalities

Chapter 8

National supply chain

As presented in Chapter 6, national instances include 15 initially open food banks ($|OB| = 15$) and three potential sites to set-up new facilities ($|PB| = 3$). The food bank network is supplied by 53 donors that deliver their products at the location of the food banks ($|DD| = 53$) and nine product donors that require collection by the food banks ($|CD| = 9$). Additionally, food products can be purchased with the donations provided by five financial donors ($|FD| = 5$). Initially, the national supply chain serves 100 frontline agencies ($|SC| = 100$). During the planning horizon, 20 new charities may also be supplied ($|HC| = 20$).

The supply chain manages 18 different food products ($|P| = 18$). Similar to the regional instances, these products are aggregated into three product families ($|K| = 3$). Most are dry products (11). Although there are only four different fresh products, they account for a large share of the total volume of products redistributed by the food bank network. There are also three different frozen products. The description of the products considered in the national instances is presented in Table 6.2 on page 109.

Also identical to the regional instances, there are three discrete sizes available to install or expand both storage and transport capacity ($|L| = 3$) throughout the five planning periods ($|T| = 5$). Other relevant features of the national instances concern the minimum level of supply ensured for the initially served charities (70%, i.e. $\beta_2 = 0.7$), and for the charities that are included in the supply chain for the first time during the planning horizon (50%, i.e. $\beta_3 = 0.5$). The same maximum distance between charities and assigned food banks of the regional case (250 d.u.) applies to the national instances. However, in the case of the national instances the largest number of changes in food bank status (open/close) that can occur in a single period is limited to 25% of the total number of facilities, open or potential ($\beta_1 = 0.25$).

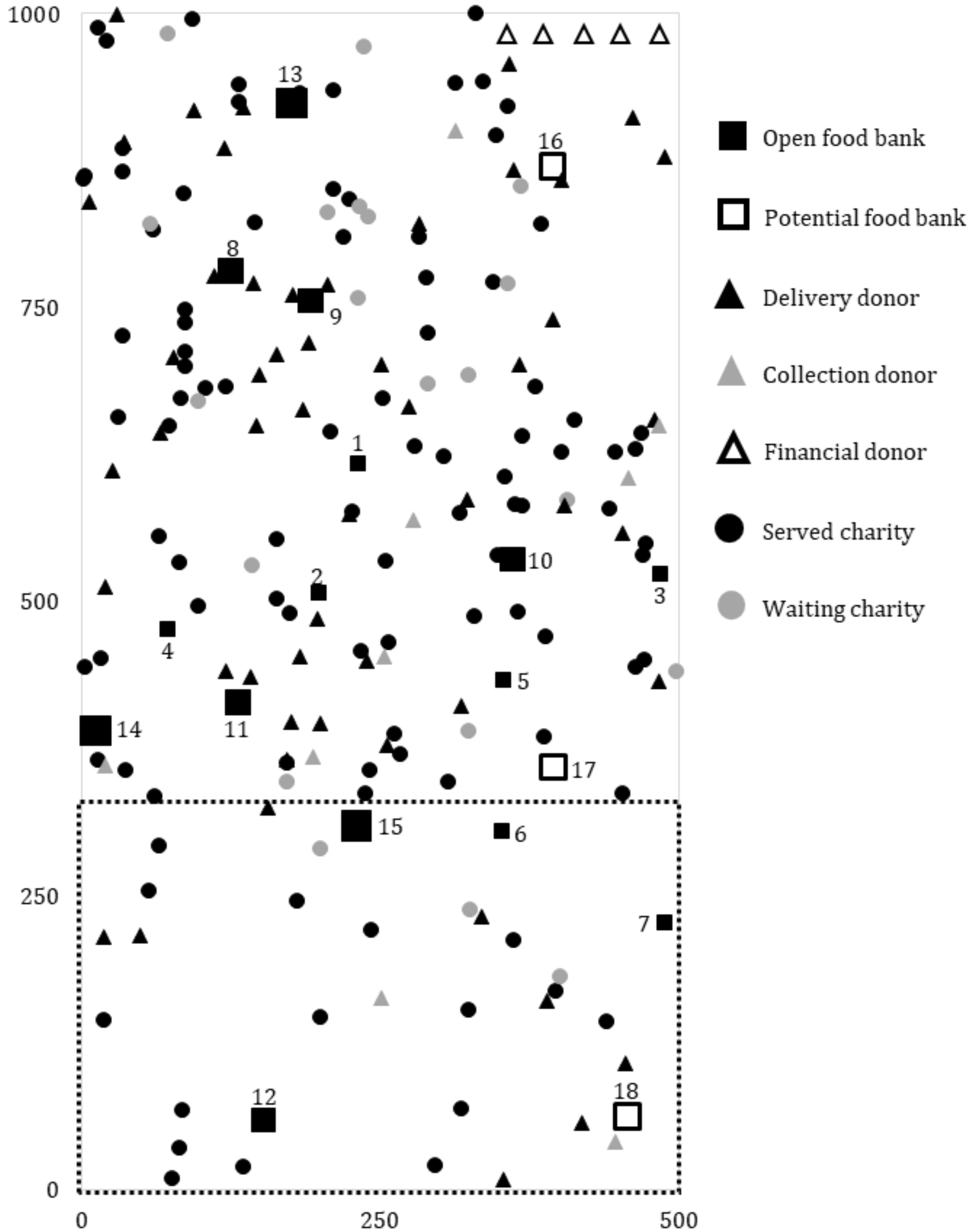


Figure 8.1: National supply chain: instance 15

Tests are performed over a set of 20 instances. For illustration purposes, the national supply chain of instance 15 is depicted in Figure 8.1. All instances share the same locations of food banks. The size of initially open facilities is also the same in all instances, but the specific storage and transport resources differ from instance to instance. Regarding donors and charities, the only commonality among instances is their cardinality (see above). Otherwise, each instance is characterized by individual location of donors and charities, as well as by distinct supply and demand conditions over the planning horizon.

Section 8.1 is dedicated to the methodology adopted to solve the national instances. The reasoning leading to the development of heuristic methods, the chief concept of those methods, and their quality assessment are discussed. Afterwards, the results obtained with the heuristic selected to solve the national instances are reported and discussed in Section 8.2. All results of this chapter report to case C1 of the weighting factors introduced in Section 7.2.5.

8.1 Solving methodology

The increase in dimension from regional to national instances prevents CPLEX from solving the decision problem based on the lexicographic ordering method. In all computational tests performed with the national instances, it was never possible to obtain lexicographic solutions for any instance. In fact, only the first problem P_1 was regularly concluded after over two CPU hours. Recall that, solving the first problem for the regional instances takes approximately 0.5% of the total time required to solve one instance (see Table 7.13 on page 182). It is therefore unsurprising that, after several hours spent on solving problem P_2, CPLEX always terminated with an "out of memory" error message. The associated Logfile revealed that usually no solution had been found for the second problem until termination.

Several tests involving CPLEX parameters tuning also proved unfruitful in solving national instances on the basis of the lexicographic method. Among the parameters tested were *EpGap* that sets a relative tolerance on the gap between the best integer objective and the objective of the best node remaining, *EpOpt* governing how closely CPLEX must approach the theoretically optimal solution, and $EpRHS$ specifying the feasibility tolerance, that is, the degree to which the basic variables of a model may violate their bounds (IBM, 2018a).

Tests were also performed setting a time limit for the conclusion of each problem (CPLEX parameter $TiLim$). This was tried in an attempt to progress the furthest according to the lexicographic solving method even though some problems may not have been concluded to optimality within that time limit (but some solution(s) had been obtained). Setting $TiLim = 3,600$ (seconds) frequently led to the termination of the lexicographic method by problem P_2 or P_3, for which no solution had been found until the time limit was reached. In the atypical cases that solving progressed further than those initial problems, the process was terminated at most by P_5, always with considerable gaps between best bound and best integer solution found (frequently more than 100%). Notice that the selected optimizer time limit was set to the actual physical time elapsed (one hour) and not to CPU seconds.

In all these tests, the opportunistic parallel search mode and the adjustment factor used in solving the regional instances were also involved.

Faced with the impossibility of obtaining solutions for the national instances by the lexicographic method, the alternative identified resided in developing heuristics tailored for the decision problem. Hence, recognizing that the MO-MILP model presented in Chapter 5 includes both strategic and tactical decisions, the underlying concept defining the heuristic method developed is to ease the solving of the problem by decomposing those decisions into two distinct MO-MILP problems.

It is expected that, by solving first the long-term decisions, postponing the medium-term decisions for a subsequent solving phase will overcome the computational obstacles found and described above.

In the coming sections, three heuristics following this approach are presented. The heuristics are assessed based on their performance in solving the regional instances, for which the lexicographic solutions are known.

8.1.1 Heuristic *LAS-T*

This heuristic first addresses the location, assignment, and storage capacity decisions, deferring transport capacity decisions to the second solving phase. Product flows are included in the first phase to ensure that solutions observe the supply and demand conditions, but are ultimately decided in phase two. Given the decomposition criterion adopted, this heuristic is denoted as LAS-T. For convenience, the MO-MILP model presented in Chapter 5 is referred to as initial, complete or original model.

Phase 1 Reducing the problem to location, assignment and storage capacity decisions allows disregarding in the first phase several constraints of the initial model. It also requires some changes to the constraints, and terms of the objective functions of the complete MO-MILP model pertaining to the decisions involved in this phase.

Donor-related constraints (5.1) to (5.3) are included in the first phase of heuristic LAS-T to ensure that donations received by food banks do not exceed the quantities available at suppliers.

Institution-related constraints concerning location, storage capacity acquisition, and respective utilization are also relevant for the first phase. Hence, constraints (5.4) and (5.5) in reference to location decisions, and constraints (5.6) to (5.9) determining storage capacity acquisition conditions are included. Similarly, constraints (5.13) and (5.14) that limit the quantity of products received by food banks to their storage resources are also involved in the first phase of the heuristic.

Considering that transport capacity decisions are excluded from this phase, the associated acquisition costs are not material to the decision problem tackled at the first phase. Accordingly, the following budget constraints replace constraints (5.12) of the initial MO-MILP model:

$$\sum_{b \in PB} FI^t \, y_b^t + \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VSI_{\ell k}^t \, M_{\ell k} \, w_{\ell k b}^t + \sum_{b \in OB} \left(FU^t + \sum_{k \in K} VU_k^t \, \overline{M}_{kb} \right) y_b^t + \gamma^t = O^t \qquad t \in T \tag{8.1}$$

Charity-related constraints (5.17) to (5.21) enforce assignment conditions and are therefore considered in the first phase of the heuristic. Moreover, constraints (5.23) and (5.24) establish the minimum level of supply to served charities and are also included in this phase. The initial model constraints (5.25) guarantee that for each product $p \in P$, the volume of supply to each served charity does not exceed its demand. These constraints also enforce that charities only receive food products from the food banks to which they are assigned to, in each period $t \in T$. As product flows decisions are ultimately taken in the second phase, the main purpose of including these constraints in the first phase is to ensure the single supply source of each charity. To that end, constraints (5.25) are reformulated as follows:

$$\sum_{p \in P} x_{pbc}^t \leq \sum_{p \in P} R_{pc}^t \, z_{bc}^t \qquad b \in B, \; c \in C, \; t \in T \tag{8.2}$$

These constraints guarantee that all products supplied to charity $c \in C$ are exclusively provided by the food bank $b \in B$ to which it is assigned to in each period $t \in T$ ($z_{bc}^t = 1$). Considering the dimensions of the national instances, ensuring this condition based on inequalities (8.2) instead of constraints (5.25) allows the number of constraints to decrease from $|B| \times |C| \times |P| \times |T| = 194,400$ to $|B| \times |C| \times |T| = 10,800$.

In order to further relieve the effort required to solve phase 1, the social objectives of minimizing the distance between charities and the assigned food banks, and of achieving the best balance in product distribution are deferred to the next phase. Recall that these goals are expressed by *minmax* terms. Hence, variables ε^t and δ^t are not considered in the first phase, nor are the respective initial MO-MILP model constraints (5.22) and (5.26). All operating constrains (5.27) to (5.31) are retained, and the domain of the variables involved in this phase - y_b^t, z_{bc}^t, $w_{\ell kb}^t$, x_{pij}^t, ξ_d^t, and γ^t - is the same as in the initial model.

The economic (8.3) and social (8.4) objective functions of phase 1 reflect the absence of variables, and respective decisions, relating to transport capacity ($v_{\ell kb}^t$ and θ_{kb}^t), proximity of charities to food banks (ε^t), and service equity provided to frontline agencies (δ^t). The environmental objective function of the complete model is included unchanged.

$$\begin{aligned}\text{Min}\, z_1 = & \sum_{t\in T}\sum_{b\in B}\sum_{c\in C} FC_{bc}^t\, z_{bc}^t + \sum_{t\in T}\sum_{b\in OB}\sum_{k\in K} VS_{kb}^t\, \overline{M}_{kb} \left(1 - \sum_{\widetilde{t}=1}^{t} y_b^{\widetilde{t}}\right) + \\ & \sum_{t\in T}\sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} VS_{kb}^t\, M_{\ell k} \sum_{\widetilde{t}=1}^{t} w_{\ell kb}^{\widetilde{t}} + \\ & \sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\sum_{p\in P_k}\sum_{i\in D\cup B\setminus\{b\}} VH_{kb}^t\, x_{pib}^t - \alpha_2 \sum_{d\in FD} \xi_d^{|T|} \end{aligned} \tag{8.3}$$

$$\begin{aligned}\text{Max}\, z_3 = & \,\alpha_5 \sum_{t\in T}\sum_{b\in B}\sum_{c\in HC} z_{bc}^t + \alpha_6 \sum_{t\in T} \gamma^t + \\ & \alpha_7 \sum_{t\in T} \psi^t \left[\sum_{b\in OB}\sum_{k\in K} \overline{M}_{kb} \left(1 - \sum_{\widetilde{t}=1}^{t} y_b^{\widetilde{t}}\right) + \sum_{b\in B}\sum_{\ell\in L}\sum_{k\in K} M_{lk} \sum_{\widetilde{t}=1}^{t} w_{\ell kb}^{\widetilde{t}}\right] \end{aligned} \tag{8.4}$$

Phase 1 of the *LAS-T* heuristic solves the model described above following the same lexicographic ordering method presented in Section 7.1. Accordingly, the outcome of this phase is the set of six lexicographic solutions for the decision problem, obtained after solving 15 single-objective problems that essentially disregard transport decisions. For the national instances, this model has 11,700 binary variables, 324,030 continuous variables, and includes 49,465 constraints.

Phase 2 The next phase of the heuristic starts by fixing location (y_b^t), assignment (z_{bc}^t), and storage capacity ($w_{\ell kb}^t$) variables to the values obtained in each of the six lexicographic solutions. These six network configurations provide the set-up to decide about transport capacity acquisition ($v_{\ell kb}^t$), use of transport resources (θ_{kb}^t), and fairness in product distribution (δ^t). Notice that variables influencing the proximity of charities to food banks (ε^t) are implicitly determined by the assignment choices made in the first phase.

The procedure of the second phase involves solving 18 additional MILP problems as depicted in

Figure 8.2 on page 198. For each of the six initial configurations, three problems are solved. Similar to the lexicographic ordering method, the three objective functions are accounted for observing the ranking of objectives followed to obtain the respective lexicographic solutions. Thus, heuristic solution 1 (HS1) is obtained from the network configuration of LS1$^{\{ph1\}}$. This last solution was obtained considering the economic objective as the first optimization priority, followed by the environmental objective, and finally the social objective. Therefore, to obtain solution HS1 in phase 2 the first problem optimizes the economic objective, then the second problem tackles the environmental objective, and lastly the social objective is optimized in the third problem. Likewise, HS2 is determined by optimizing first the economic objective, but afterwards, similar to the process leading to LS2$^{\{ph2\}}$, the order by which the other two objectives are considered is exchanged in relation to HS1. Each optimization factors in the optimal values found in previous problems. The purpose of the procedure is to obtain heuristic solutions that, while decomposing the decisions of the initial model in two phases, respect in both phases the same optimization priorities. This will enable their comparison with the solutions obtained by the lexicographic ordering method.

The procedure was implemented using *MIP starts* (IBM, 2018c) in every problem, with the exception of problems P_1, P_6, and P_{11}. *MIP starts* are solutions that may be feasible or unfeasible, complete or incomplete, processed by CPLEX before starting the branch-and-cut procedure during an optimization. These advanced, or warm starts enable the elimination of segments of the search space and thus may result in smaller branch-and-cut trees, thereby increasing the efficiency of the optimization process. The procedure feeds each problem, except the first ones, with the solution of the previous problem. Notice that, for example, the solution of P_1 is a feasible solution to P_2 and P_3. Likewise, the solution of P_2 is a feasible solution to P_4. Therefore, the solution of P_2 becomes an incumbent solution in the optimization process of P_4.

In the second phase, the first set of problems are warm started by the respective lexicographic solutions obtained in the first phase. LS1$^{\{ph1\}}$ provides a *MIP start* for P_{16}, and in turn the solution of P_{16} becomes a *MIP start* for P_{17}. Moreover, the process employs the opportunistic parallel search model and the adjustment factor introduced in Section 7.2.6.

Having addressed the location, assignment and storage capacity decisions in phase 1, allows discarding all constraints that affect exclusively those decisions in phase 2, considerably alleviating the computational effort required to solve the problems of this phase.

Accordingly, the second phase of *LAS-T* keeps donor-related constrains (5.1) to (5.3), but abandons location and storage acquisition constrains (5.4) to (5.9). Transport acquisition constraints (5.10) and (5.11) are included, and the budget constraints account for all investment costs, exactly like in constraints (5.12) of the initial model. Given that product flows are settled in the second

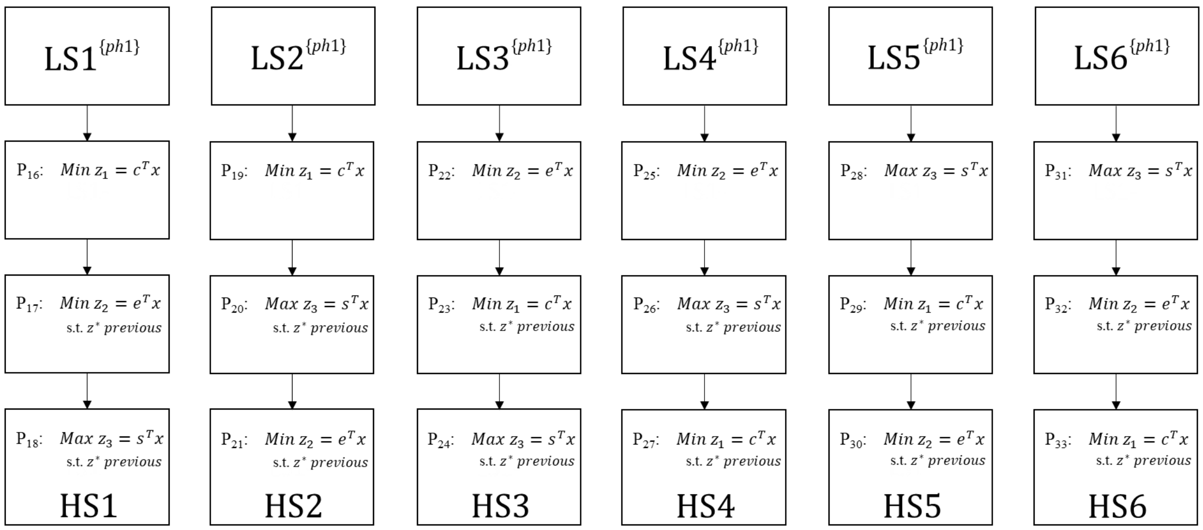


Figure 8.2: Phase 2 of heuristic *LAS-T*

phase of the heuristic, both storage and capacity utilization constraints are material. Accordingly, constraints (5.13) to (5.16) are included. Conversely, charity-related constraints pertaining to assignment decisions (5.17) to (5.21) are waived. Although redundant for location decisions, constraints (5.22) are included as they are the only constraints involving variables ε^t. Supply conditions constraints (5.23) to (5.26) are also included in their initial formulation. Finally, given that operating constraints (5.27) to (5.30) only involve variables y_b^t and z_{bc}^t they can be dispensed from phase 2 of *LAS-T*. The same does not apply to the conservation flow constraints (5.31) that are thus maintained, as are all domain constraints.

Note that by solving these sets of constraints of the complete model in the second phase after having solved in the first phase constraints (5.1) to (5.9), (5.13), (5.14), (5.17) to (5.21), (5.23), (5.24), and (5.27) to (5.31), and subsequently fixing the values obtained for variables y_b^t, z_{bc}^t, and $w_{\ell kb}^t$, it is ensured that, if existent, heuristic solutions are feasible for the original FBNR decision problem as formulated in Chapter 5.

For the national instances, the model of the second phase comprises 12,510 binary variables but, as 11,700 of those have fixed values, actually only 810 binary variables are to be determined. Additionally there are 324,310 continuous variables. There are 224,640 functional constraints, plus 11,700 constraints to set variables y_b^t, z_{bc}^t, and $w_{\ell kb}^t$ at the values obtained in the first phase.

Performance Benefiting from the results obtained in the previous chapter, the quality of heuristic *LAS-T* is assessed by comparing the average lexicographic and heuristic results over the set of 20 regional instances. Results are expressed by the values obtained for the economic, environmental and social objectives of the solutions, and by the average computational time required to solve one instance. As mentioned earlier in this chapter, all results report to case C1 of weighting factors.

Table 8.1 on page 201 shows that economic-centric heuristic solutions HS1-HS2 reveal minor differences to the corresponding lexicographic solutions LS1-LS2 regarding the economic value. Solutions LS1 and LS2 are strongly influenced by the results obtained in P_1 that set the value of the economic objective. Likewise, $LS1^{\{ph1\}}$ and $LS2^{\{ph1\}}$ are heavily conditioned by the outcome of problem P_1 of the first phase of *LAS-T*. The economic objective function of the complete model does not differ significantly from the economic function of phase 1 of the heuristic. In fact, the difference resides only in the exclusion of the penalty term for unused transport capacity from the economic objective of the heuristic. In the second phase of the heuristic, the term is included and the objective function entirely corresponds to the expression of the complete model. However, this term is weighted by a very small factor (α_1), which limits its impact in the economic results of solutions HS1-HS2 to a great degree.

The slight increase of the economic cost from the lexicographic to the heuristic results of the economic-centric solutions is actually accompanied by improved environmental and social values. This improvement however is not too expressive and should be interpreted bearing in mind that these results are obtained for problems that are subject to optimal values obtained in previous problems, which as discussed in Section 7.2.6 is usually associated with numerical issues.

In contrast to the economic cost, the environmental value is quite influenced by transport decisions, namely with respect to the CO_2 emissions cost. By deferring these decisions to the second phase of the heuristic, after the location, assignment and storage capacities are set, the optimal environmental costs of solutions LS3-LS4 are not attainable by the heuristic. Yet, the environmental costs obtained by solutions HS3 and HS4 exceed those of the corresponding lexicographic solutions by just 4.68% and 2.37%, respectively, which is considered a good result. The heuristic environmental-centric results of these solutions improve over the lexicographic results in terms of the economic cost, which also occurs in the social-centric solutions HS5-HS6. Naturally, in both cases said improvement is made possible respectively by the worse environmental (of HS3-HS4) and social results (of HS5-HS6). This relation is attributed to the fact that the variables at play in phase 1 of *LAS-T* have a stronger influence on the economic results than on the other two objectives.

The most striking difference between these heuristic and lexicographic results concerns the social cost of solutions HS3-LS3. Even if in absolute terms the values are within the range of usually observed values for this objective, the percent difference of the heuristic to the lexicographic result is substantial. It should be noted that that large percent difference is in part due to the small value of the lexicographic solution. More meaningful perhaps is the fact that the social results are obtained after the environmental and the economic objectives are optimized and thus optimized subject to their optimal values. This combination, associated with the fact that the social objective function is composed of five terms, with pre-normalizing different magnitudes, including two *minmax* elements, can result is greater differences. In this case, the extreme deviation observed is largely attributed to the numerical issues already identified in the computational experience involving the regional instances, and to the effects of having to rely on the opportunistic parallel search mode to obtain solutions.

Finally, the social results of heuristic solutions HS5-HS6 are approximately 6% worse than the corresponding results of LS5-LS6. Like in the environmental-centric solutions, the economic results of HS5-HS6 improve the economic cost of the lexicographic solutions LS5-LS6, and in the case of LS6 a similar improvement is also registered concerning the environmental cost (second optimization priority in the process of obtaining these solutions).

On average over the 20 regional instances the heuristic LAS-T is able to solve one instance in approximately one fifth of the time required by the lexicographic ordering method. These are substantial savings of computational resources that can be fundamental in solving the national instances. Yet, is is noteworthy that 99.26% of the 355.14 CPU seconds necessary to conclude an instance are spent solving the 15 problems of phase 1, whereas the 18 problems of the second phase take only 0.74% of the total time. This striking difference between the two phases derives from the fact that most binary variables are determined in the first phase. In fact, out of the 12,510 binary variables involved in the national instances, 11,700 (93.5%) are fixed in phase 1.

Motivated by the results obtained with heuristic LAS-T, and the possibility of improving the results by addressing more decisions expressed by binary variables in the second phase of the heuristic, particularly with regard to the computational time, the next section presents an alternative decomposition criterion between the first and second phases of the heuristic method.

8.1.2 Heuristic *LA-ST*

In light of the results obtained by deferring the transport decisions to the second phase of heuristic *LAS-T*, the heuristic presented in this section postpones both storage and transport capacity decisions to the second solving phase.

Objective functions	Solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1-HS1	LS2-HS2	LS3-HS3	LS4-HS4	LS5-HS5	LS6-HS6
Economic (m.u.)						
LO method	6,690.34	6,690.34	8,688.94	9,801.13	9,378.17	9,418.56
H. *LAS-T*	6,690.35	6,690.35	8,097.86	9,077.66	8,729.46	8,893.17
Diff. (%)	-	-	-6.80	-7.38	-6.92	-5.58
Environmental (k€)						
LO method	463.53	477.20	166.82	166.82	348.50	340.54
H. *LAS-T*	443.84	475.72	174.62	170.77	389.44	321.57
Diff. (%)	-4.25	-0.31	4.68	2.37	11.75	-5.57
Social						
LO method	-91.73	-89.46	2.26	156.38	241.49	241.49
H. *LAS-T*	-90.00	-82.30	-54.71	163.45	227.44	227.19
Diff. (%)	-1.89	-8.00	-2,517.99	4.52	-5.82	-5.92
CPU (seconds)						
LO method	1,767.20					
H. *LAS-T*	355.14					
Diff. (%)	-79.90					

Table 8.1: Comparison of lexicographic ordering method with heuristic *LAS-T*

Phase 1 Denoted as *LA-ST*, this decomposition heuristic dedicates the first phase exclusively to location and assignment decisions, expressed by binary variables y_b^t and z_{bc}^t, respectively. However, decisions of phase 1 should not be based exclusively on the storage capacity of the initial food banks. Disregarding the possibility of expanding the capacity of these food banks throughout the planning horizon would not correspond to the assumptions of the initial model. Moreover, constraints (5.9) forbid setting-up new facilities unless storage capacity is installed. Therefore, although storage (and transport) capacity decisions are not taken in the first phase of *LA-ST*, location and capacity decisions must account for the possibility of installing additional capacity in the second phase. In *LA-ST* this is addressed by introducing constraints (8.5) to (8.8) as the capacity utilization constraints (corresponding to constraints (5.13) to (5.16) of the initial MO-MILP model).

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x^t_{pib} \leq M_{3k} \sum_{\widetilde{t}=1}^{t} y^{\widetilde{t}}_b \qquad b \in PB,\ k \in K,\ t \in T \tag{8.5}$$

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x^t_{pib} \leq \overline{M}_{kb} \left(1 - \sum_{\widetilde{t}=1}^{t} y^{\widetilde{t}}_b \right) + M_{3k} \sum_{\widetilde{t} \in T} (1 - y^{\widetilde{t}}_b) \qquad b \in OB,\ k \in K,\ t \in T \tag{8.6}$$

$$\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x^t_{pib} \leq \sum_{\ell \in L} N_{\ell k} \sum_{\widetilde{t}=1}^{t} \left(t - \widetilde{t} + 1\right) y^{\widetilde{t}}_b \qquad b \in PB,\ k \in K,\ t \in T \tag{8.7}$$

$$\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x^t_{pib} \leq \left(\overline{N}_{kb} + t \sum_{\ell \in L} N_{\ell k} \right) \left(1 - \sum_{\widetilde{t}=1}^{t} y^{\widetilde{t}}_b \right) \qquad b \in OB,\ k \in K,\ t \in T \tag{8.8}$$

These constraints allow the storage ((8.5) and (8.6)), or transport ((8.7) and (8.8)) of food products up to the largest possible capacities of food banks. The largest capacity is expressed appealing exclusively to variables y^t_b, instead of $w^t_{\ell kb}$ or $v^t_{\ell kb}$.

In the case of potential food banks, the largest possible storage capacity results from installing level $\ell = 3$ from the period the facility is deployed, for all product families $k \in K$ (see (8.5)). For initial food banks, the largest capacity is achieved by adding the highest available level of capacity M_{3k} to the existent capacity $\overline{M}_{kb}$, as long as the facility remains operational throughout the planning horizon. If the food bank shuts-down in some period, then the second term on the right-hand side of constraints (8.6) is zero, and the largest capacity is expressed only by the first term corresponding to the initial storage capacity up until the period that the facility is closed.

Contrary to storage capacity, new transport resources can be acquired accumulatively in every period, and all three levels $\ell \in L$ can be installed once per period. Furthermore, initial food banks can install transport resources even if they terminate operations in later periods. Constraints (8.7) and (8.8) express these conditions for potential and initially open food banks, respectively.

With regard to the budget constraints, the first planning period requires a formulation distinct from the expression pertaining to the following periods. This is due to the fact that, while new food banks install (the largest) storage capacity from the period in which they begin operations, for initial food banks that do not close during the planning horizon the largest capacity is achieved if expansion occurs immediately in the first period. Therefore, constraint (8.9) states that, besides the costs of installing (first term on the left-hand side) and closing (sixth term) a facility, investment expenses of the first period account for the cost of adding the largest storage capacity in initial food banks that remain operational until the final period (second term), the cost of installing capacity M_{3k} in facilities deployed in the first period (third term), and transport acquisition costs occurring in that period both for initial (fourth term) and possibly new food banks (fifth term).

Regarding the remaining planning periods, it is known that storage capacity will not be installed in initial food banks. As, according to initial constraints (5.7), storage areas can be installed only once during the planning horizon, if storage expansions were to occur (i.e. food bank does not close), they would have occurred already in the first period. Hence, storage acquisition spendings may exist only if and when new facilities are set up, as expressed by the second term on the left-hand side of (8.10). Costs of adding new transport resources must be supported in all periods that initial food banks remain open (third term) and that new facilities are operational (fourth term).

Notice that, whereas in heuristic *LAS-T* transport costs were not considered in the budget constraints of the first phase, in *LA-ST* they are factored in, at the largest value possible, although variables $v^t_{\ell kb}$ (or $w^t_{\ell kb}$ for storage decisions) are not involved.

$$\sum_{b\in PB} FI^t\, y^t_b + \sum_{b\in OB}\sum_{k\in K} VSI^t_{3k}\, M_{3k}\left(1-\sum_{\tilde{t}\in T} y^{\tilde{t}}_b\right) + \sum_{b\in PB}\sum_{k\in K} VSI^t_{3k}\, M_{3k}\, y^t_b + \sum_{b\in OB}\sum_{\ell\in L}\sum_{k\in K} VTI^t_{\ell k}\, N_{\ell k}\,\left(1-y^t_b\right) + \sum_{b\in PB}\sum_{\ell\in L}\sum_{k\in K} VTI^t_{\ell k}\, N_{\ell k}\, y^t_b + \sum_{b\in OB}\left(FU^t + \sum_{k\in K} VU^t_k\,\overline{M}_{kb}\right) y^t_b + \gamma^t = O^t \qquad t = 1 \tag{8.9}$$

$$\sum_{b\in PB} FI^t\, y^t_b + \sum_{b\in PB}\sum_{k\in K} VSI^t_{3k}\, M_{3k}\, y^t_b + \sum_{b\in OB}\sum_{\ell\in L}\sum_{k\in K} VTI^t_{\ell k}\, N_{\ell k}\left(1-\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) + \sum_{b\in PB}\sum_{\ell\in L}\sum_{k\in K} VTI^t_{\ell k}\, N_{\ell k}\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b + \sum_{b\in OB}\left(FU^t + \sum_{k\in K} VU^t_k\,\overline{M}_{kb}\right) y^t_b + \gamma^t = O^t \qquad t = 2,\ldots,|T| \tag{8.10}$$

Apart from these, the other constraints of phase 1 of *LA-ST* maintain the formulation of the complete model. Accordingly, constraints (5.1) to (5.3) concerning the quantity of donations available, (5.4) and (5.5) with regard to location decisions, and (5.17) to (5.21) pertaining to the assignment of charities to food bank are, similar to heuristic *LAS-T*, included in phase 1 of *LA-ST*. Also identical to *LAS-T*, this heuristic includes constraints (8.2) as a simplified and "compacted" version of initial constraints (5.25). Finally, supply constraints (5.23) and (5.24), operational constraints (5.27) to (5.31), and domain constrains of variables y^t_b and z^t_{bc} are also included.

Forgoing variables $w^t_{\ell kb}$ and $v^t_{\ell kb}$ in the economic and social objective functions results in expressions (8.11) and (8.12), respectively. The cost of operating storage areas is represented by the second, third and fourth terms of (8.11). In the complete model, or in the previous heuristic, the term expressing this cost in relation to new capacity engages variables $w^t_{\ell kb}$. In this heuristic it is expressed by the third and fourth terms that only involve variables y^t_b, on the assumption that capacity is always installed at the highest level. The other terms are identical to the components of the economic objective function of the previous heuristic.

The social objective function requires reformulation of the term expressing the value of creating social work. Originally, this term enlists variables $w^t_{\ell kb}$ to factor in the installed capacity. In (8.12) it originates the two terms weighted by α_7.

$$\begin{aligned}\text{Min}\, z_1 = & \sum_{t\in T}\sum_{b\in B}\sum_{c\in C} FC^t_{bc}\, z^t_{bc} + \sum_{t\in T}\sum_{b\in OB}\sum_{k\in K} VS^t_{kb}\,\overline{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) + \\ & \sum_{t\in T}\sum_{b\in OB}\sum_{k\in K} VS^t_{kb}\, M_{3k}\left(1-\sum_{\tilde{t}\in T} y^{\tilde{t}}_b\right) + \sum_{t\in T}\sum_{b\in PB}\sum_{k\in K} VS^t_{kb}\, M_{3k}\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b + \\ & \sum_{t\in T}\sum_{b\in B}\sum_{k\in K}\sum_{p\in P_k}\sum_{i\in D\cup B\setminus\{b\}} VH^t_{kb}\, x^t_{pib} - \alpha_2 \sum_{d\in FD} \xi^{|T|}_d \end{aligned} \tag{8.11}$$

$$\begin{aligned}\text{Max}\, z_3 = & \alpha_5 \sum_{t\in T}\sum_{b\in B}\sum_{c\in HC} z^t_{bc} + \alpha_6 \sum_{t\in T}\gamma^t + \\ & \alpha_7 \sum_{t\in T}\psi^t\left[\sum_{b\in OB}\sum_{k\in K}\overline{M}_{kb}\left(1-\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) + \sum_{b\in OB}\sum_{k\in K} M_{3k}\left(1-\sum_{\tilde{t}\in T} y^{\tilde{t}}_b\right)\right] + \\ & \alpha_7 \sum_{t\in T}\psi^t\left(\sum_{b\in PB}\sum_{k\in K} M_{3k}\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) \end{aligned} \tag{8.12}$$

Just as in the previous heuristic, phase 1 of *LA-ST* solves the model described above following the lexicographic ordering method, resulting in six solutions $\text{LS1}^{\{ph1\}}$–$\text{LS6}^{\{ph1\}}$.

Phase 2 Phase 2 follows the same process described for heuristic *LAS-T*. Variables y^t_b and z^t_{bc} are fixed at the values obtained in the first phase, and three problems are consecutively solved based on the network configuration determined by each lexicographic solution obtained at the end of phase 1.

The model of phase 2 corresponds to the model used in the same phase of *LAS-T* complemented by constraints (5.6) to (5.9) of the complete MO-MILP model, concerning storage capacity acquisition.

Recall that initial transport capacity acquisition constraints (5.10) and (5.11) are also included in the second phase of *LAS-T*.

Thus, in this phase the optimal levels of capacity are selected for the network of food banks and assignment arrangements determined in the first phase. The process followed in phase 1 guarantees that all combinations of capacity levels that are feasible for the complete model are available in phase 2 of the heuristic. Besides, it also ensures that the location and assignment decisions taken in the first phase are compatible with every capacity option of phase 2.

Accordingly, solutions HS1-HS6 obtained after solving all 33 (15+18) problems involved in heuristic *LA-ST* are feasible for the original decision problem of Chapter 5.

Performance Table 8.2 on page 206 compares the results obtained by heuristic *LA-ST* for the regional instances with the values of the corresponding lexicographic solutions. Comparison is based on the average over 19 instances because no solution was obtained for instance 7.

By deferring both storage and transport decisions to the second phase of the heuristic, solutions HS reveal a greater percent difference in relation to solutions LS than the results obtained with *LAS-T*. This decrease in the quality of results is attributed to the fact that in *LA-ST* capacity decisions, on the one hand, and location and assignment decisions, on the other hand, are largely independent.

Addressing all capacity decisions in the second phase of the heuristic allows however a significant decrease of the computational effort. On average *LA-ST* takes less than 55 CPU seconds to solve an instance, which is about 3% of the time required by the lexicographic method. It is also considerably less than the 355.14 CPU seconds demanded by *LAS-T* (approximately 15%).

Heuristic *LA-ST* spends 85.51% of the time solving the problems of phase 1 and the other 14.49% occupied with the problems of phase 2. In comparison with *LAS-T*, this corresponds to an expected shift of computational effort from the first to the second phase. It does also suggest the opportunity of improving the performance of the second phase, which is addressed by the heuristic presented in the next section.

8.1.3 Heuristic *LA-STc*

Heuristic *LA-STc* differs from *LA-ST* by replacing original binary variables $w^t_{\ell kb}$ and $v^t_{\ell kb}$ with continuous variables $\hat{w}^t_{kb}$ and $\hat{v}^t_{kb}$. The purpose of this change in the domain of variables expressing storage and transport capacity decisions is to decrease the computational effort required by the second phase of the heuristic. Changing the domain of the capacity variables demands several modifications of the model and procedures performed in phase 2 of the heuristic.

Objective functions	Solutions					
	Economic-centric		Environmental-centric		Social-centric	
	HS1-LS1	HS2-LS2	HS3-LS3	HS4-LS4	HS5-LS5	HS6-LS6
Economic (m.u.)						
LO method	6,684.49	6,684.49	8,737.34	9,833.26	9,372.49	9,411.58
H. *LA-ST*	6,971.86	6,971.87	8,369.65	8,847.73	9,098.37	9,461.50
Diff. (%)	4.30	4.30	-4.21	-10.02	-2.92	0.53
Environmental (k€)						
LO method	470.85	484.75	168.71	168.71	356.80	348.44
H. *LA-ST*	452.77	473.40	175.59	173.08	450.44	379.47
Diff. (%)	-3.84	-2.34	4.08	2.59	26.25	8.91
Social						
LO method	-94.09	-91.70	0.66	154.38	242.98	242.98
H. *LA-ST*	-131.75	-122.86	-80.60	106.68	162.86	166.11
Diff. (%)	40.02	33.98	-12,263.70	-30.90	-32.98	-31.64
CPU (seconds)						
LO method	1,753.29					
H. *LA-ST*	54.26					
Diff. (%)	-96.91					

Table 8.2: Comparison of lexicographic ordering method with heuristic *LA-ST*

Phase 1 Identical to phase 1 of heuristic *LA-ST*.

Phase 2 Upon obtaining the six lexicographic solutions LS1$^{\{ph1\}}$–LS6$^{\{ph1\}}$ at the end of phase 1, the second phase of *LA-STc* solves 18 MILP problems following the same procedure of the previous heuristics. The model corresponds to the one used in the second phase of *LA-ST* with positive real variables $\hat{w}^t_{kb}$ and $\hat{v}^t_{kb}$ taking the place of binary variables $w^t_{\ell kb}$ and $v^t_{\ell kb}$ to represent storage and transport capacity decisions, respectively. Accordingly, in this heuristic $\hat{w}^t_{\ell kb}$ is the storage capacity in tonnes installed in food bank $b \in B$ for product family $k \in K$ in period $t \in T$. $\hat{v}^t_{\ell kb}$ has the same meaning regarding transport capacity, and is also expressed in tonnes.

This change in the capacity variables requires a modification in the parameters that represent the cost of installing new capacity. Thus, in *LA-STc* $V\hat{S}I^t_k$ is the cost of installing one tonne of storage capacity for product family $k \in K$ in period $t \in T$, and $V\hat{T}I^t_k$ is the cost acquiring one tonne of transport resources for family k in period t. The values of these parameters are obtained from the average cost per tonne of initial parameters $VSI^t_{\ell k}$ and $VTI^t_{\ell k}$.

Donor-related constraints (5.1) to (5.3) do not required any changes and are therefore included as in the complete model. The first set of institution-related constrains however is rewritten as follows.

$$\sum_{t\in T} \hat{w}^t_{kb} \leq M_{3k} \sum_{t\in T} y^t_b \qquad b \in PB,\ k \in K \tag{8.13}$$

$$\sum_{t\in T} \hat{w}^t_{kb} \leq M_{3k} \left(1 - \sum_{t\in T} y^t_b\right) \qquad b \in OB,\ k \in K \tag{8.14}$$

$$\hat{w}^t_{kb} \leq M_{3k} \sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b \qquad b \in PB,\ k \in K,\ t \in T \tag{8.15}$$

$$\sum_{k\in K} \hat{w}^t_{kb} \geq y^t_b \qquad b \in PB,\ t \in T \tag{8.16}$$

$$\hat{v}^t_{kb} \leq \sum_{\ell\in L} N_{\ell k} \sum_{\tilde{t}=1}^{t} \hat{w}^{\tilde{t}}_{kb} \qquad b \in PB,\ k \in K,\ t \in T \tag{8.17}$$

$$\hat{v}^t_{kb} \leq \sum_{\ell\in L} N_{\ell k} \left[\overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) + \sum_{\tilde{t}=1}^{t} \hat{w}^{\tilde{t}}_{kb}\right] \qquad b \in OB,\ k \in K,\ t \in T \tag{8.18}$$

$$\hat{v}^t_{kb} \leq \sum_{\ell\in L} N_{\ell k} \qquad b \in B,\ k \in K,\ t \in T \tag{8.19}$$

$$\sum_{b\in PB} FI^t\, y^t_b + \sum_{b\in B}\sum_{k\in K} V\hat{S}I^t_k\, \hat{w}^t_{kb} + \sum_{b\in B}\sum_{k\in K} V\hat{T}I^t_k\, \hat{v}^t_{kb} + \sum_{b\in OB}\left(FU^t + \sum_{k\in K} VU^t_k\, \overline{M}_{kb}\right) y^t_b + \gamma^t = O^t \qquad t \in T \tag{8.20}$$

These sets of constraints correspond to constraints (5.4) to (5.12) of the complete model, but occasionally acquire a different interpretation due the replacement of binary with continuous capacity variables, and subsequent reformulation of the inequalities.

Hence, contrary to initial constraints (5.6) and (5.7), constraints (8.13) and (8.14) do not impose that storage capacity can be added in only one of the planning periods. In *LA-STc* storage increases may occur in multiple periods up to the capacity limit determined by the largest level of storage capacity available ($\ell = 3$) for each family of products k (M_{3k}). Similar to constrains (5.7), constraints (8.14) also establish that initial food banks can install additional storage capacity provided that they do not close until the end of the planning horizon.

Storage capacity can only be added in potential facilities from the period when they are deployed (constraints (8.15)). In that period, constraints (8.16) compel the installation of a minimum storage quantity. Whereas in the original model the minimum capacity is determined by the quantity of the smallest level $\ell = 1$, in this case the minimum quantity corresponds to one tonne ($y_b^t = 1$) for any product family k.

Regarding transport capacity, constraints (8.17) and (8.18) convey a somewhat different notion than original constraints (5.10) and (5.11). The latter entitle the acquisition of transport capacity for the same product families that can be stored in a food bank, whereas the former also establish a relation between the additional transport capacity of each period, in tonnes, and the existent storage capacity. This relation is increased by the largest transport capacity that can be installed in any period, expressed by the sum of all capacity levels $\ell \in L$. Constraints (8.19) are introduced in order to cap the acquisition of transport capacity, for each product family k in every period t, to the limits foreseen in the original model.

The last constraints of the first set of institution-related constraints pertain to the investment budget. Constraints (8.20) appeal to the average costs of purchasing storage and transport capacity, $V\hat{SI}_k^t$ and $V\hat{TI}_k^t$, to reformulate the original budget constraints. Notice that $\hat{w}_{kb}^t$ and $\hat{v}_{kb}^t$ are expressed in tonnes, and that $V\hat{SI}_k^t$ and $V\hat{TI}_k^t$ are unitary costs per tonne of capacity.

The second of institution-related constraints pertain to the issue of capacity utilization. In *LA-STc* they are formulated by constraints (8.21) to (8.24) that retain the original meaning.

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \sum_{\tilde{t}=1}^{t} \hat{w}_{kb}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \qquad (8.21)$$

$$\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} x_{pib}^t \leq \overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \sum_{\tilde{t}=1}^{t} \hat{w}_{kb}^{\tilde{t}} \qquad b \in OB,\ k \in K,\ t \in T \qquad (8.22)$$

$$\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x_{pib}^t + \theta_{kb}^t = \sum_{\tilde{t}=1}^{t} \hat{v}_{kb}^{\tilde{t}} \qquad b \in PB,\ k \in K,\ t \in T \qquad (8.23)$$

$$\sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x_{pib}^t + \theta_{kb}^t = \overline{N}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \sum_{\tilde{t}=1}^{t} \hat{v}_{kb}^{\tilde{t}} \qquad b \in OB,\ k \in K,\ t \in T \qquad (8.24)$$

Further to the replacement of binary by continuous capacity variables, the economic and social objective functions register the modifications expressed in (8.25) and (8.26). In both cases the respective terms are faithful to the original terms.

$$\begin{aligned}
\text{Min } z_1 = {} & \sum_{t \in T} \sum_{b \in B} \sum_{c \in C} FC_{bc}^t \, z_{bc}^t + \sum_{t \in T} \sum_{b \in OB} \sum_{k \in K} VS_{kb}^t \, \overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \\
& \sum_{t \in T} \sum_{b \in B} \sum_{k \in K} VS_{kb}^t \sum_{\tilde{t}=1}^{t} \hat{w}_{kb}^{\tilde{t}} + \sum_{t \in T} \sum_{b \in B} \sum_{k \in K} \sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b\}} VH_{kb}^t \, x_{pib}^t + \\
& \alpha_1 \sum_{t \in T} \sum_{b \in B} \sum_{k \in K} \theta_{kb}^t - \alpha_2 \sum_{d \in FD} \xi_d^{|T|} \qquad (8.25)
\end{aligned}$$

$$\begin{aligned}
\text{Max } z_3 = {} & \alpha_5 \sum_{t \in T} \sum_{b \in B} \sum_{c \in HC} z_{bc}^t + \alpha_6 \sum_{t \in T} \gamma^t + \\
& \alpha_7 \sum_{t \in T} \psi^t \left[\sum_{b \in OB} \sum_{k \in K} \overline{M}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}\right) + \sum_{b \in B} \sum_{k \in K} \sum_{\tilde{t}=1}^{t} \hat{w}_{kb}^{\tilde{t}} \right] \\
& - \alpha_8 \sum_{t \in T} \varepsilon^t - \alpha_9 \sum_{t \in T} \delta^t \qquad (8.26)
\end{aligned}$$

Based on this formulation, the model of the second phase comprises 10,890 binary variables, all with fixed values (i.e. actually there are no binary variables to be determined), and 324,850 continuous variables for the national instances. There are 225,024 functional constraints, plus 10,890 constraints to set variables y_b^t and z_{bc}^t at the values obtained in the first phase.

Post-processing In order to obtain solutions that are feasible for the original problem, the results of the second phase of *LA-STc* for continuous variables $\hat{w}_{kb}^t$ and $\hat{v}_{kb}^t$ have to be post-processed as described in Algorithms 8.1 (p. 210) and 8.2 (p. 212). The procedures described in these algorithms convert the values of the continuous variables into the equivalent binary values for variables $w_{\ell kb}^t$ and $v_{\ell kb}^t$.

Observing that storage capacity can be installed only once during the planning horizon for each family of products $k \in K$, Algorithm 8.1 identifies the first period in which variables $\hat{w}_{kb}^t$ assume a positive value for every food bank. If existent, then total storage capacity required until the final period is determined in line 9. The adequate discrete storage capacity level $M_{\ell k}$ is identified in line 12, and the associated variable $w_{\ell kb}^t$ assumes the value one. Accordingly, it is ensured that storage capacity is in place from the first period it is needed, and that the installed capacity suits the storage requirements of all forthcoming periods.

Converting variables $\hat{v}_{kb}^t$ into $v_{\ell kb}^t$ requires a different procedure, as described in Algorithm 8.2.

Data: $\hat{w}^t_{kb}$, $M_{\ell k}$
Result: $w^t_{\ell kb}$

```
begin
    for b ∈ B do
        for k ∈ K do
            M_0k ← 0.0
            verified ← 0
            selectstorage ← 0
            for t ∈ T do
                if verified = 0 and ŵ^t_kb > 0.0 then
                    determine all storage capacity required until last period
                    for t̃ = 1 to |T| do
                        selectstorage += ŵ^t̃_kb
                    end
                    select appropriate capacity level ℓ ∈ L
                    for ℓ ∈ L do
                        if verified = 0 and M_{ℓ−1,k} < selectstorage ≤ M_ℓk then
                            w^t_ℓkb ← 1
                            verified ← 1
                        end
                    end
                end
            end
        end
    end
end
```

Algorithm 8.1: Procedure *storage* to determine the values of variables $w^t_{\ell kb}$

Transport resources can be acquired in multiple periods, and in different discrete levels $N_{\ell k}$ in each period. Thus, opposite to the conversion of storage decision variables that adopts a forward planning perspective, the transformation of transport decision variables considers the reverse approach.

First, the total capacity required until the current period, according to continuous variables $\hat{v}^t_{kb}$ is determined in line 11. Next, past decisions expressed in terms of discrete capacity levels $N_{\ell k}$ are accounted in line 14. This allows the identification in line 19 of the current transport needs that cannot be satisfied by capacity levels installed in previous periods. The selection of the appropriate capacity level, or levels, for the transport necessities of current period is performed from line 21. Starting from the largest discrete level, the procedure chooses the smallest capacity level or levels that can accommodate the transport needs of the current period. Transport needs of future periods are not acknowledged, nor are the differences in unit costs of each capacity level.

Following these procedures, the value of variables θ^t_{kb} and γ^t is deduced on the basis of the values of binary variables $w^t_{\ell kb}$ and $v^t_{\ell kb}$ according to expressions (8.27), (8.28), and (8.29) derived from initial constraints (5.15), (5.16), and (5.12), respectively. Finally, the economic and social value of the solutions is assessed considering the objective functions (5.39) and (5.41) of the complete model.

$$\theta^t_{kb} = \sum_{\ell \in L} N_{\ell k} \sum_{\tilde{t}=1}^{t} v^{\tilde{t}}_{\ell kb} - \sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x^t_{pib} \qquad b \in PB,\ k \in K,\ t \in T \tag{8.27}$$

$$\theta^t_{kb} = \overline{N}_{kb} \left(1 - \sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b\right) + \sum_{\ell \in L} N_{\ell k} \sum_{\tilde{t}=1}^{t} v^{\tilde{t}}_{\ell kb} - \sum_{p \in P_k} \sum_{i \in CD \cup B \setminus \{b\}} x^t_{pib} \qquad b \in OB,\ k \in K,\ t \in T \tag{8.28}$$

$$\gamma^t = O^t - \sum_{b \in PB} FI^t\, y^t_b - \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VSI^t_{\ell k}\, M_{\ell k}\, w^t_{\ell kb} - \sum_{b \in B} \sum_{\ell \in L} \sum_{k \in K} VTI^t_{\ell k}\, N_{\ell k}\, v^t_{\ell kb} - \sum_{b \in OB} \left(FU^t + \sum_{k \in K} VU^t_k\, \overline{M}_{kb}\right) y^t_b \qquad t \in T \tag{8.29}$$

Performance The results obtained with *LA-STc* for the regional instances with regard to the objective function values are identical to the solutions provided by *LA-ST* (see Table 8.3 on page 213). Minor differences, benefiting in general the performance of *LA-STc*, are attributed to the previously discussed numerical issues of CPLEX. However, heuristic *LA-STc* was able to solve all 20

```
Data: $\hat{v}^t_{kb}$, $N_{\ell k}$
Result: $v^t_{\ell kb}$
begin
    for $b \in B$ do
        for $k \in K$ do
            $N_{0k} \leftarrow 0.0$
            for $t \in T$ do
                $conttransport \leftarrow 0$
                $inttransport \leftarrow 0$
                $selecttransport \leftarrow 0$
                $need \leftarrow 0$
                if $\hat{v}^t_{kb} > 0.0$ then
                    determine all transport capacity required until current period
                    for $\widetilde{t} = 1$ to $t$ do
                        $conttansport \mathrel{+}= \hat{v}^{\widetilde{t}}_{kb}$
                    end
                    determine transport capacity installed until current period
                    according to level of capacity $\ell \in L$
                    for $\widetilde{t} = 0$ to $t - 1$ do
                        for $\ell \in L$ do
                            $inttansport \mathrel{+}= N_{\ell k}\, v^{\widetilde{t}}_{\ell kb}$
                        end
                    end
                    if $conttransp > inttransp$ then
                        determine transport capacity required
                        $need \leftarrow conttransp - inttransp$
                        select appropriate capacity level $\ell \in L$
                        for $\ell = |L|$ to $1$ do
                            $selecttransp \leftarrow 0$
                            for $\widetilde{\ell} = 0$ to $\ell - 1$ do
                                $selecttransp \mathrel{+}= N_{\widetilde{\ell} k}$
                            end
                            if $need > selecttransp$ then
                                $v^t_{\ell kb} \leftarrow 1$
                                $need \mathrel{-}= N_{\ell k}$
                            end
                        end
                    end
                end
            end
        end
    end
end
```

Algorithm 8.2: Procedure *transport* to determine the values of variables $v^t_{\ell kb}$

instances whereas *LA-ST* did not solve one of the instances.

Moreover, the average solving time of *LA-STc* is less than the time required by *LA-ST*. *LA-STc* takes on average over the 20 regional instances less than 50 CPU seconds to solve one instance, which is only 2.7% of the time employed by the lexicographic method. As expected, compared to the distribution of time registered in *LA-ST*, *LA-STc* spends considerably less time solving the problems comprising the second phase. Phase 1 of the heuristic occupies 96.57% of the total time, while phase 2 requires only 3.43%, which is a distribution more similar to the performance observed in *LAS-T*.

Objective functions	Solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1-HS1	LS2-HS2	LS3-HS3	LS4-HS4	LS5-HS5	LS6-HS6
Economic (m.u.)						
LO method	6,690.34	6,690.34	8,688.94	9,801.13	9,378.17	9,418.56
H. *LA-STc*	6,963.35	6,963.35	8,391.46	8,833.13	8,984.90	9,301.78
Diff. (%)	4.08	4.08	-3.42	-9.88	-4.19	-1.24
Environmental (k€)						
LO method	463.53	477.20	166.82	166.82	348.50	340.54
H. *LA-STc*	455.00	472.45	173.44	170.97	435.33	356.26
Diff. (%)	-1.84	-1.00	3.96	2.49	24.92	4.62
Social						
LO method	-91.73	-89.46	2.26	156.38	241.49	241.49
H. *LA-STc*	-127.68	-127.65	-80.88	109.86	159.56	163.17
Diff. (%)	39.19	42.69	-3,674.92	-29.75	-33.93	-32.43
CPU (seconds)						
LO method	1,767.20					
H. *LA-STc*	48,49					
Diff. (%)	-97,26					

Table 8.3: Comparison of lexicographic ordering method with heuristic *LA-STc*

8.1.4 Comparison of heuristics

Table 8.4 on page 214 summarizes the decisions taken on each phase of the three heuristics introduced in the previous sections.

Preliminary tests performed on the national instances revealed that computational time is a critical issue in solving problems of larger dimensions. Therefore, the computational effort required

Phases	*LAS-T*		*LA-ST*		*LA-STc*	
	Decision	Vars.	Decision	Vars.	Decision	Vars.
Phase 1	Location	y_b^t	Location	y_b^t	Location	y_b^t
	Assignment	z_{bc}^t	Assignment	z_{bc}^t	Assignment	z_{bc}^t
	Storage	$w_{\ell kb}^t$				
Phase 2			Storage	$w_{\ell kb}^t$	Storage	$\hat{w}_{\ell kb}^t$
	Transport	$v_{\ell kb}^t$	Transport	$v_{\ell kb}^t$	Transport	$\hat{v}_{\ell kb}^t$
	Product flow	x_{pij}^t	Product flow	x_{pij}^t	Product flow	x_{pij}^t
Post-					Storage	$w_{\ell kb}^t$
Processing					Transport	$v_{\ell kb}^t$

Table 8.4: Phases of heuristics

by each heuristic becomes the chief criterion in selecting the heuristic to present results for the national instances.

Table 8.5 summarizes and compares the quantitative evaluation of the three heuristics described earlier, based on the results obtained for the regional instances. Comparison of results obtained for each solution HS invokes the *dist* measure introduced in Section 7.2.2. In this case, the measure expresses the euclidean distance between the points identifying solutions HS and the points identifying the corresponding LS solution, given by the respective economic, environmental, and social values. This measure, expressed in relation to the optimal values of the lexicographic solutions, enables a succinct comparative assessment of the three heuristics.

As anticipated, considering the results presented in the previous sections, the results of heuristic *LAS-T* are closest to the lexicographic solutions. Solution HS3 is the only with *dist* greater than 2.0. Actually, this solution, whose process optimizes the social objective lastly, registers the largest distances in all heuristics. Heuristics *LA-ST* and *LA-STc* are very similar with regard to the relative distances of their solutions to the lexicographic results. Including all results obtained, and with the exception of HS3, *LA-STc* shows minor advantages over *LA-ST*.

The bottom half of Table 8.5 shows the results obtained excluding outliers, i.e. disregarding the instances with the single best and worst results for each heuristic. It is noticeable that results of *LAS-T* do not deviate considerably from results relating to the complete set of instances, which further attests its overall superior quality. The results pertaining to the other two heuristics, although still inferior to the results obtained by *LAS-T*, improve considerably when two outlier instances are excluded from the average results.

More significantly in view of their efficiency in solving the national instances, heuristic *LA-STc* is able to provide results with the least use of computational resources. If outliers are excluded, this heuristic solves the decision problem in less than 2% of the time demanded by the lexicographic method. Overall, factoring in the relevant criteria, heuristic *LA-STc* is chosen to obtain results for the national instances.

	Heuristic solutions							CPU
	Economic-centric		Environmental-centric		Social-centric			
	HS1	HS2	HS3	HS4	HS5	HS6	Avg.	(secs.)
dist to LO solution								
H. *LAS-T*	0.08	0.13	4.02	0.14	0.21	0.19	0.79	20.42%
H. *LA-ST*	1.22	1.24	5.22	0.57	0.58	0.46	1.55	3.00%
H. *LA-STc*	1.16	1.23	5.25	0.55	0.56	0.45	1.53	2.73%
dist to LO solution excluding outliers								
H. *LAS-T*	0.07	0.10	2.84	0.14	0.19	0.18	0.58	17.20%
H. *LA-ST*	0.60	0.61	3.88	0.39	0.55	0.37	1.07	2.20%
H. *LA-STc*	0.57	0.63	3.96	0.38	0.53	0.38	1.08	1.84%

Table 8.5: Comparison of heuristics

8.2 Computational study

The computational study performed with heuristic *LA-STc* provided solutions for all 20 national instances. Runs were executed setting an optimizer time limit of $TiLim = 3,600$ (one physical hour elapsed time) for solving each of the 33 problems involved per instance.

It was observed in preliminary tests that the optimizer, after having found feasible solutions for the first problem P_1, spent a large number of hours (over seven) occupied in improving the solutions obtained, as expressed by the best bound to best integer solution gap. This occurred frequently when gaps were already considered small (less than 1%), and often improvement was registered not by the identification of better solutions but rather by updating the best bound value, which also results in smaller gaps even if the solution remains unchanged. Moreover, after the progress registered during the first hours, further improvements in the solution value took considerably longer to obtain.

Upon comparison of results yielded by setting $TiLim = 3,600$ and $TiLim = 7,200$, it was concluded that the latter did not pay-off, as doubling the computational resources invested was not adequately rewarded by a sizable improvement in the solutions value. Apart from P_6, all other 14 problems of phase 1 of *LA-STc* were still not concluded before exhausting the deadline, albeit smaller gaps were regularly obtained as expected. Problem P_6 is usually concluded before reaching the time limit, either with $TiLim = 3,600$ or $TiLim = 7,200$. Observe that this problem, corresponding to the minimization of the environmental objective function, only involves continuous variables, and is not subject to optimal values obtained in prior problems.

Therefore, upon assessing the most efficient use of the computational resources available, the optimizer time limit was set to one hour.

8.2.1 Results

Table 8.6 shows the values obtained for the three objective functions in each of the six heuristic solutions. Values refer, as usual, to the average over the 20 instances.

In general, the results reflect the same profile observed in the lexicographic solutions obtained for the regional instances. The best economic outcome is achieved by economic-centric solutions HS1-HS2, with a minor difference of 0.93% between the value of the two solutions. Similar to LS1-LS2 concerning the regional instances, these solutions lead to a social outcome of negative value.

The smallest environmental cost is achieved by environmental-centric solutions HS3-HS4. In this case, the value of the two solutions is quite similar, diverging by less than 0.11%. Among the two, and matching the profile of regional solutions LS3-LS4, HS3 offers the smallest economic cost, while HS4 achieves superior social results.

Solutions HS5-HS6 provide the best social results, with HS5 outperforming HS6 by approximately 12.26%. Although HS5 provides superior social results, this solution also entails greater economic and environmental costs than HS6.

Also included in Table 8.6, signaled in italic font on lines "*continuous var.*", are the results obtained after the conclusion of the 33 problems defining heuristic *LA-STc*, and prior to the post-processing procedures that convert them into results of integer-based solutions. As described in Section 8.1.3, conversion affects only the economic and social results.

As expected, selecting discrete size storage and transport capacities to replace capacities expressed by continuous variables leads to larger (worse) economic costs, but also to larger (better) social outcomes. Replacement ensures that all new capacity installed throughout the planning horizon as expressed by continuous variables $\hat{w}^t_{\ell kb}$ and $\hat{v}^t_{\ell kb}$ is covered by (i.e. is less or equal to) the corresponding capacity levels expressed on the basis of binary variables $w^t_{\ell kb}$ and $v^t_{\ell kb}$. Therefore, in the case of economic results, if storage areas increase, so do the costs of operating those areas. Additionally, once the volume of products handled does not register any changes from the continuous to binary conversion procedures, greater transport capacity results in more unused transport resources, and consequently in a larger penalty associated with that inefficiency.

Regarding the social value of the solutions, converting continuous into integer-based solutions has opposite partial outcomes. On the one hand, the associated investment capital raising effort increases in order to support the acquisition of larger capacities of storage and transport resources, which in turn decreases the social value of the solutions. On the other hand, larger storage areas imply an increase in social work value creation, which improves the social results. Overall, the impact, as seen in Table 8.6 is negative in the sense that continuous-based social results outperform integer-based results.

Objective functions	Heuristic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	HS1	HS2	HS3	HS4	HS5	HS6
Economic (m.u.)	41,776.15	41,392.30	47,491.87	53,290.41	56,914.44	56,563.14
continuous var.	*38,284.61*	*37,971.99*	*43,044.18*	*49,138.24*	*53,985.01*	*53,387.90*
Environmental (k€)	9,343.25	9,368.31	7,286.28	7,278.37	8,617.15	8,265.42
Social	-161.31	-158.20	-159.84	19.66	161.92	144.24
continuous var.	*-96.59*	*-94.52*	*-72.91*	*98.63*	*205.41*	*194.23*

Table 8.6: Objective functions values of the heuristic solutions: average over 20 instances

The characteristics of heuristic solutions HS1-HS6 are reported in Table 8.7 on page 223.

Possibly, the most striking feature, common to all solutions, is the encompassed reduction of the food bank network dimension. In particular, solutions HS1-HS2 and HS5-HS6 close around 3.6 to 3.7 facilities during the five planning periods. Concurrently, fewer new facilities are deployed in solutions HS5-HS6 than in any other solution. Hence, the average number of operating facilities in each planning period in these solutions is reduced from the initial 15 to less than 10.5. This represents a departure from the profile of social-centric solutions obtained for the regional instances that operated the fewest changes in network design of all solutions.

Yet, like in the regional instances, this smaller network of food banks is able to include the most charities in the supply chain (close to nine out of the 20 on hold at the beginning of the planning horizon), redistribute the largest volume of food products (approximately 140 thousand tonnes over the five periods), and achieve the greatest level of demand satisfaction (over 78% considering all 120 charities). Moreover this is accomplished while installing the smallest new storage capacity of all solutions, and not investing in new transport resources.

As seen earlier, these solutions provide the best social value, but also the largest economic costs, and environmental results markedly exceeding the best reference values found in solutions HS3-HS4.

The economic cost of these solutions is negatively affected mainly by the large number of new charities supported, and by the total volume of food items handled by the supply chain.

Concerning the environmental impact, although these solutions contribute the most to the objective of reducing food waste (only 2.5% (HS5) to 2.7% (HS6) of the available product donations are not redistributed to charities), transport resources are frequently engaged. In fact, around 12% of all products supplied to frontline agencies in these solutions are collected by food bank vehicles at the location of the donors. HS5-HS6 also register the largest number of products flows between food banks. Consequently, the resulting CO_2 emissions cost is quite significant, and just as observed in regard to the regional instances, partially offsets the environmental results derived from the smaller volumes of food waste. Actually, the CO_2 cost associated with solution HS5 is the largest of any solution. Notice that in HS5, opposite to HS6, more than 85% of the food waste is located at delivery donors, and that only 3.1% of CD donations are not picked-up, which is the lowest record of any solution.

Interestingly, the social results of solutions HS5-HS6 are achieved in spite of poor performances regarding the generation of social work value, especially comparing with solutions HS2-HS3. Those are due to smaller investments in storage capacity, which naturally also have the upside social effect of requiring less effort raising investment capital.

HS5-HS6 results concerning the maximum distance between charities and assigned food banks are indistinct from the remaining solutions. Recall that assignments are decided in phase 1 of *LA-STc* disregarding variables ε_t. This explains the very similar results obtained for that social indicator across all solutions (around 248 d.u.).

For the rest, economic-centric solutions HS1-HS2 and environmental-centric solutions H3-HS4 exhibit features analogous to lexicographic solutions LS1-LS2 and LS3-LS3 pertaining to the network redesign of the regional supply chain.

HS1-HS2 redistributes the smallest volume of food assistance (less than 104 thousand tonnes over five periods), thus originating the highest levels of food waste (around 21% of available food donations is left for disposal by the donors). As financial donations are mostly unused, demand satisfaction of served charities is met at the smallest admissible values (70% of their supply in period 0 corresponds on average to 69.6% of their demand in each planning period). Moreover, the largest unsatisfied demand by served charities as measured by δ^t is also registered in these solutions.

Just like solutions LS1-LS2, solutions HS1-HS2 avoid the inclusion of new charities. The single, and minor exception is registered by solution HS2 that account for an average of 0.1 new agencies in the supply chain.

Therefore, considering also the investment level required to close on average 3.7 food banks, open 0.8 facilities, and installing 11 to 12 thousand tonnes of storage capacity and 14 to 35 tonnes of transport resources throughout the planning horizon, both HS1 and HS2 have a negative social outcome.

Regarding the environmental performance, it should be noticed that the above mentioned food waste results mostly from not receiving available donations from product donors DD. 20.1% of all products offered by these donors are not received by the food bank network in HS1 (18.7% in HS2). At the same time only 5.0% of products made available by donors CD are left uncollected (4.5% in HS2). The ensuing food waste is therefore mostly located at the first type of product donors (around 95%). Following this practice, solutions HS1-HS2 generate the highest level of CO_2 emissions, which results in an overall environmental cost that, on average over the two solutions, surpasses the best performances of HS3-HS4 by approximately 28.5%. These latter solutions, additionally to exhibiting the smallest environmental costs, display in-between economic and social results compared with the other pairs of solutions.

Environmental-centric solutions manage between 120 (HS3) and 131 (HS4) tonnes of food products over the five periods. They have the largest average operating networks of food banks (around 13.4 facilities in LS2 and 12.3 in LS3), and add the largest storage and transport capacities of all solutions.

However, following the profile showcased by the economic-centric solutions, HS3 only includes 0.5% of all waiting charities, and HS4 is able to accommodate more than a quarter of all charities initially on hold. This allows an average demand satisfaction for all charities ranging from 67.2% in the case of HS3 to 73.5% with respect to HS4. Notice however that, if only the served charities are considered, then these performances surpass 80%, and actually slightly outperform social-centric solutions HS5-HS6. As discussed regarding the regional instances, the chief driver of this policy is the reduction of food waste, to which supplying the population seeking food assistance is instrumental.

Similar to what is also observed in the results obtained for the regional supply chain, although solutions HS5-HS6 ensure a smaller food waste volume than HS3-HS4, which is significantly influenced by the fact that a larger number of charities are assisted in the former solutions, solutions HS3-

HS4 guarantee the least CO_2 emissions costs. On average over the two solutions, 60% of product donations offered by CD donors are not collected by the food banks, while only 0.4% of all products made available by DD donors are not accepted. Therefore, around 96% of waste is located at donors that require pick-up of food items by the institution transport resources.

The capacity expansion policy of environmental-centric demands investment expenses that exceed the reference budget by 11.1 pp in HS3 and 5.5 pp in HS4. It also generates the largest social work value of all solutions, which, as reflected by the overall social results of these solutions, is larger in HS4 than in HS3.

Lastly, one interesting salient feature also present in all solutions is the implicit propensity to revise the size of the initial food banks, and consequently the role that each original facility plays in the national redesigned network.

Accepting the number of charities assigned to food banks as proxy for their size, Table 8.7 reveals that (initially) small facility 1 (see location in Figure 8.1 on page 192) has the largest average number of assigned charities in solutions HS1 (21.9), HS2 (22.5), and HS3 (16.3). In HS4 it also serves a considerable number of agencies (14.1), but in social-centric solutions the original profile of small facility is kept. In these former solutions that role is assumed by initially large facility 13 (27.8 charities in HS5 and 24.4 in HS6), although food bank 9, originally of medium size, also supplies a large share of served charities.

An upward revision in food bank sizes is also discernible with regard to initially small food banks 2 (solutions HS1-HS4), 4 (all solutions, particularly HS5-HS6), and to some extent also in facility 7.

Inversely, food bank 14, one of the three originally large facilities, supplies a very small number of charities in all network redesign solutions obtained, assuming the profile of a small size facility.

Notice that, as depicted in Figure 8.1, of the three initially large facilities, food bank 14 has the most peripheral location. In contrast, sites of small food bank 1 and medium size food bank 9 that serve a sizable number of charities in the redesign solutions have a central position in the national map.

Even if the density of population seeking food assistance registered in each food bank influence area, measured in terms of the number of charities located within a 250 d.u. radius of the food bank site, differs in every instance, it is reasonable to expect that centrally located facilities are indeed better positioned to serve a larger number of charities. Moreover, the number and capacity resources available at other food banks partially covering the same service area is also relevant for location and assignment decisions. These criteria contribute to the fact that new locations 16, 17, and 18 are not frequently deployed in any solution, and that when opened they assume the profile of small size food banks.

Features	Heuristic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	HS1	HS2	HS3	HS4	HS5	HS6
Food banks						
Banks closed (#)	3.7	3.7	3.0	3.2	3.6	3.7
Banks opened (#)	0.8	0.8	1.1	0.9	0.1	0.1
Operating banks (#)	12.0	11.8	13.4	12.3	10.3	10.4
Total storage capacity added (t)	12,338.0	11,331.0	12,867.3	12,685.6	9,367.0	10,605.0
dry products	6,600.0	3,150.0	3,675.0	4,425.0	2,625.0	3,375.0
fresh products	5,800.0	7,712.5	8,637.8	7,675.0	6,200.0	6,687.5
frozen products	938.0	468.5	554.5	585.6	542.0	542.5
Total transp. capacity added (t)	35.0	13.8	526.3	612.5	-	-
dry products	-	-	187.5	225.0	-	-
fresh products	-	-	335.0	382.5	-	-
frozen products	35.0	13.8	3.8	5.0	-	-
Charities						
Included (#)	-	0.1	0.1	5.4	8.7	8.6
Included (%)	-	0.3	0.5	26.8	43.5	43.0
Avg. satisfied demand (%)						
of all charities SC	69.6	69.6	80.4	81.2	80.5	80.8
of served charities HC	-	4.0	9.2	44.0	69.2	69.4
of served charities C	69.6	69.6	80.4	80.8	80.0	80.4
of all charities HC	-	0.2	0.5	34.6	66.9	65.9
of all charities C	58.1	58.1	67.2	73.5	78.2	78.4
Max. unsatisfied demand (δ^t)	10.5	10.5	8.2	1.8	1.7	1.6
Min. assigned to a bank (#)	1.0	1.1	1.0	1.1	1.0	1.2
Max. assigned to a bank (#)	32.2	32.1	29.7	30.3	36.1	34.4
Changes in assignments banks-charities (#)	252.2	240.1	240.9	218.7	115.4	144.0
Assignments (#) to						
food bank 1	21.9	22.5	16.3	14.1	2.3	3.4
food bank 2	10.7	8.9	8.5	9.0	3.2	2.7
food bank 3	1.8	1.9	1.7	2.3	6.3	6.3
food bank 4	5.9	5.0	7.6	8.9	12.3	16.8
food bank 5	0.1	0.1	1.3	2.1	1.0	1.8
food bank 6	0.3	0.5	0.4	0.9	6.2	5.2

Features	Heuristic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	HS1	HS2	HS3	HS4	HS5	HS6
food bank 7	5.6	5.4	5.2	5.5	6.2	5.7
food bank 8	8.4	7.9	10.5	7.7	0.5	2.5
food bank 9	9.6	10.8	9.1	9.5	22.1	21.2
food bank 10	1.4	1.4	0.6	4.4	10.1	8.6
food bank 11	1.5	3.2	6.1	4.9	1.6	2.1
food bank 12	4.1	3.9	3.8	4.6	8.0	8.0
food bank 13	13.8	15.5	14.0	19.4	27.8	24.4
food bank 14	1.1	1.0	1.8	3.8	3.6	2.6
food bank 15	11.4	10.5	9.4	7.6	5.8	5.4
food bank 16	1.7	0.8	1.6	2.7	0.2	0.2
food bank 17	0.3	0.3	1.0	1.5	0.1	0.1
food bank 18	0.5	0.5	1.1	0.8	-	-
Max. distance to an assigned bank (d.u.) (ε^t)	247.9	247.8	248.7	248.4	248.8	248.6
Donations						
Total food donations (k€)	146,738.7	146,821.5	176,043.1	190,487.3	202,196.4	202,877.8
Total food donations (t)	103,702.4	103,765.6	119,953.0	131,246.2	139,491.1	139,947.6
from donors DD (%)	81.0	80.9	91.6	83.7	77.0	78.3
from donors CD (%)	18.2	18.2	7.0	7.0	14.2	12.6
from donors FD (%)	0.8	0.8	1.5	9.3	8.8	9.1
Unused financial donations (k€)	14,516.2	14,416.7	13,525.0	266.0	786.6	-
Unused financial donations (%)	85.8	85.2	79.9	1.5	4.5	-
Network flows						
Flows donors-food banks (#)	1,758.4	1,742.6	2,131.8	2,028.1	2,260.8	2,078.8
from donors DD (%)	75.9	75.4	83.8	79.5	65.1	70.6
from donors CD (%)	18.8	19.1	4.6	4.8	12.2	12.1
from donors FD (%)	5.3	5.4	11.6	15.7	22.7	17.3
Flows between food banks (#)	-	-	1.0	1.7	3.5	6.6
Flows food banks-charities (#)	8,847.5	8,855.8	8,915.7	9,882.0	10,562.4	10,535.4
Environmental indicators						
Total food waste (k€)	1,773.5	1,770.8	793.2	741.2	219.2	222.3

Features	Heuristic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	HS1	HS2	HS3	HS4	HS5	HS6
Total food waste (t)	27,771.3	27,731.4	12,421.4	11,604.9	3,410.4	3,453.2
Total food waste (%)	21.2	21.2	9.5	8.9	2.5	2.7
donors *DD* share (%)	94.8	95.1	4.1	4.1	86.8	22.5
donors *CD* share (%)	5.2	4.9	95.9	95.9	13.2	77.5
of donors *DD* offer (%)	20.1	18.7	0.4	0.4	2.2	0.6
of donors *CD* offer (%)	5.0	4.5	61.0	59.0	3.1	11.6
Total CO_2 emissions ((k€)	7,879.8	8,202.1	5,014.3	5,050.7	8,223.1	7,481.5
Total CO_2 (t-d.u.)	9,052,335.5	9,420,132.1	5,761,576.7	5,803,297.1	9,442,195.0	8,593,355.5
Social indicators (others)						
Total social work (k€)	10,248.2	10,102.2	11,433.6	12,132.6	10,728.3	10,898.8
Total investment capital required (% of reference budget)	98.1	97.1	111.1	105.5	72.6	80.1
Periods with investment (#)	4.3	2.1	2.2	1.8	1.2	1.3
Periods over budget (#)	1.3	0.7	0.6	0.6	0.7	0.7

Table 8.7: Characteristics of the heuristic solutions: average over 20 instances

Additional insights can be derived from Figure 8.3 on page 225 analyzing the performance of each heuristic solution with regard to the KPIs introduced in Section 7.2.3. Comparable with the results obtained for the neutral weight factors case of the regional instances (see p. 165), the two economic-centric solutions present a similar performance in terms of the eight selected KPIs. Clearly, *%Cost* is the only KPI for which these two solutions offer a benefit over the remaining. In general, for most of the other KPIs the area corresponding to the outcome of solutions HS1-HS2 is wider than the area of the other solutions, conveying a poorer performance.

One exception is KPI *%Investment*. In this case, the network redesign policy of solutions HS3-HS4 originates the largest investment capital raising effort of all solutions. The environmental-centric solutions also display poor *%Distance* records, but in this case, as observed earlier, all solutions have fairly identical performances. HS3 and HS4 form the pair of most distinct solutions among them, which is noticeable by the different shapes of the two areas in the middle of Figure 8.3. While HS3 presents better *%Cost* and *%Storage* performances, HS4 achieves superior *%Demand* and *%Work* outcomes. As expected, in relation to the environmental oriented KPIs *%Waste* and *%CO2* their performance is almost indistinct.

Finally, concerning the two radar charts on the bottom of Figure 8.3 illustrating the performance of social-centric solutions HS5-HS6, the most discernible differences refer to *%CO2*, for which HS5 has an inferior performance, and oppositely to *%Investment*, for which HS6 exhibits worse results.

The companion Figure 8.4 on page 226 offers another perspective relevant for the interpretation of results obtained by each solution. Notice that, as discussed above, the difference in performance of all solutions concerning *%Distance* is virtually null. Reversely, the largest gap between best and worst values obtained by all solutions is found in KPI *%Waste* (88 pp).

These two perspectives of the results obtained complement each other and support the critical assessment of the solutions obtained by heuristic *LA-STc*. Equally important, the computational performance of the heuristic for the national instances is reported in the next, and final, section.

8.2.2 Computational effort

On average over the 20 national instances, it takes close to 51 CPU hours to solve one instance. As shown in Table 8.8 on page 228, individual times range from a minimum of around 37 hours to solve instance 11 to over 63 hours required to obtain solutions for instance 19.

Approximately 99.81% of the total CPU time is occupied solving the first phase of *LA-STc* that involves binary variables, while phase 2 resorting exclusively to continuous variables takes only 0.19%.

Environmental-centric solutions HS3-HS4 require the smallest portion of time (28.3%), while social-centric HS5-HS6 take the longest time to obtain (37.8% of total time). The remaining 33.9% of the time is dedicated to obtaining economic-centric solutions HS1-HS2. In this regard it could be concluded that the dimension increase from regional to national instances impacts differently the distribution of time according to the type of solutions. By comparison with the CPU times pertaining to regional instances (see Table 7.14 on page 183), national instances reveal a more balanced distribution of time spent obtaining each pair of solutions. However, these results are conditioned by the limit imposed on time spent solving each problem. Frequently, problems are concluded before an optimal solution is reached, and therefore the time reported in Table 8.8 refers to the CPU time spent until the physical time limit runs out.

On this subject, Table O.1 in Appendix O presents the percent gap from best bound of *LA-STc* to optimal solution value of the original FBNR problem. The best bound of *LA-STc* is obtained upon solving the problem to optimality, or, most frequently, upon reaching the time limit established.

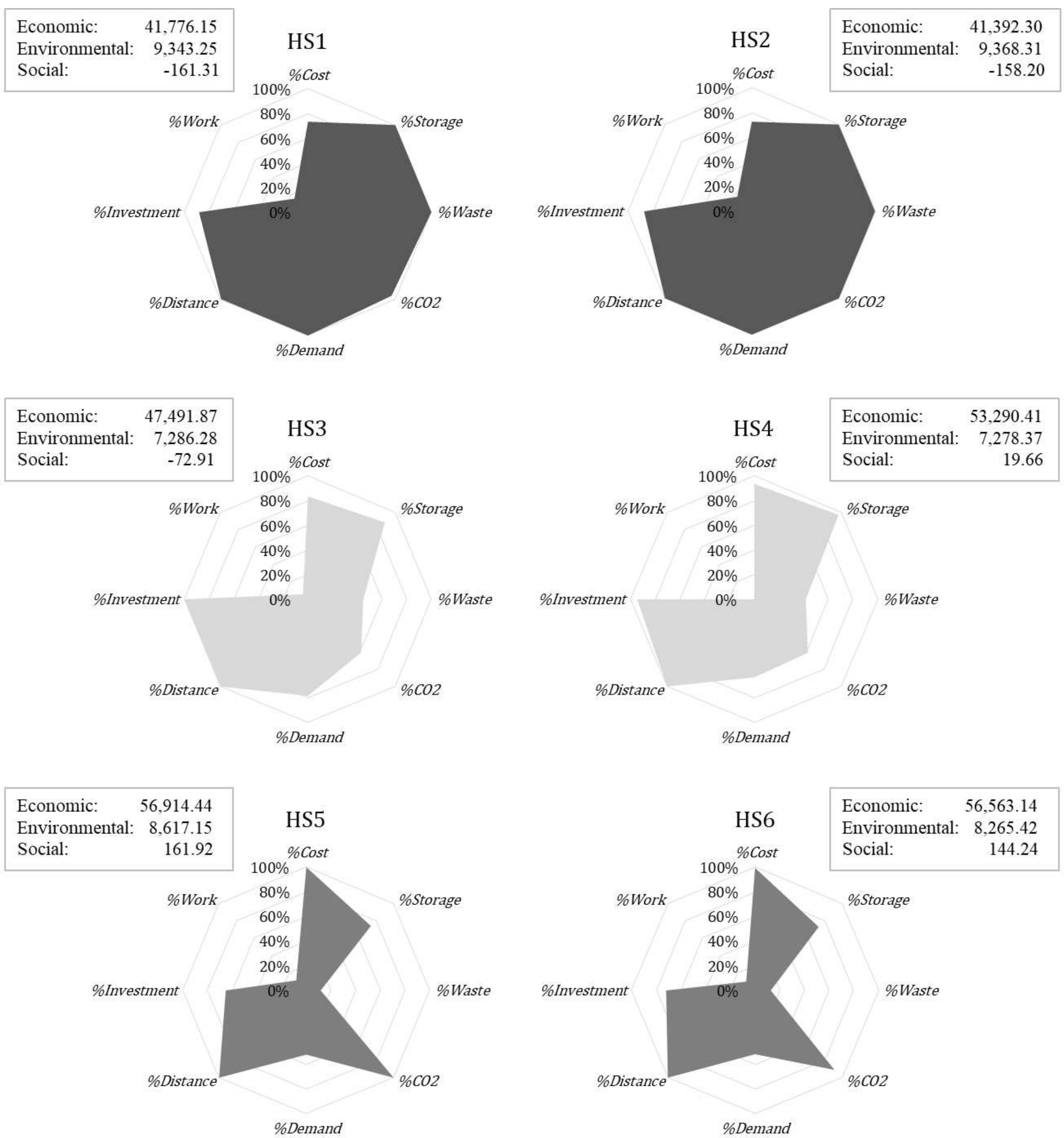


Figure 8.3: Comparison of selected KPIs per heuristic solution

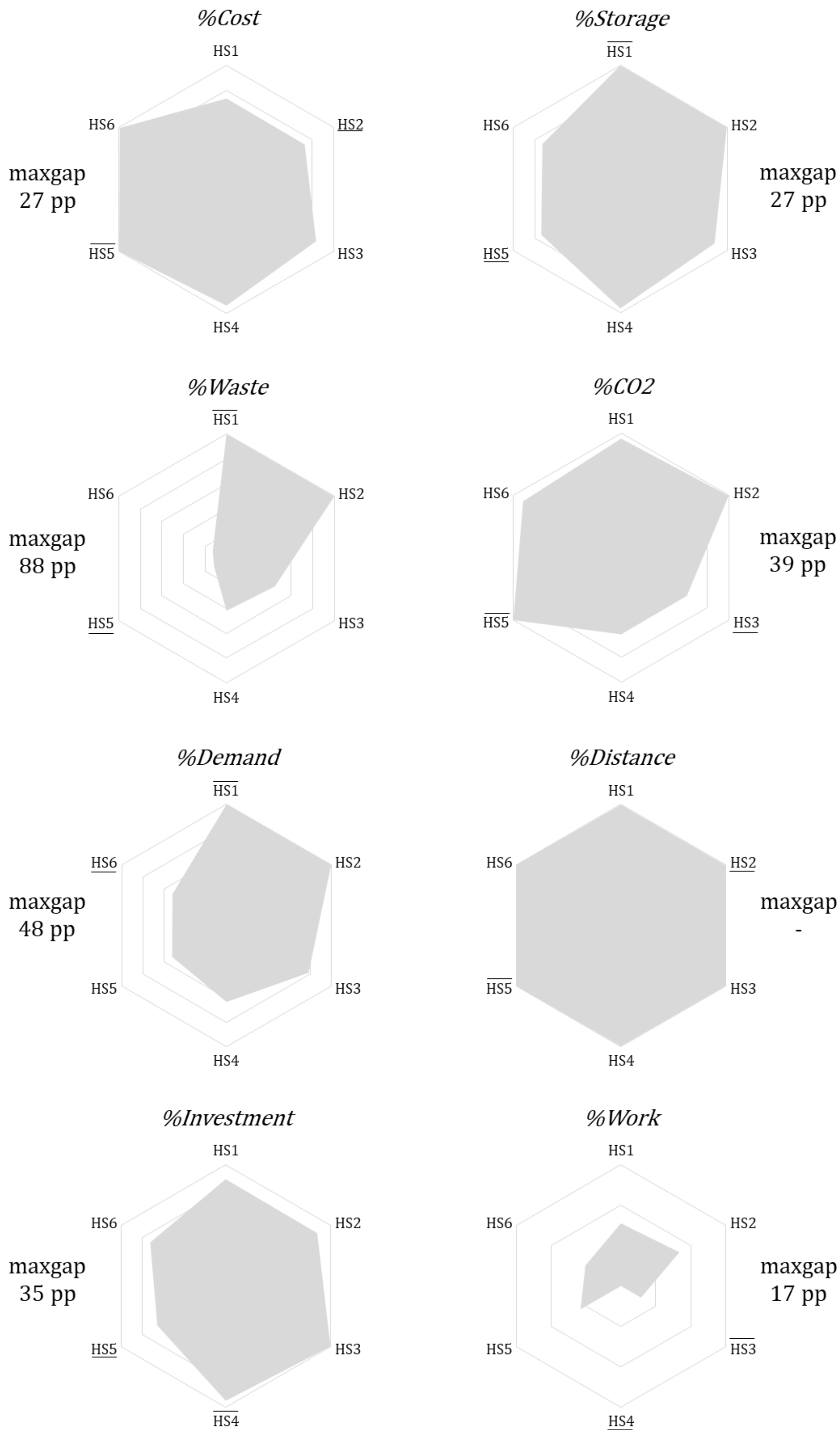


Figure 8.4: Comparison of heuristic solutions per selected KPI

Comparison is based on results concerning regional instances, for which optimal solutions are known. In most cases, the time limit is enforced resulting in average gaps of 24% when the problem minimizes the economic objective function, or 39% in the case of maximization of the social objective function. Problems minimizing the environmental function present considerably smaller gaps of around 3%. This is greatly due to the fact that P_6 is often solved to optimality. In this problem the optimization of the environmental objective function $z_2(x)$ is not subject to previous values obtained for the other objectives. In fact, even for problems that minimization of $z_2(x)$ is subject to the best economic or social values determined in preceding problems, respectively problems P_2, P_5, and P_{13}, P_{14}, and although the available time is exhausted in these cases, the final gaps are considerably smaller than in problems optimizing one of the other two objective functions.

As anticipated in light of the preliminary set of tests performed on the national instances, CPU time is in fact a fundamental issue solving national instances. Arguably, considering the strategic and tactical nature of the decisions involved in the problem, obtaining solutions in a very short period of time may not be critical. Nevertheless, the method selected to solve the national instances, besides not guaranteeing optimal solutions, and requiring on average close to 51 CPU hours to conclude the problem, is the most efficient of the three heuristics developed. Recall that, based on tests conducted on the regional instances, heuristic *LA-STc* takes approximately 2% of the time demanded by the lexicographic method, which is also around one tenth of the time required by heuristic *LAS-T* that provided better quality solutions.

The computational requirements of the methods relating to the complexities of the decision problem and corresponding formulation are further addressed in the conclusion chapter presented next.

	Instances										
	1	2	3	4	5	6	7	8	9	10	*cont.*
CPU hours	51.88	50.46	57.00	47.85	37.94	43.68	54.58	62.18	52.62	50.11	
HS1-HS2	43.93	32.58	42.69	21.79	30.93	23.32	20.73	34.60	22.91	37.45	
HS3-HS4	18.27	31.62	26.83	29.35	31.94	37.42	37.99	32.03	35.70	27.04	
HS5-HS6	37.80	35.80	30.48	48.86	37.13	39.25	41.28	33.37	41.39	35.51	
Phase 1	99.94	99.71	99.90	99.91	99.87	99.79	99.81	99.91	99.90	99.92	
Phase 2	0.06	0.29	0.10	0.09	0.13	0.21	0.19	0.09	0.10	0.08	
Ph1 $z_1(x)$	23.33	25.56	17.82	36.22	29.75	23.29	30.39	16.80	19.20	24.82	
Ph1 $z_2(x)$	33.35	35.07	30.67	34.62	32.40	39.58	37.23	38.80	43.00	28.48	
Ph1 $z_3(x)$	43.32	39.37	51.51	29.16	37.85	37.13	32.38	44.40	37.80	46.71	

	Instances										Avg.
	11	12	13	14	15	16	17	18	19	20	
CPU hours	37.28	38.72	55.31	49.19	59.14	54.88	49.48	48.87	63.47	54.65	50.96
HS1-HS2	42.42	40.31	37.03	32.10	35.56	42.21	40.26	26.13	33.53	37.05	33.91
HS3-HS4	23.69	21.65	23.25	26.36	34.37	19.18	21.64	34.40	25.49	26.40	28.28
HS5-HS6	33.89	38.04	39.72	41.54	30.07	38.62	38.10	39.46	40.98	36.56	37.81
Phase 1	99.79	99.32	99.60	99.73	99.84	99.92	99.88	99.90	99.95	99.43	99.81
Phase 2	0.21	0.68	0.40	0.27	0.16	0.08	0.12	0.10	0.05	0.57	0.19
Ph1 $z_1(x)$	27.40	26.47	19.69	30.88	19.22	22.11	22.48	23.36	26.47	19.94	23.92
Ph1 $z_2(x)$	44.99	42.89	31.63	20.40	32.87	34.96	35.70	33.26	29.91	48.50	35.21
Ph1 $z_3(x)$	27.61	30.64	48.68	48.72	47.92	42.93	41.82	43.38	43.62	31.56	40.87

Table 8.8: Computational time (CPU hours) required to solve one instance and in percent of groups of problems

Summary Chapter 8

This chapter reported the experiments performed on 20 national supply chain instances. National instances feature 15 initially open food banks and three additional sites for potential set-up of new facilities. There are 120 charities seeking food assistance, but only 100 are included in the supply chain from the first period. These charities receive food items donated by 53 delivery donors, nine collection donors, and five financial donors. Location of the food banks is the main common element to all 20 instances. Otherwise, parameters vary similarly to the regional supply chain instances.

Early computational tests revealed the inviability of relying on the lexicographic ordering method to solve these larger dimension instances. Therefore, three heuristic methods were developed in order to obtain solutions for the national instances.

The three heuristics share the same concept. Realizing that the network redesign decision problem comprises both strategic and tactical decisions, the solving process separates the set of decision into two phases. The first phase addresses the longer term decisions, which are then fixed while solving the medium term decisions in the second solving phase.

In heuristic *LAS-T* the first phase includes food bank location decisions, as expressed by variables y_b^t, charity assignment decisions conveyed by variables z_{bc}^t, and storage capacity decisions indicated by variables $w_{\ell kb}^t$. The values of these variables are fixed upon solving the corresponding modified MO-MILP model following the lexicographic ordering method. In the second phase 18 sequential single-objective problems are executed to decide the adequate transport resources (variables $v_{\ell kb}^t$), and determine the product flows in the supply chain (variables x_{pij}^t). Given the procedure embedded in the heuristic, it is possible to establish a correspondence between the six heuristic solutions obtained and the six solutions resulting from the lexicographic method, which is helpful in evaluating the quality of the heuristic.

Based on the results obtained for *LAS-T*, a different decomposition criterion is adopted in the second heuristic developed. In heuristic *LA-ST*, the first phase is restricted to location and assignment decisions, postponing both storage and transport capacity decisions for the second phase, where product flows continue to be ultimately established. The solving procedure replicates the method followed in the first heuristic, with the necessary modifications operated in the MILP models solved in the respective first and second phases.

In these two heuristics, all variables have the same domain as in the original decision problem. The third heuristic, denoted *LA-STc*, introduces continuous variables $\hat{w}_{\ell kb}^t$ and $\hat{v}_{\ell kb}^t$ to replace

binary variables $w_{\ell kb}^{t}$ and $v_{\ell kb}^{t}$, representing storage and capacity decisions. The new variables are called upon in the second phase of the heuristic after considering in the first phase, similarly to *LA-ST*, that maximum storage and transport capacities can be installed if necessary to enable the location and assignment decisions. This change requires rewriting several original constraints and the economic and social objective functions in terms of continuous rather than binary capacity variables. It also requires converting the continuous based solutions into binary based solutions. To that end two post-processing procedures were developed.

The three heuristics were assessed based on the results obtained for the regional instances. They reveal that solutions produced by *LAS-T* are more similar to the optimal solutions solutions generated by the lexicographic method. On the other hand, heuristics *LA-ST*, and particularly *LA-STc* offer significant advantages in relation to the CPU resources required to conclude the problems.

Accordingly, national results were obtained appealing to heuristic *LA-STc*. Several CPLEX tuning parameters were tested and eventually selected to improve the computational performance of the optimizer for this particular problem and method. Namely a one hour physical time limit was imposed to conclude each of the 33 MILP problems involved in solving one national instance.

Supply chain configurations of the six heuristic solutions obtained by instance share various features found in the corresponding lexicographic solutions of the regional instances.

Notable divergences concern the propensity to reduce the national supply chain in all six heuristic solutions, and the underlying revision of the sizes of some initial food banks, based on the number of charities assigned to them. Elsewhere, economic-centric solutions HS1-HS2 display characteristics identical to lexicographic solutions LS1-LS2, and the same is verified in terms of environmental-centric solutions HS3-HS4 in regards to LS3-LS4, and of social-centric solutions HS5-HS6 relatively to LS5-LS6.

Regarding the computational effort, on average over the 20 national instances, approximately 51 CPU hours are required to solve one instance. This performance is achieved with the aforementioned $TiLim = 3,600$, which is enforced in most problems of the first phase. Accordingly, and particularly for problems that have the economic or the social functions as the optimization objectives, solving is terminated before optimal solutions are determined.

Keywords: National instances; Heuristic LAS-T; Heuristic LA-ST; Heuristic LA-STc; Computational effort

Chapter 9

Conclusion

The network redesign of supply chains is an opportunity to improve its efficiency and efficacy. It can structurally impact the overall performance of all elements of the supply chain.

As discussed in Chapter 2, multi-dimensional perspectives on sustainable development, featuring economic, environmental, and social objectives, have gained particular relevance in recent years. Commercial organizations are increasingly embracing their environmental and social responsibilities. Practitioners' interest has been met with growing research attention toward the topic of sustainable supply chain. Concurrently, humanitarian supply chain literature is also experiencing a period of particular vitality.

In this study, the network redesign of a food bank supply chain was considered under multiple objectives of distinct natures. The particularities of the food bank supply chain make it specially suited for, and in fact warrant multi-dimension analysis that can account for environmental and social criteria, additionally to the economic factors.

Similar to other humanitarian agencies, the activity of food banks is primarily guided by environmental and social objectives, namely the minimization of food waste, and the maximization of food assistance provided to underprivileged population. Nevertheless, achieving economic sustainability is still a requirement to ensure the success and longevity of the operation.

In spite of the level of professional management involved in running a food bank supply chain, the network of facilities is predominantly the outcome of operational decisions taken over time, and of occasionally identified donation opportunities. It appears therefore appropriate to consider the strategic redesign of the food bank supply chains following a triple bottom line outlook on sustainable development that can address simultaneously economic, environmental, and social targets.

The FBNR problem formulated in this study was greatly inspired by the FPBA supply chain.

The decision problem addresses location, assignment, and respective product flow decisions in a multi-layered food bank supply chain. Multiple product flows run between each of the three layers, corresponding to suppliers, food banks, and charities, and also between the facilities of the intermediate layer. This design is not common in the literature (Melo et al., 2012). Furthermore, the food bank literature, reviewed in Chapter 3, is essentially concerned with solving operational problems, particularly the distribution of food assistance from a single facility. This study **contributes to the food bank literature** by introducing a novel strategic network redesign problem that also includes tactical decisions.

Corresponding to a declared **objective of the study**, the decision problem defined in Chapter 4, denoted as FBNR, establishes three distinct and conflicting objectives that were formulated by the programming model described in Chapter 5. The dynamic and capacitated MO-MILP model comprises the economic objective of minimizing fixed costs derived from including charities in the supply chain, costs of operating storage areas, and of handling food products. Moreover the inefficient use of transport resources is penalized, and using financial donations to purchase food products is discouraged. Environmental targets are included aiming at the cost minimization of food waste disposal, and of CO_2 emissions generated by vehicles under the control of the institution managing the food bank network. Finally, tailored metrics were developed for this study to account for a social objective conveying values of inclusiveness, fairness, and proximity. Accordingly, the third objective function promotes the creation of social capital by the food bank supply chain by including the largest number possible of new charities in the supply chain, involving volunteer and paid work in the operation of facilities, redistributing the available donations equitably, reducing the length traveled by the frontline agencies to pick-up food assistance, all the while attempting to require the least capital investment from institutional partner as possible.

The formulation of the social objective function of the FBRN problem was designed bearing in mind the regularly mentioned **research gap** pertaining to the need of improving the inclusion of the social factor in supply chain quantitative models.

Hence, the study **contributes to the supply chain sustainability literature** by incorporating several detailed features of a real-life case in a MO-MILP model, classified as NP-hard in Chapter 5.

Addressing one of the chief objectives of the study, instances were generated following an extensive in-field work conducted at the FPBA, as well as at the Lisbon food bank. This initial work was meant not only to have a clear understanding of the FPBA structure and operating processes, but also to collect and analyze data that supported the generation of real-life based instances. As presented in Chapter 6, through data profiling and the development of customized procedures it was possible to generate regional and national instances adherent to a real case, yet non-specific enough so that the results obtained can be significant to other supply chains with identical profile.

This feature of the study contributes to fill the often cited **research gap** encouraging the application of quantitative supply chain studies to real-life decision problems, and addresses another pursued **objective** of this study.

In this study, the lexicographic ordering method was employed to solve the regional instances (Chapter 7), and three new decomposition heuristics were proposed to obtain solutions for the national instances (Chapter 8). Resorting to heuristics, and accessory tuning of the CPLEX optimizer parameters, was required in face of the difficulties encountered attempting to solve the national instances following the same algorithm adopted for the regional instances with the standard optimizer configuration. As previously reported in the literature, heuristics and meta-heuristics are frequently appealed to in order to solve large and complex decision problems such as the FBNR. The solving algorithms adopted in the three proposed heuristics, involving decomposition of the MO-MILP model into two MO-MILP models, and appealing to the CPLEX optimizer to solve 33 single objective MILP problems per instance, following a lexicographic approach, allowed overcoming some computational limitations. The decomposing solving methods developed for the FBNR problem are another contribution of the study.

Relevant managerial insights were derived from the results obtained by the computational experiment performed. The supply chain configuration of each solution, and its economical, environmental and social implications were examined in detail. Furthermore, comparison of the features of each solution enables informed repositioning decisions by the food bank decision maker. Therefore, these learnings are a **contribution to institutions managing food bank supply chains**.

Although it was considered more meaningful for the purpose of this study to focus on a concise set of non-dominated solutions that allowed a detailed and insightful managerial interpretation of the results obtained, it could be interesting to identify, exactly or approximately, the Pareto frontier with greater granularity. This **limitation of the study** can be addressed in **future work**. To that end, the exact methods proposed by Mavrotas and Florios (2013) (AUGMECON2) or Zhang and Reimann (2014) (SAUGMECON), which improve the efficiency of the AUGMECON methods by extending the early loop exit algorithm, and including a new acceleration algorithm with bouncing steps, should be considered.

Recent methodologies posited by Boland et al. (2017a) and Boland et al. (2017b), based on novel solutions space decomposition schemes, are also particularly appealing alternatives to obtain exact solutions. The first work consists of an extension of the L-shaped method, whereas the second is a variation of the full 2-split algorithm denoted as Quadrant Shrinking Method. Regarding approximate methods, the reviewed literature suggests a variety of genetic algorithms based on the NSGA-II algorithm introduced by Deb et al. (2002) among the most promising options.

One other limitation that can be attributed to the study concerns the assessment of the specific case of the current FPBA netwok. The study has a purposely generic intent, and is not meant to strictly analyze the FPBA case. Regardless, Chapter 7 offers a comparison between the lexicographic solutions and an estimated scenario, based on the average values over the 20 regional instances, corresponding to the "as is" alternative, i.e. maintaining the initial network configuration over the planning horizon. It would be interesting to replace the estimated scenario with actual data from the FPBA and carry out an analysis of the expected economic, environmental, and social benefits from redesigning the current FPBA supply chain. This study would be meaningful if solving methodologies, exact or approximate, that can efficiently and effectively solve national instances are employed. Accordingly, it should be considered along with the previous opportunity for future work.

Linked with this topic is the issue of aggregation, concerning the number of suppliers and charities considered both in the national and regional instances. Although this can be signaled as a limitation of the study, it is considered that it is in fact appropriate given the strategic nature of the decisions in play. Moreover, this technique is often employed in studies involving complex decisions, where the dimension of the instances can greatly influence, or determine, the successful attainment of solutions for the problem.

This issue relates to another stream of future work inspired by the FBNR problem, and already echoed in the literature as a significant research opportunity. It concerns the inclusion of strategic, tactical, and operational decisions in an integrated problem. This would enable addressing relevant topics for the food bank supply chain such as uncertainty of supply, and perishability of products that do not find place in long term decision problems like the FBNR.

Considering short and medium term decisions regarding, for example the routes designed for collecting stochastic quantities of donations by the vehicles of the food banks, or the monthly and weekly calendar for food delivery considering time windows that account for product spoilage and preferences of charities, would translate into problems meaningful for the management of the food bank network.

Such complex problems could be formulated with a view to be solved by methods based, for instance, on Benders decomposition (Benders, 1962).

It would likely still require simplifications to the FBNR model. These could encompass, among others, the use of discrete variables to express capacity decisions, or alleviating some formulations made for the FBNR in this study, namely pertaining to the social objective. Modeling a static, instead of a multi-period decision problem would also contribute to benefit from lighter computational requirements. Tests on the national instances carried out but not included in the reporting sections of this study, revealed that by using a single period formulation of the FBNR problem, and a time limit of $TiLim = 7,200$ seconds, it was possible to solve the problem following the lexicographic method, albeit for only five of the 20 national instances.

Finally, hybrid solving techniques involving local or tabu search could also prove to be useful solving assignment decisions of large instances.

This critical reflection over the objectives achieved by this study, its limitations and subsequent research opportunities for future work reveals the rich research material that can be found in non-commercial supply chains, such as the FPBA. The present study attempted to contribute both to the supply chain literature, and to the promotion of the applicability of Operations Research techniques for solving real-life problems. This work, and the proposed research opportunities identified in this final chapter can stimulate practitioners and scholars to pursue the study of sustainable supply chains.

Appendix A

Tertiary study: Literature reviews

[#]	Author (year)	Journal	Country	Period covered	No. of articles	Type of review	Sust. focus
[1]	Abbasi (2017)	EBR	SE	2000-2015	267	SY	SOC
[2]	Abbasi and Nilsson (2012)	SCMij	SE	NM	190	SY	ENV
[3]	Adams et al. (2016)	IJMR	UK	1992-2012	127	SY	TBL
[4]	Ahi and Searcy (2013)	JCP	CA	2002-2012	180	SY	ENV
[5]	Ahi and Searcy (2015)	JCP	CA	1989-2012	445	SY	TBL
[6]	Ahi et al. (2016)	SPC	CA	1996-2012	115	SY	ENV
[7]	Ahmad et al. (2017)	JEPM	NL	2007-2011	10	SY	TBL
[8]	Aivazidou et al. (2016)	JCP	GR	2008-2016	74	SY	ENV
[9]	Akkerman et al. (2010)	ORS	DK	NM	175R	NR	TBL
[10]	Alexander et al. (2014)	SCMij	UK	1980-2013	160	SY	TBL
[11]	Amui et al. (2017)	JCP	BR	2005-2015	33	SY	TBL
[12]	Ansari and Kant (2017)	JCP	IN	2002-2016	286	SY	TBL
[13]	Appolloni et al. (2014)	JCP	IT	1996-2013	86	SY	ENV
[14]	Arnette et al. (2014)	JCP	US	1983-2012	122	SY	TBL
[15]	Asgari et al. (2016)	IMA-JMM	UK	1982-2015	152R	SY	TBL
[16]	Ashby et al. (2012)	SCMij	UK	1983-2011	134	SY	TBL
[17]	Awudu and Zhang (2012)	RSER	US	NM	87R	NR	TBL
[18]	Barbosa-Póvoa et al. (2018)	EJOR	PT	1999-2016	220	SY	TBL
[19]	Bastas and Liyanage (2018)	JCP	UK	2005-2017	93	SY	TBL
[20]	Baumann et al. (2002)	JCP	SE	1970-1999	127R	SY	ENV
[21]	Baydar et al. (2017)	JCP	TR	1998-2015E	71	SY	TBL
[22]	Bazan et al. (2016)	AMM	CA	NM	183	SY	ENV
[23]	Bechtsis et al. (2017)	JCP	GR	2009-2016	39	SY	TBL
[24]	Bengo et al. (2016)	JSE	IT	NM	106R	NR	SOC
[25]	Bertoni (2017)	S	SE	2007-2017	193	SY	TBL
[26]	Beske et al. (2014)	IJPE	DE	2002-2011	52	SY	TBL

[#]	Author (year)	Journal	Country	Period covered	No. of articles	Type of review	Sust. focus
[27]	Beske-Janssen et al. (2015)	SCMij	DE	1995-2015	149	SY	TBL
[28]	Bloemhof-Ruwaard et al. (1995)	EJOR	NL	NM	32R	NR	ENV
[29]	Boons et al. (2012)	EE	NL	NM	129R	NR	TBL
[30]	Brandenburg et al. (2014)	EJOR	DE	1994-2012	134	SY	TBL
[31]	Burgess et al. (2006)	IJOPM	AU	1985-2003	100	NR	TBL
[32]	Bush et al. (2015)	JCP	NL	NM	181R	NR	TBL
[33]	Caldera et al. (2017)	JCP	AU	1996-2015	102	SY	ENV
[34]	Cambero and Sowlati (2014)	RSER	CA	NM	142R	NR	TBL
[35]	Carter and Easton (2011)	IJPDLM	US	NM	165R	NR	TBL
[36]	Carter and Rogers (2008)	IJPDLM	US	1991-2010	80	SY	TBL
[37]	Centobelli et al. (2017)	TRpD	IT	2002-2015	46	SY	ENV
[38]	Chamorro et al. (2009)	BSE	ES	1993-2003	160	SY	ENV
[39]	Chan et al. (2017)	IJPR	HK	1994-2015	147	SY	TBL
[40]	Chang et al. (2014)	JCP	SG	NM	122R	SY	ENV
[41]	Chatha and Butt (2015)	IJOPM	PK	1966-2010	506	SY	TBL
[42]	Chen et al. (2014)	IJPE	SE	1990-2011	81	SY	TBL
[43]	Chen et al. (2017)	IJPE	CN	1987-2015	90	SY	TBL
[44]	Cherrafi et al. (2016)	JCP	MA	1990-2015	118	SY	TBL
[45]	Chugani et al. (2017)	IJLSS	UK	2000-2015	70	SY	ENV
[46]	Chun and Bidanda (2013)	IJPR	US	1960-2010	41R	NR	ENV
[47]	Ciccullo et al. (2018)	JCP	IT	2001-2017	73	SY	TBL
[48]	Correia et al. (2017)	S	PT	2000-2015	11	SY	TBL
[49]	Cuček et al. (2012)	JCP	HU	NM	147R	NR	TBL
[50]	Dangelico and Vocalelli (2017)	JCP	IT	1993-2015	114	SY	ENV
[51]	Dania et al. (2018)	JCP	AU	1996-2017	30	SY	SOC
[52]	Davarzani et al. (2016)	TRpD	AU	1975-2014	338	SY	ENV
[53]	de Campos et al. (2017)	SCMij	BR	1996-2015	39	SY	ENV
[54]	de Jesus et al. (2018)	JCP	PT	1992-2015	141	SY	ENV
[55]	de Medeiros et al. (2014)	JCP	BR	NM	67	SY	ENV
[56]	De Meyer et al. (2014)	RSER	BE	1997-2012	71	NR	TBL
[57]	de Oliveira et al. (2018)	JCP	BR	2006-2016	339	SY	ENV
[58]	de Sousa Jabbour et al. (2013)	IJESD	BR	2000-2011	36	SY	ENV
[59]	Dekker et al. (2012)	EJOR	NL	NM	75	NR	ENV
[60]	Demir et al. (2014)	EJOR	NL	2006-2013	58	NR	ENV
[61]	Denham et al. (2015)	JCP	AU	2000-2013	76	SY	ENV
[62]	Dey et al. (2011)	MRR	US	NM	99R	NR	TBL
[63]	Djekic et al. (2018)	JCP	RS	1991-2016	170R	NR	ENV
[64]	Drohomeretski et al. (2015)	EMJ	BR	2001-2012	67	SY	TBL
[65]	Dubey et al. (2017c)	SPC	IN	NM	284	SY	ENV
[66]	Dubey et al. (2017a)	IJLM	IN	NM	268R	NR	TBL

[#]	Author (year)	Journal	Country	Period covered	No. of articles	Type of review	Sust. focus
[67]	Dubey et al. (2017b)	Bij	IN	NM	262	SY	ENV
[68]	Dubey et al. (2015)	JCP	IN	NM	102	SY	TBL
[69]	Dües et al. (2013)	JCP	UK	1990-2011	46R	NR	ENV
[70]	Elia and Floudas (2014)	ARCBE	US	NM	157	NR	TBL
[71]	Ellram and Murfield (2017)	TJ	US	1990-2015	60	SY	ENV
[72]	Eskandarpour et al. (2015)	O	FR	1990-2014	87	SY	TBL
[73]	Fahimnia et al. (2015a)	IJPE	AU	1992-2013	884	SY	ENV
[74]	Fayezi et al. (2012)	SCMij	AU	1996-2011	19	SY	SOC
[75]	Feng et al. (2017)	JCP	CN	1997-2017	628	SY	SOC
[76]	Fiorini and Jabbour (2017)	IJIM	BR	2000-2015	22	SY	ENV
[77]	Fritz et al. (2017)	JCP	AT	2008-2013	295	SY	TBL
[78]	Gahm et al. (2016)	EJOR	DE	1990-2014	87	SY	ENV
[79]	Gao et al. (2017)	JCP	CN	1995-2014	107	SY	TBL
[80]	Garza-Reyes (2015)	JCP	UK	1997-2015	59	SY	ENV
[81]	Gaussin et al. (2013)	IJPE	FR	NM	57R	NR	ENV
[82]	Geissdoerfer et al. (2017)	JCP	UK	2006-2016	67	SY	ENV
[83]	Genovese et al. (2013)	IJPR	UK	1997-2010	28	SY	ENV
[84]	Ghaderi et al. (2016)	ICP	IR	1997-2016	146	SY	TBL
[85]	Ghadimi et al. (2015)	IJPR	IE	2008-2014	61	SY	TBL
[86]	Gimenez and Tachizawa (2012)	SCMij	ES	1996-2011	41	SY	TBL
[87]	Gold (2011)	MASGC	DE	2000-2009	54	SY	TBL
[88]	Gold et al. (2010a)	CSREM	DE	1994-2007	70	SY	TBL
[89]	Gold et al. (2010b)	PIE-AIJ	DE	1994-2007	70	SY	TBL
[90]	Gong et al. (2018)	RCR	UK	2007-2016	74	SY	TBL
[91]	Gosling et al. (2016)	JCP	UK	NM	44	SY	TBL
[92]	Govindan et al. (2015a)	JCP	DK	1996-2011	33	SY	ENV
[93]	Grossmann and Guillén-Gosálbez (2010)	CCE	US	NM	89R	NR	ENV
[94]	Gungor and Gupta (1999)	CIE	US	NM	331R	NR	ENV
[95]	Gurtu et al. (2015)	MRR	CA	2007-2012	629	SY	ENV
[96]	Hahn and Kuhnen (2013)	JCP	DE	1999-2011	178	SY	TBL
[97]	Hansen and Schaltegger (2016)	JBE	DE	1994-2013	69	SY	TBL
[98]	Hassini et al. (2012)	IJPE	CA	2000-2010	87	SY	TBL
[99]	Hazen et al. (2016)	CIE	US	NM	117R	NR	TBL
[100]	He et al. (2018)	JCP	CN	2006-2015	395	SY	ENV
[101]	Hervani et al. (2005)	B:AIJ	US	NM	83R	NR	ENV
[102]	Hoejmose and Adrien-Kirby (2012)	JPSM	UK	2000-2010	188	SY	TBL
[103]	Homrich et al. (2018)	JCP	BR	2001-2016	327	SY	TBL
[104]	Ibáñez Forés et al. (2014)	JCP	ES	2000-2013	77	NR	TBL
[105]	Igarashi et al. (2013)	JPSM	NO	1991-2011	60	SY	ENV
[106]	Ilgin and Gupta (2010)	JEM	TR	NM	540	NR	ENV

[#]	Author (year)	Journal	Country	Period covered	No. of articles	Type of review	Sust. focus
[107]	Ilgin et al. (2015)	JMS	TR	NM	190	NR	ENV
[108]	Islam et al. (2017)	MMCKS	MY	1998-2016	91	SY	ENV
[109]	Jabbour (2013)	RCR	BR	1994-2013	44	SY	ENV
[110]	Jaehn (2016)	EJOR	DE	NM	364R	NR	TBL
[111]	Jensen (2012)	IJPDLM	DK	2006-2010	115	SY	ENV
[112]	Jia and Jiang (2018)	S	CN	1989-2017	287	SY	TBL
[113]	Jia et al. (2018)	JCP	UK	2000-2016	85	SY	TBL
[114]	Johansson and Sundin (2014)	JCP	SE	2000-2012	102	SY	ENV
[115]	Johnsen et al. (2017)	IMM	DK	1978-2015	276	SY	TBL
[116]	Karaosman et al. (2017)	S	IT	2006-2016	38	SY	TBL
[117]	Khalid et al. (2015)	SCMij	DE	2000-2014	77	SY	TBL
[118]	Kim et al. (2016)	JBE	UK	1979-2013	155	SY	SOC
[119]	Kleindorfer et al. (2005)	POM	US	1992-2012	76R	NR	TBL
[120]	Klewitz and Hansen (2014)	JCP	DE	1987-2010	84	SY	ENV
[121]	Köksal et al. (2017)	S	DE	2005-2016	45	SY	SOC
[122]	Kühnen and Hahn (2015)	JCP	FI	2003-2012	29	NR	ENV
[123]	Kühnen and Hahn (2017)	JIE	DE	2003-2015	141	SY	SOC
[124]	Kumar et al. (2013)	GBR	IN	1996-2011	80	SY	TBL
[125]	Lam and Gu (2013)	IJSTL	SG	1972-2012	50	SY	ENV
[126]	León and Calvo-Amodio (2017)	JCP	US	1987-2014	57	SY	TBL
[127]	Lin et al. (2014)	ESA	HK	1959-2012	280	SY	ENV
[128]	Liu et al. (2011)	IJSE	UK	NM	113R	NR	ENV
[129]	Liu et al. (2017)	S	CN	2006-2015	101	SY	TBL
[130]	Maloni and Brown (2006)	JBE	US	NM	147R	NR	SOC
[131]	Malviya and Kant (2015)	Bij	IN	1998-2013	177	SY	ENV
[132]	Marchet et al. (2014)	JMTM	IT	1994-2011	72	SY	ENV
[133]	Marchi and Zanoni (2017)	E	IT	2003-2017	44	SY	ENV
[134]	Martínez-Jurado and Moyano-Fuentes (2014)	JCP	ES	1990-2012	58	SY	TBL
[135]	Masi et al. (2017)	S	UK	2005-2017	77	SY	TBL
[136]	Matopoulos et al. (2015)	SCMij	UK	1998-2012	96	SY	ENV
[137]	Mayyas et al. (2012)	RSER	US	NM	100	NR	TBL
[138]	Meixell and Luoma (2015)	IJPDLM	US	1994-2013	49	SY	TBL
[139]	Mejías et al. (2016)	IJOPM	ES	1990-2010	194	SY	TBL
[140]	Melander (2017)	BSE	SE	1990-2016	67	SY	ENV
[141]	Memari et al. (2016)	IJOR	MY	2001-2015	31	SY	ENV
[142]	Miemczyk et al. (2012)	SCMij	FR	NM	73	SY	TBL
[143]	Min and Kim (2012)	LR	US	1995-2010	519	SY	ENV
[144]	Mishra et al. (2017)	SPC	IN	1995-2016	653	SY	ENV
[145]	Moldavska and Welo (2017)	JCP	NO	1990-2016	189	SY	TBL
[146]	Mollenkopf et al. (2010)	IJPDLM	US	NM	135R	NR	ENV

[#]	Author (year)	Journal	Country	Period covered	No. of articles	Type of review	Sust. focus
[147]	Moon (2017)	IJSE	US	2000-2015	192	SY	TBL
[148]	Morioka and de Carvalho (2016)	JCP	BR	2006-2015	261	SY	TBL
[149]	Movahedipour et al. (2016)	JIEM	CN	1994-2016	1610	SY	TBL
[150]	Nakamba et al. (2017)	SCMij	UK	2007-2017	109	SY	SOC
[151]	Nikolopoulou and Ierapetritou (2012)	CCE	US	NM	98R	NR	ENV
[152]	Ntabe et al. (2015)	IJPE	CA	2000-2012	45	SY	ENV
[153]	Pérez et al. (2017)	RSER	FR	2006-2015	72	SY	TBL
[154]	Pimentel et al. (2016)	JCP	BR	1949-2015	121R	SY	TBL
[155]	Qaiser et al. (2017)	IMDS	UK	1994-2015	40	SY	TBL
[156]	Quarshie et al. (2016)	JPSM	FI	2007-2013	195	SY	SOC
[157]	Rabe and Deininger (2012)	IJAT	DE	NM	49R	NR	ENV
[158]	Rajeev et al. (2017)	JCP	IN	2000-2015	168	SY	TBL
[159]	Ramani et al. (2010)	JMD	US	NM	218R	NR	ENV
[160]	Ray and Mondal (2017)	Bij	IN	NM	78	NR	ENV
[161]	Roy and Singh (2017)	JCP	IN	1990-2016	71	SY	TBL
[162]	Rugani et al. (2013)	JCP	LU	NM	35	NR	ENV
[163]	Saavedra et al. (2018)	RSER	BR	2007-2017	10	SY	ENV
[164]	Sahamie et al. (2013)	BSE	DE	NM	178	SY	ENV
[165]	Sarkis (2012)	SCMij	US	NM	138R	NR	ENV
[166]	Sarkis et al. (2011)	IJPE	US	NM	177R	NR	ENV
[167]	Sauer and Seuring (2017)	JCP	DE	2007-2015	67	SY	TBL
[168]	Searcy (2012)	JBE	CA	2000-2010	101R	SY	TBL
[169]	Seuring (2013)	JCP	DE	1994-2007	191	SY	TBL
[170]	Seuring and Müller (2008)	DSS	DE	1997-2010	36	SY	TBL
[171]	Shaw et al. (2010)	Bij	UK	NM	64R	NR	ENV
[172]	Singh and Trivedi (2016)	CR	IN	2005-2014	138	SY	ENV
[173]	Sivakumar et al. (2012)	IJSOM	IN	NM	177R	NR	ENV
[174]	Soda et al. (2017)	IJISE	IN	NM	86R	NR	ENV
[175]	Soysal et al. (2012)	IJFSD	NL	NM	36	NR	TBL
[176]	Srivastava (2007)	IJMR	IN	1990-2005	227	SY	ENV
[177]	Stindt (2017)	JCP	DE	1995-2016	133	SY	TBL
[178]	Tachizawa and Wong (2014)	SCMij	ES	2000-2014	39	SY	TBL
[179]	Tajbakhsh and Hassini (2015)	IJPPM	CA	1994-2013	140	SY	TBL
[180]	Tang and Zhou (2012)	EJOR	US	NM	74R	NR	TBL
[181]	Taticchi et al. (2015)	IJPPM	IT	2002-2012	205	SY	TBL
[182]	Terouhid et al. (2017)	JSD	US	1971-2011	38	NR	TBL
[183]	Thoni and Tjoa (2017)	EIS	AT	1999-2014	55	SY	TBL
[184]	Touboulic and Walker (2015)	IJPDLM	UK	1995-2013	308	SY	TBL
[185]	Varsei et al. (2014)	SCMij	AU	NM	162R	NR	TBL
[186]	Wang et al. (2016)	IJPE	US	2004-2014	101	SY	TBL

[#]	Author (year)	Journal	Country	Period covered	No. of articles	Type of review	Sust. focus
[187]	Wichmann and Kaufmann (2016)	IJPDLM	DE	1995-2014	24	SY	SOC
[188]	Winter and Knemeyer (2013)	IJPDLM	DE	1995-2010	456	SY	TBL
[189]	Wong et al. (2015)	IJPDLM	UK	1994-2012	142	SY	ENV
[190]	Wood (2010)	IJMR	US	NM	255R	NR	TBL
[191]	Xavier et al. (2017)	JCP	BR	1995-2015	45	SY	ENV
[192]	Yawar and Seuring (2017)	JBE	FI	2000-2013	142	SY	SOC
[193]	Zaimes et al. (2015)	P	US	NM	181R	NR	ENV
[194]	Zhang et al. (1997)	JMS	US	NM	113	NR	ENV
[195]	Zhou et al. (2018)	EJOR	CN	1996-2016	320	SY	TBL
[196]	Zimmer et al. (2015)	IJPR	DE	1997-2014	143	SY	TBL
[197]	Zorzini et al. (2015)	IJOPM	UK	1997-2013	157	SY	SOC
[198]	Zsidisin and Siferd (2001)	EJPSM	US	NM	61R	NR	ENV

NM: Not mentioned; R: Number of references; SY: Systematic; NR: Narrative

ENV: Environmental; SOC: Social; TBL: Triple bottom line

Table A.1: Literature reviews: individual information

Appendix B

Characteristics of solutions

Table B.1 on the following pages presents a brief description of each feature selected to characterize the solutions obtained. Notice that some features pertain to total values of the five planning periods, while others concern average values per period.

Features	Description
Food banks	
Banks closed (#)	Total number of food banks closed over five periods
Banks opened (#)	Total number of food banks opened over five periods
Operating banks (#)	Average number of food banks operational in a period
Total storage capacity added (t)	Total storage capacity (tonnes) installed over five periods
dry/fresh/frozen products	
Total transp. capacity added (t)	Total transport capacity (tonnes) installed over five periods
dry/fresh/frozen products	
Storage capacity utilization (%)	Percent of available storage capacity used to store products over five periods
dry/fresh/frozen products	
Transport capacity utilization (%)	Percent of available transport capacity used to move products over five periods
dry/fresh/frozen products	
Flow between food banks (t)	Quantity of products (tonnes) exchanged between food banks over five periods
Charities	
Included (#)	Total number of new charities included in the supply chain over five periods
Included (%)	Number of new charities in percent of total number of waiting charities
Avg. satisfied demand (%)	Average quantity of products (tonnes) supplied to:
of all charities SC	charities SC in percent of their demand in each period
of served charities HC	charities HC included in the supply chain in percent of their demand in each period
of served charities C	all served charities C in percent of their demand in each period
of all charities HC	all charities HC, served or not, in percent of their demand in each period
of all charities C	all charities C, served or not, in percent of their demand in each period
Max. unsatisfied demand (δ^t)	Average value of variable δ^t over five periods
Min. assigned to a bank (#)	Minimum number of charities assigned to a food bank in any period
Max. assigned to a bank (#)	Maximum number of charities assigned to a food bank in any period
Changes in assignments (#) banks-charities	Total number of changes in assignments of charities to food banks over five periods *obs.: one reassignment corresponds to two changes*
Assignments (#) to	
food bank $b \in B$	Average number of charities assigned to food bank $b \in B$ over five periods
Max. distance to an assigned bank (d.u.) (ε^t)	Average value of variable ε^t over five periods
Donations	
Total food donations (k€)	Total value of food products (k€) supplied over five periods
Total food donations (t)	Total quantity of food products (tonnes) supplied over five periods
from donors DD (%)	Percent of quantity of products supplied donated by donors DD
from donors CD (%)	Percent of quantity of products supplied donated by donors CD
from donors FD (%)	Percent of quantity of products supplied purchased with donations from donors DD
Unused financial donations (k€)	Total value of financial donations (k€) not used over five periods

Features	Description
Unused financial donations (%)	Value of unused financial donations in percent of total financial donations over five periods
Network flows	
Flows donors-food banks (#)	Total number of products flows over five periods:
from donors DD (%)	from donors DD to food banks
from donors CD (%)	from donors CD to food banks
from donors FD (%)	purchased with donations from donors FD to food banks
Flows between food banks (#)	Total number of products flows between food banks over five periods
Flows food banks-charities (#)	Total number of products flows from food banks to charities over five periods
Environmental indicators	
Total food waste (k€)	Total disposal cost of food waste (k€) over five periods
Total food waste (t)	Total quantity of food waste (tonnes) over five periods
Total food waste (%)	Total quantity of food waste in percent of quantity of food products available for donation over five periods
donors DD share (%)	Quantity of food waste located at donors DD in percent of total quantity of food waste over five periods
donors CD share (%)	Quantity of food waste located at donors CD in percent of total quantity of food waste over five periods
of donors DD offer (%)	Quantity of food waste located at donors DD in percent of total quantity of food products made available for donation by donors DD over five periods
of donors CD offer (%)	Quantity of food waste located at donors CD in percent of total quantity of food products made available for donation by donors CD over five periods
Total CO_2 emissions (k€)	Total value of CO_2 emissions (k€) over five periods
Total CO_2 emissions (t-d.u.)	Total quantity of CO_2 emissions (tonnes-d.u.) over five periods
Social indicators (others)	
Total social work (k€)	Total value of social work (k€) created over five periods
Total investment capital required	
(% of reference budget)	Total investment capital required in percent of reference budget over five periods
Periods with investment (#)	Number of periods with investment expenditure
Periods over budget (#)	Number of periods with investment expenditure exceeding reference budget

Table B.1: Characteristics of solutions

Appendix C

Case C2: Food waste

Case C2 expresses the preferences of a decision maker that is more invested in the reduction of food waste than in the reduction of the carbon footprint attributed to the food banks fleet of vehicles. Accordingly the first term of the environmental objective function is weighted by $\alpha_3 = 0.75$, and the weight α_4 associated with the second term is set at 0.25. The weight coefficients in the social objective function are the same as in the neutral case.

Table C.1 presents the results obtained for the lexicographic solutions of this case.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective functions values						
Economic (m.u.)	6,690.3	6,690.3	9,741.9	10,599.2	9,378.2	9,419.4
Environmental (k€)	370.3	376.8	100.7	100.7	188.1	182.3
Social	-91.7	-88.2	21.0	151.1	241.5	241.5
Food banks						
Banks closed (#)	1.6	1.6	1.1	0.6	0.3	0.3
Banks opened (#)	0.6	0.6	0.9	0.8	-	-
Operating banks (#)	3.0	3.0	4.0	4.4	3.8	3.8
Total storage capacity added (t)	1,574.5	1,574.5	3,884.6	3,748.8	1,511.4	1,511.4
dry products	556.1	556.1	1,011.1	859.4	-	-
fresh products	994.2	994.2	2,805.5	2,814.0	1,474.4	1,474.4
frozen products	24.3	24.3	68.1	75.5	37.1	37.1

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total transp. capacity added (t)	91.8	86.8	513.1	513.1	55.6	55.6
dry products	-	-	143.2	143.2	-	-
fresh products	87.6	84.3	357.2	357.2	50.6	50.6
frozen products	4.2	2.5	12.6	12.6	5.1	5.1
Storage capacity utilization (%)						
dry products	18.1	18.1	20.3	21.4	22.1	22.1
fresh products	42.9	42.9	38.2	37.7	45.9	46.3
frozen products	22.2	22.2	24.2	27.0	32.2	32.3
Transport capacity utilization (%)						
dry products	11.6	12.1	11.7	10.3	10.6	10.6
fresh products	30.4	31.1	24.1	22.1	31.1	30.9
frozen products	13.5	15.4	6.9	6.6	13.8	14.1
Flow between food banks (t)	2.7	2.7	1.4	1.4	184.6	170.4
Charities						
Included (#)	-	-	2.5	3.0	3.0	3.0
Included (%)	-	-	81.7	100.0	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	81.9	83.8	82.7	82.9
of served charities HC	-	-	70.2	82.2	80.8	81.1
of served charities C	69.9	69.9	81.4	83.5	82.4	82.6
of all charities HC	-	-	51.0	82.2	80.8	81.1
of all charities C	59.1	59.1	77.2	83.5	82.4	82.6
Max. unsatisfied demand (δ^t)	2.7	2.7	1.6	0.4	0.5	0.5
Min. assigned to a bank (#)	2.4	2.4	2.0	1.8	1.7	1.7
Max. assigned to a bank (#)	10.5	10.5	8.8	8.5	10.3	10.1
Changes in assignments banks-charities (#)	-	-	2.1	1.0	-	-
Assignments (#) to						
food bank 1	0.3	0.3	2.1	2.8	2.2	2.2
food bank 2	1.5	1.4	1.9	2.3	2.4	2.4
food bank 3	2.9	2.9	3.8	4.1	4.4	4.5
food bank 4	10.0	10.0	6.5	6.4	10.1	10.0
food bank 5	1.4	1.5	3.7	3.5	-	-

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Max. distance to an assigned bank (d.u.) (ε^t)	236.8	236.1	236.1	223.1	222.1	222.1
Donations						
Total food donations (k€)	11,019.7	11,019.7	14,525.5	15,663.1	15,373.3	15,418.7
Total food donations (t)	13,774.3	13,774.3	17,982.1	19,480.7	19,131.6	19,188.6
from donors DD (%)	76.6	75.9	80.3	74.1	74.6	74.7
from donors CD (%)	21.9	22.6	19.2	17.7	16.8	16.7
from donors FD (%)	1.5	1.5	0.5	8.2	8.7	8.6
Unused financial donations (k€)	1,075.8	1,069.5	1,162.8	25.2	7.1	16.4
Unused financial donations (%)	80.6	80.3	88.5	2.0	0.4	1.0
Network flows						
Flows donors-food banks (#)	130.1	131.9	162.7	192.6	178.4	178.1
from donors DD (%)	73.2	73.5	81.7	71.6	66.6	67.0
from donors CD (%)	21.4	20.8	13.7	11.7	16.0	15.8
from donors FD (%)	5.4	5.7	4.6	16.7	17.4	17.3
Flows between food banks (#)	0.2	0.2	0.4	0.6	4.6	4.6
Flows food banks-charities (#)	387.0	388.1	458.5	478.2	477.7	476.4
Environmental indicators						
Total food waste (k€)	276.7	276.5	1.1	1.1	27.6	23.6
Total food waste (t)	4,333.1	4,330.3	17.5	17.5	429.5	367.2
Total food waste (%)	24.2	24.2	0.1	0.1	2.0	1.7
donors DD share (%)	89.7	91.9	6.9	6.9	38.9	26.0
donors CD share (%)	10.3	8.1	93.1	93.1	61.1	74.0
of donors DD offer (%)	27.6	28.3	-	-	0.9	0.5
of donors CD offer (%)	9.4	6.1	1.0	1.0	4.4	4.7
Total CO_2 emissions ((k€)	651.1	677.8	399.6	399.6	669.5	658.6
Total CO_2 (t-d.u.)	750,646.1	779,381.1	459,368.1	459,368.1	770,178.4	757,795.8
Social indicators (others)						
Total social work (k€)	2,077.5	2,077.5	2,649.8	2,836.0	2,538.4	2,538.4

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total investment capital required (% of reference budget)	42.7	41.4	77.6	70.8	25.1	25.1
Periods with investment (#)	1.1	1.0	1.5	1.2	1.0	1.0
Periods over budget (#)	0.9	0.9	1.1	1.1	0.6	0.6

Table C.1: Characteristics of the lexicographic solutions: average over 20 instances. Case C2

Figure C.1 shows the performance of each solution in terms of the main KPIs selected for their characterization. The description of these KPIs is presented in Section 7.2.3. The bar charts illustrate the values of the objective functions for each solution. For representation purposes, the value of the economic objective is depicted in a scale 1:10.

Considering that this case deals with the higher preference to diminish food waste, and further to the presentation of the results of this case in Section 7.2.5, it is no surprise that the most striking differences from the radar charts that illustrate the neutral case (cf. Figure 7.14 on page 165) are located in the charts in the middle of the figure that concern the environmental-centric solutions LS3-LS4. Recall that, according to the definition of the KPIs, the larger the area that represents the performance of a solution in regard to a KPI, the poorer the respective results.

The chief differences from the radar charts of case C1 are immediately identified:

- better performance in regard to KPI *%Waste*,
- better performance in terms of KPI *%Demand*, and
- worst performance concerning KPI *%CO2*.

Figure C.2 presents the relative results of the six solutions in terms of each KPI.

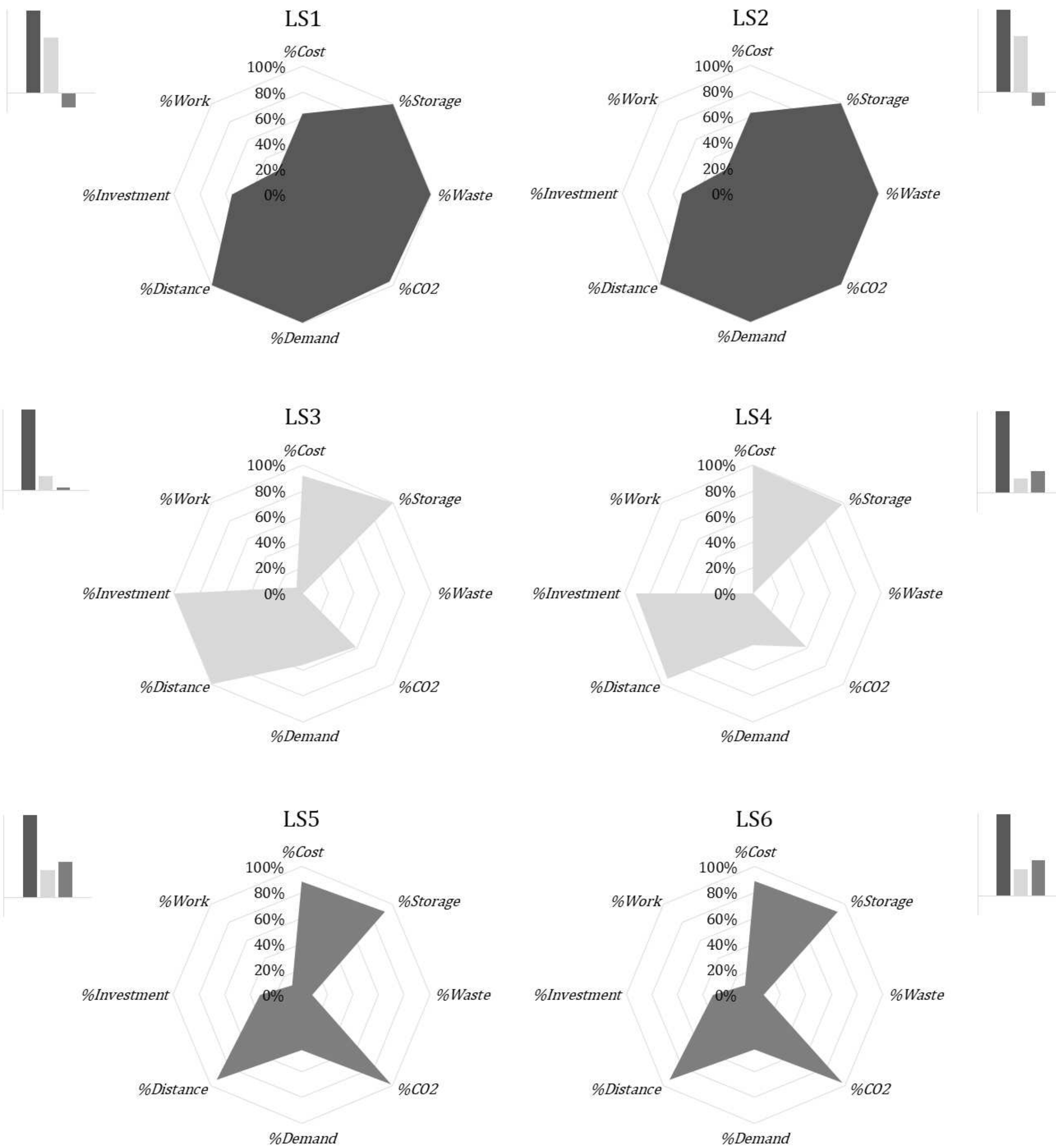


Figure C.1: Comparison of selected KPIs per lexicographic solution

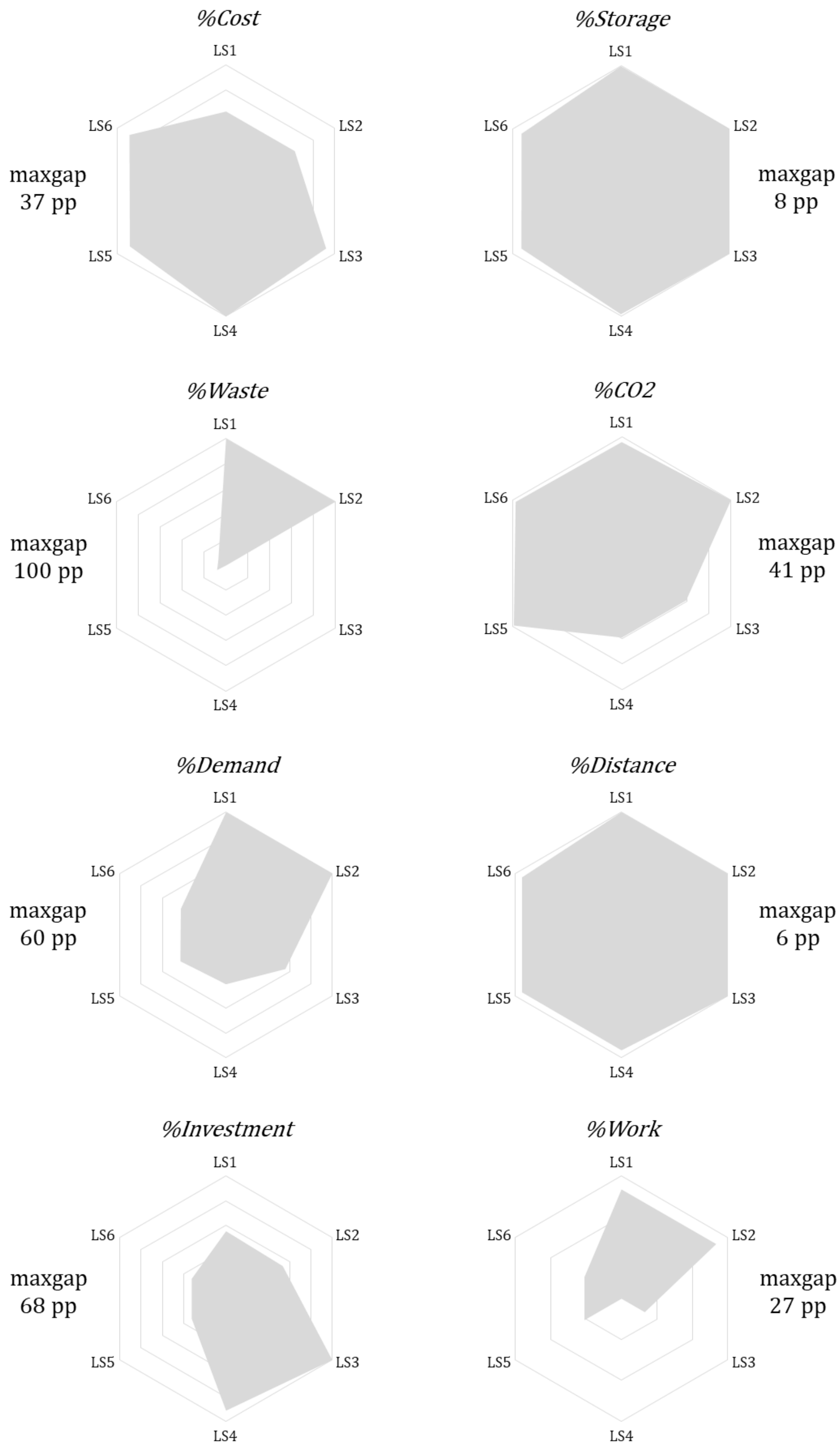


Figure C.2: Comparison of lexicographic solutions per selected KPI

Appendix D

Case C3: CO_2 emissions

Case C3 reflects the inclination on the decision maker part toward the reduction of CO_2 emissions. The favoring of this environmental factor is uphold by setting $\alpha_4 = 0.75$. Subsequently, the weight coefficient of the term accounting for food waste cost is reduced to $\alpha_3 = 0.25$. The weight coefficients in the social objective function are the same as in the neutral case.

Table D.1 presents the results obtained for the lexicographic solutions of this case.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective functions values						
Economic (m.u.)	6,690.3	6,690.3	8,064.2	9,023.9	9,378.2	9,418.6
Environmental (k€)	555.3	577.5	177.9	177.9	508.8	497.6
Social	-91.7	-88.2	-20.9	120.5	241.5	241.5
Food banks						
Banks closed (#)	1.6	1.6	1.8	0.5	0.3	0.3
Banks opened (#)	0.6	0.6	0.8	0.5	-	-
Operating banks (#)	3.0	3.0	3.0	4.0	3.8	3.8
Total storage capacity added (t)	1,574.5	1,574.5	2,654.2	2,523.1	1,511.4	1,511.4
dry products	556.1	556.1	758.3	455.0	-	-
fresh products	994.2	994.2	1,845.1	2,013.6	1,474.4	1,474.4
frozen products	24.3	24.3	50.9	54.6	37.1	37.1
Total transp. capacity added (t)	91.8	86.8	118.0	118.0	55.6	55.6

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
dry products	-	-	25.3	25.3	-	-
fresh products	87.6	84.3	91.0	91.0	50.6	50.6
frozen products	4.2	2.5	1.7	1.7	5.1	5.1
Storage capacity utilization (%)						
dry products	18.1	18.1	21.9	17.6	22.1	22.1
fresh products	42.9	42.9	43.9	37.3	45.9	46.3
frozen products	22.2	22.2	29.3	23.1	32.2	32.3
Transport capacity utilization (%)						
dry products	11.6	12.1	1.8	1.4	10.6	10.3
fresh products	30.6	31.1	3.7	3.4	31.1	30.9
frozen products	13.5	15.4	0.8	0.3	13.8	14.1
Flow between food banks (t)	2.7	2.7	-	-	184.6	170.4
Charities						
Included (#)	-	-	1.4	2.5	3.0	3.0
Included (%)	-	-	46.7	81.7	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	78.0	75.8	82.7	82.8
of served charities HC	-	-	38.8	53.2	80.8	81.1
of served charities C	69.9	69.9	77.5	75.2	82.4	82.6
of all charities HC	-	-	18.8	46.6	80.8	81.1
of all charities C	59.1	59.1	68.8	71.2	82.4	82.6
Max. unsatisfied demand (δ^t)	2.7	2.7	1.8	1.0	0.5	0.5
Min. assigned to a bank (#)	2.4	2.4	3.4	1.6	1.7	1.7
Max. assigned to a bank (#)	10.5	10.5	9.6	9.2	10.3	10.1
Changes in assignments banks-charities (#)	-	-	2.0	1.3	-	-
Assignments (#) to						
food bank 1	0.3	0.3	1.1	2.1	2.2	2.2
food bank 2	1.4	1.4	1.1	2.2	2.4	2.4
food bank 3	2.9	2.9	3.9	3.7	4.4	4.5
food bank 4	10.0	10.0	7.6	7.9	10.1	10.0
food bank 5	1.5	1.5	3.2	2.1	-	-
Max. distance to an assigned						

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
bank (d.u.) (ε^t)	236.8	236.1	234.7	216.0	222.1	222.1
Donations						
Total food donations (k€)	11,019.7	11,019.7	12,967.5	13,377.0	15,373.3	15,411.4
Total food donations (t)	13,774.3	13,774.3	16,023.2	16,571.2	19,131.6	19,178.9
from donors DD (%)	76.3	75.9	90.1	87.1	74.6	74.8
from donors CD (%)	22.1	22.6	3.7	3.6	16.8	16.4
from donors FD (%)	1.7	1.5	6.3	9.4	8.7	8.8
Unused financial donations (k€)	1,063.0	1,069.4	409.3	-	4.9	-
Unused financial donations (%)	79.6	80.3	31.6	-	0.3	-
Network flows						
Flows donors-food banks (#)	129.6	131.8	134.6	167.1	178.2	177.8
from donors DD (%)	73.2	73.6	85.9	82.2	67.0	66.8
from donors CD (%)	21.1	20.8	2.3	2.4	15.9	15.6
from donors FD (%)	5.7	5.7	11.8	15.4	17.1	17.7
Flows between food banks (#)	0.2	0.2	-	0.1	4.6	4.6
Flows food banks-charities (#)	387.0	388.1	416.7	450.3	477.3	476.2
Environmental indicators						
Total food waste (k€)	278.3	276.5	184.2	184.2	28.0	26.4
Total food waste (t)	4,358.0	4,330.3	2,883.3	2,883.2	434.1	409.7
Total food waste (%)	24.4	24.2	15.9	15.9	2.0	1.9
donors DD share (%)	90.1	91.9	0.1	0.1	39.7	23.3
donors CD share (%)	9.9	8.1	99.9	99.9	60.3	76.7
of donors DD offer (%)	27.9	28.3	-	-	0.9	0.5
of donors CD offer (%)	8.8	6.1	81.9	81.9	4.4	6.3
Total CO_2 emissions ((k€)	647.6	677.8	175.8	175.8	669.1	654.7
Total CO_2 (t-d.u.)	746,581.6	779,377.4	202,294.0	202,295.4	769,732.7	753,579.9
Social indicators (others)						
Total social work (k€)	2,077.5	2,077.5	2,170.1	2,638.2	2,538.4	2,538.4
Total investment capital required						

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
(% of reference budget)	42.7	41.4	55.4	43.0	25.1	25.1
Periods with investment (#)	1.1	1.0	1.3	1.1	1.0	1.0
Periods over budget (#)	0.9	0.9	1.1	0.9	0.6	0.6

Table D.1: Characteristics of the lexicographic solutions: average over 20 instances. Case C3

Figure D.1 shows the performance of each solution in terms of the main KPIs selected for their characterization. The description of these KPIs is presented in Section 7.2.3. The bar charts illustrate the values of the objective functions for each solution. For representation purposes, the value of the economic objective is depicted in a scale 1:10.

As expected, in light of the preferences conveyed by this case and of the conclusions deducted in Section 7.2.5, the radar charts in the middle of the figure deviate the most from charts describing the neutral case (cf. Figure 7.14 on page 165). While the top and bottom charts indicate that attributing higher preference to the reduction of the carbon footprint has no relevant impact on the economic costs or social value of assuming a neutral positioning in relation to the environmental factors, the charts in the middle register some differences.

Observing that larger areas correspond to worst performances of the solution in relation the values registered by other solutions, it is possible to recognize as main differences from the neutral case:.

- performance decline of KPI *%Waste*,
- slight deterioration of KPI *%Demand*, and
- superior performance of KPI *%CO2*.

Figure D.2 presents the relative results of the six solutions in terms of each KPI.

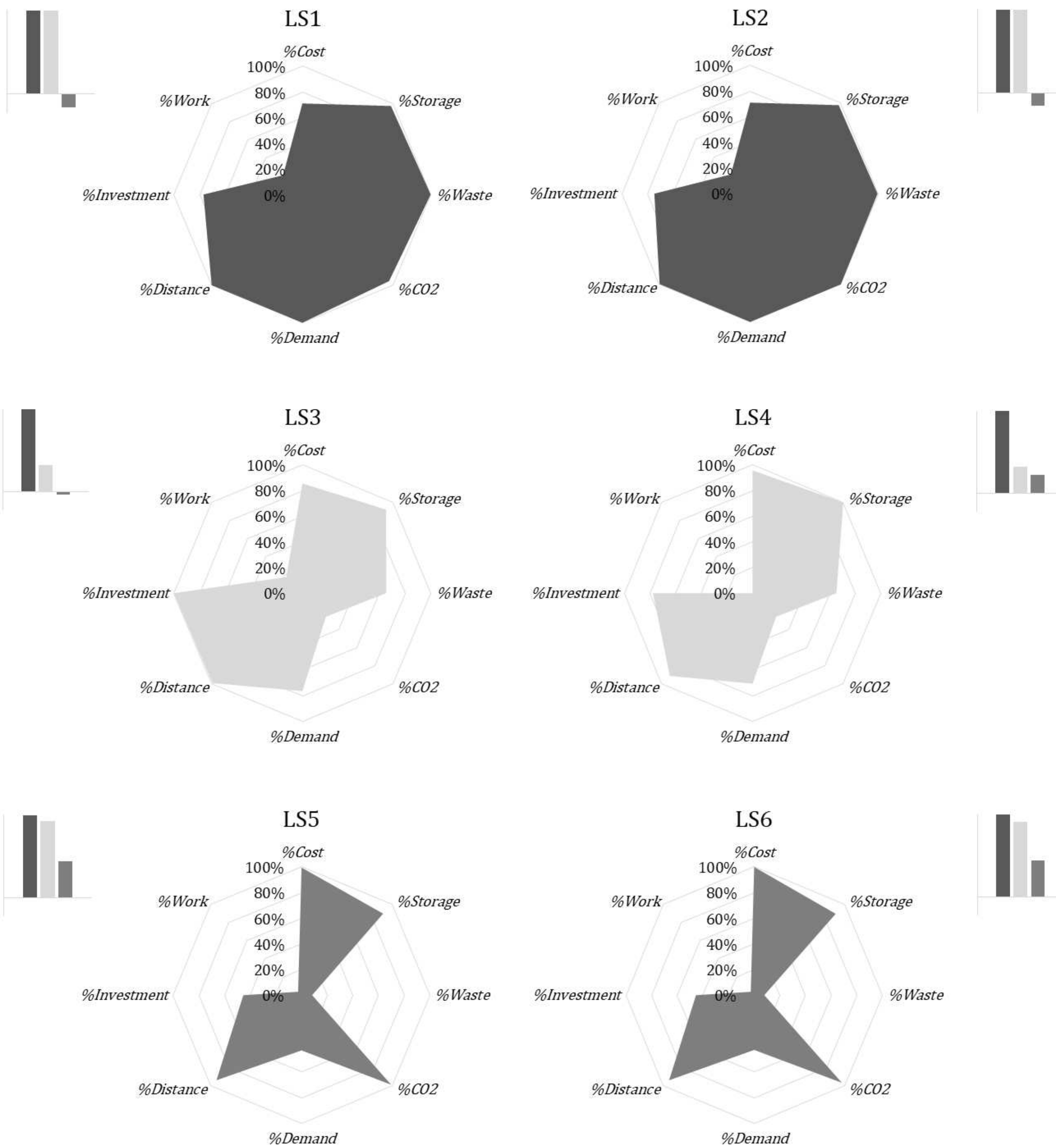


Figure D.1: Comparison of selected KPIs per lexicographic solution

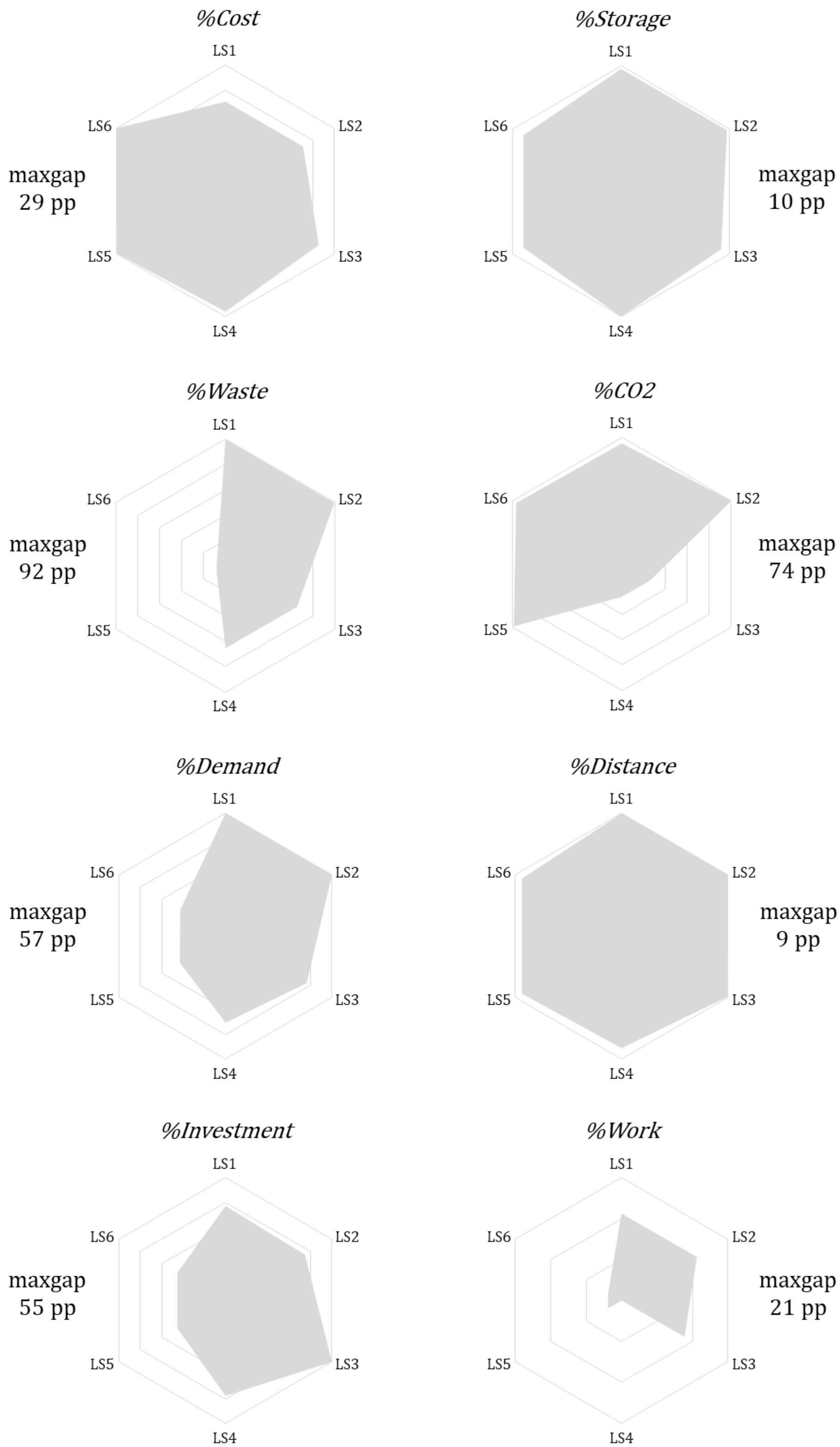


Figure D.2: Comparison of lexicographic solutions per selected KPI

Appendix E

Case C4: Inclusion

In case C4 the preferences of the decision maker favor the expansion of the food supply chain by the introduction of new supported charities. This preference translates into is selecting the value of 0.4 for the coefficient α_5 related to the social term that accounts for the inclusion of charities $c \in HC$. The remaining total weight is redistributed equally among the other four social terms, whose coefficients are set at 0.15 each. In this case the decision maker adopts a neutral positioning in regard to the environmental factors that are weighted at 0.5 each.

Table E.1 presents the results obtained for the lexicographic solutions of this case.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective functions values						
Economic (m.u.)	6,690.3	6,690.3	8,688.9	9,800.9	9,373.7	9,414.3
Environmental (k€)	463.5	477.2	166.8	166.8	348.0	340.0
Social	-68.8	-67.1	111.7	336.4	431.1	431.1
Food banks						
Banks closed (#)	1.6	1.6	1.6	0.3	0.3	0.3
Banks opened (#)	0.6	0.6	0.8	0.5	-	-
Operating banks (#)	3.0	3.0	3.2	4.3	3.8	3.8
Total storage capacity added (t)	1,574.5	1,574.5	3,153.0	3,002.7	1,511.4	1,511.4
dry products	556.1	556.1	909.9	657.2	-	-
fresh products	994.2	994.2	2,182.1	2,283.2	1,474.4	1,474.4

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
frozen products	24.3	24.3	61.0	62.3	37.1	37.1
Total transp. capacity added (t)	91.8	88.5	303.3	304.1	55.6	55.6
dry products	-	-	67.4	67.4	-	-
fresh products	87.6	85.9	232.5	232.5	50.6	50.6
frozen products	4.2	2.5	3.4	4.2	5.1	5.1
Storage capacity utilization (%)						
dry products	18.1	18.1	22.3	18.0	22.2	22.1
fresh products	42.9	42.9	43.2	37.2	45.9	46.2
frozen products	22.2	22.2	25.7	24.3	32.2	32.3
Transport capacity utilization (%)						
dry products	11.7	12.1	6.4	4.8	10.6	10.3
fresh products	30.6	31.2	15.1	12.4	31.0	30.8
frozen products	13.5	15.4	4.8	2.4	13.8	14.1
Flow between food banks (t)	2.7	2.7	-	-	175.5	161.4
Charities						
Included (#)	-	-	1.8	2.8	3.0	3.0
Included (%)	-	-	60.0	93.3	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	80.4	78.9	82.7	82.8
of served charities HC	-	-	50.4	67.8	80.8	81.1
of served charities C	69.9	69.9	79.9	78.3	82.4	82.6
of all charities HC	-	-	30.6	65.0	80.8	81.1
of all charities C	59.1	59.1	72.7	76.7	82.4	82.6
Max. unsatisfied demand (δ^t)	2.7	2.7	1.5	0.7	0.5	0.5
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	10.3	10.1
Changes in assignments banks-charities (#)	-	-	1.9	0.9	-	-
Assignments (#) to						
food bank 1	0.3	0.3	1.4	2.2	2.2	2.2
food bank 2	1.4	1.4	1.8	3.0	2.4	2.4
food bank 3	2.9	2.9	4.1	4.0	4.4	4.5
food bank 4	10.0	10.0	7.0	7.3	10.1	10.0

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
food bank 5	1.5	1.5	2.9	2.1	-	-
Max. distance to an assigned bank (d.u.) (ε^t)	236.8	236.1	236.3	213.8	222.1	222.1
Donations						
Total food donations (k€)	11,019.7	11,019.7	13,676.1	14,382.5	15,373.1	15,411.1
Total food donations (t)	13,774.3	13,774.3	16,940.5	17,852.6	19,131.3	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	16.7	16.4
from donors FD (%)	1.7	1.5	3.8	8.7	8.7	8.8
Unused financial donations (k€)	1,063.0	1,069.4	706.4	-	6.5	-
Unused financial donations (%)	79.6	80.3	54.1	-	0.4	-
Network flows						
Flows donors-food banks (#)	129.3	133.0	139.9	179.6	178.4	178.0
from donors DD (%)	72.9	73.7	84.0	78.3	66.6	67.5
from donors CD (%)	21.3	20.8	6.8	5.5	16.0	15.6
from donors FD (%)	5.8	5.5	9.2	16.2	17.4	16.9
Flows between food banks (#)	0.2	0.2	-	-	4.6	4.5
Flows food banks-charities (#)	387.0	388.1	432.2	467.3	477.1	475.3
Environmental indicators						
Total food waste (k€)	278.3	276.5	102.9	102.9	27.7	26.4
Total food waste (t)	4,358.0	4,330.3	1,613.0	1,612.9	430.7	409.3
Total food waste (%)	24.4	24.2	8.9	8.9	2.0	1.9
donors DD share (%)	90.2	91.9	0.2	0.2	38.8	23.4
donors CD share (%)	9.8	8.1	99.9	99.8	61.2	76.6
of donors DD offer (%)	27.9	28.3	-	-	0.9	0.5
of donors CD offer (%)	8.7	6.2	53.0	53.0	4.5	6.3
Total CO_2 emissions ((k€)	648.7	677.9	230.8	230.8	668.3	653.7
Total CO_2 (t-d.u.)	747,820.6	779,455.0	265,194.1	265,196.8	768,834.6	752,452.7
Social indicators (others)						

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total social work (k€)	2,077.5	2,077.5	2,305.3	2,818.3	2,538.4	2,538.4
Total investment capital required (% of reference budget)	42.7	42.0	65.0	51.7	25.1	25.1
Periods with investment (#)	1.1	1.1	1.3	1.1	1.0	1.1
Periods over budget (#)	0.9	0.9	1.1	0.9	0.6	0.6

Table E.1: Characteristics of the lexicographic solutions: average over 20 instances. Case C4

Figure E.1 shows the performance of each solution in terms of the main KPIs selected for their characterization. The description of these KPIs is presented in Section 7.2.3. The bar charts illustrate the values of the objective functions for each solution. For representation purposes, the value of the economic objective is depicted in a scale 1:10.

Although this case attributes higher preference to the particular social goal of increasing the number of assisted charities than to the other social criteria, its results are indistinct of the results obtained from assuming a neutral positioning in regard to all five social terms. In fact, the six radar charts of Figure E.1, notably the bottom two that concern the social results, are identical to representation of the results obtained for case C1 (cf. Figure 7.14 on page 165).

Observing that larger areas correspond to worst performances of the solution in relation to the values of the other solutions, Figure E.2 presents the relative results of the six solutions in terms of each KPI.

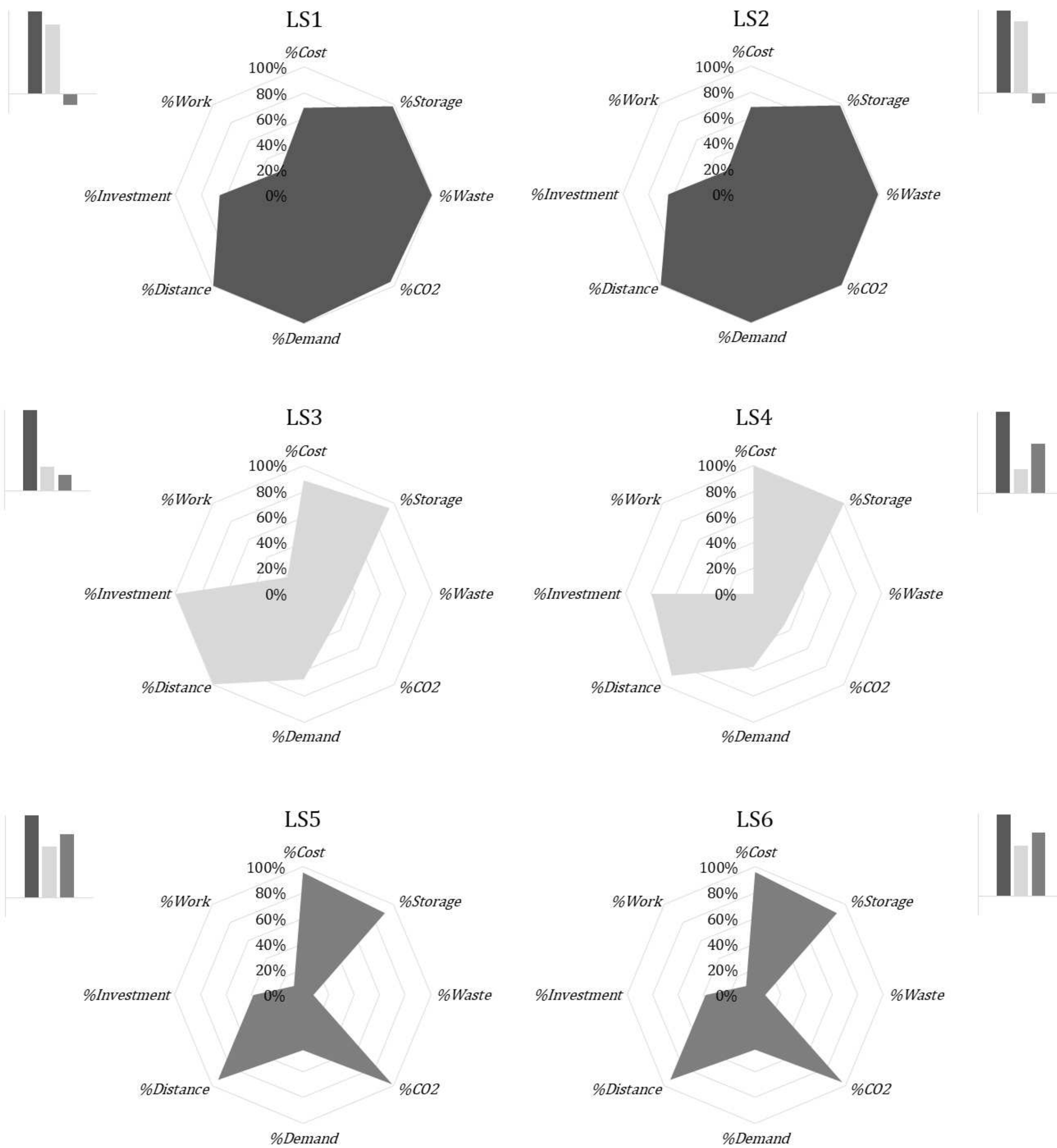


Figure E.1: Comparison of selected KPIs per lexicographic solution

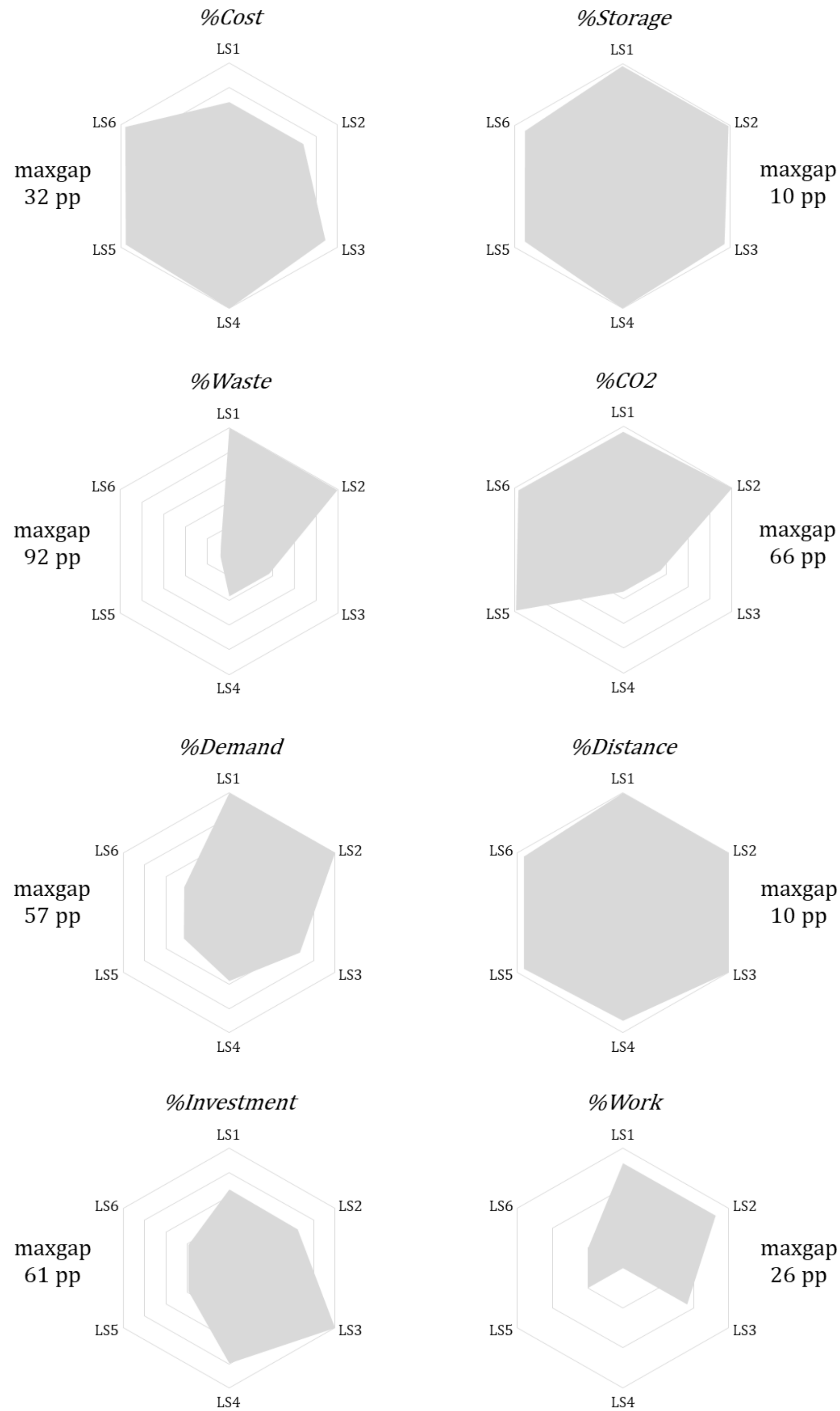


Figure E.2: Comparison of lexicographic solutions per selected KPI

Appendix F

Case C5: Investment

Case C5 translates the positioning of the decision maker that favors reducing the social effort of raising investment capital to open or close food banks, and to install storage or transport capacity. Accordingly, the social objective function term that expresses that effort is weighted with $\alpha_6 = 0.40$, and each of the other social terms is weighted at 0.15. No particular preferences are expressed in regard to the two environmental factors that are weighted at 0.5 each.

Table F.1 presents the results obtained for the lexicographic solutions of this case.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective functions values						
Economic (m.u.)	6,690.3	6,690.3	8,694.1	9,701.3	9,101.7	9,159.3
Environmental (k€)	463.0	477.1	166.8	166.8	345.7	331.1
Social	74.4	80.4	88.9	240.0	370.9	370.9
Food banks						
Banks closed (#)	1.6	1.6	1.6	0.4	0.3	0.3
Banks opened (#)	0.6	0.6	0.8	0.5	-	-
Operating banks (#)	3.0	3.0	3.2	4.2	3.7	3.7
Total storage capacity added (t)	1,574.5	1,574.5	3,153.0	2,816.6	1,283.3	1,283.3
dry products	556.1	556.1	909.9	606.6	-	-
fresh products	994.2	994.2	2,182.1	2,148.4	1,246.9	1,246.9
frozen products	24.3	24.3	61.0	61.7	36.4	36.4

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total transp. capacity added (t)	91.8	86.8	303.3	304.1	28.6	28.6
dry products	-	-	67.4	67.4	-	-
fresh products	87.6	84.3	232.5	232.5	25.3	25.3
frozen products	4.2	2.5	3.4	4.2	3.4	3.4
Storage capacity utilization (%)						
dry products	18.1	18.1	22.3	18.2	22.1	21.9
fresh products	42.9	42.9	43.2	38.4	46.7	47.1
frozen products	22.2	22.2	25.7	24.3	31.8	31.9
Transport capacity utilization (%)						
dry products	11.6	12.1	6.4	4.9	10.5	9.8
fresh products	30.6	31.1	15.1	12.4	30.6	30.0
frozen products	13.5	15.4	4.8	2.4	11.8	12.4
Flow between food banks (t)	2.7	2.7	-	-	149.1	127.1
Charities						
Included (#)	-	-	1.8	2.8	3.0	3.0
Included (%)	-	-	60.0	91.7	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	80.5	79.2	81.9	82.1
of served charities HC	-	-	49.2	68.2	79.7	79.9
of served charities C	69.9	69.9	79.9	78.7	81.6	81.7
of all charities HC	-	-	30.1	62.9	78.6	78.8
of all charities C	59.1	59.1	72.7	76.7	81.4	81.6
Max. unsatisfied demand (δ^t)	2.7	2.7	1.5	0.7	0.5	0.5
Min. assigned to a bank (#)	2.4	2.4	3.1	1.6	1.8	1.9
Max. assigned to a bank (#)	10.5	10.5	9.2	8.9	10.7	10.4
Changes in assignments banks-charities (#)	-	-	1.9	1.0	0.2	0.2
Assignments (#) to						
food bank 1	0.3	0.3	1.5	2.2	2.1	2.2
food bank 2	1.4	1.4	1.8	2.9	2.2	2.2
food bank 3	2.9	2.9	4.1	4.0	4.2	4.4
food bank 4	10.0	10.0	7.0	7.4	10.5	10.2
food bank 5	1.5	1.5	2.9	2.0	-	-

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Max. distance to an assigned bank (d.u.) (ε^t)	236.8	236.1	235.5	222.1	227.3	227.3
Donations						
Total food donations (k€)	11,019.7	11,019.7	13,675.7	14,379.0	15,162.8	15,200.7
Total food donations (t)	13,774.3	13,774.3	16,940.2	17,845.0	18,864.1	18,912.4
from donors DD (%)	76.3	75.9	85.2	80.9	75.3	75.7
from donors CD (%)	22.0	22.6	11.0	10.4	16.2	15.6
from donors FD (%)	1.7	1.5	3.8	8.7	8.5	8.8
Unused financial donations (k€)	1,063.0	1,069.4	706.4	3.6	15.0	-
Unused financial donations (%)	79.6	80.3	54.1	0.3	1.0	-
Network flows						
Flows donors-food banks (#)	129.7	132.4	139.5	175.7	176.0	175.0
from donors DD (%)	73.1	73.6	84.4	78.5	66.9	68.3
from donors CD (%)	21.0	20.8	6.7	5.6	15.9	15.3
from donors FD (%)	5.8	5.6	8.9	15.9	17.2	16.5
Flows between food banks (#)	0.2	0.2	-	-	3.9	3.6
Flows food banks-charities (#)	387.0	388.1	432.8	465.6	474.9	474.0
Environmental indicators						
Total food waste (k€)	278.3	276.5	102.9	102.9	41.4	42.1
Total food waste (t)	4,358.0	4,330.3	1,613.0	1,612.9	643.2	650.9
Total food waste (%)	24.4	24.2	8.9	8.9	3.0	3.1
donors DD share (%)	90.1	91.9	0.2	0.2	36.7	19.6
donors CD share (%)	9.9	8.1	99.8	99.8	63.3	80.4
of donors DD offer (%)	27.9	28.3	-	-	1.4	0.8
of donors CD offer (%)	8.8	6.2	53.0	53.0	6.8	10.6
Total CO_2 emissions ((k€)	647.6	677.8	230.8	230.8	650.1	620.0
Total CO_2 (t-d.u.)	746,581.6	779,342.4	265,194.1	265,198.9	747,957.5	714,541.9
Social indicators (others)						
Total social work (k€)	2,077.5	2,077.5	2,305.3	2,766.0	2,480.6	2,480.6

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total investment capital required (% of reference budget)	42.7	41.4	65.0	49.7	23.2	23.2
Periods with investment (#)	1.1	1.0	1.3	1.1	1.0	1.0
Periods over budget (#)	0.9	0.9	1.1	0.9	0.6	0.6

Table F.1: Characteristics of the lexicographic solutions: average over 20 instances. Case C5

The performance of each solution in terms of the main KPIs selected for their characterization is depicted in Figure F.1. The description of these KPIs is presented in Section 7.2.3. The bar charts illustrate the values of the objective functions for each solution. For representation purposes, the value of the economic objective is depicted in a scale 1:10.

As discussed in Section 7.2.5, the most significant changes to the results obtained for the neutral case are registered in relation to the installed capacity and the disposal cost of food waste. However, by comparison with the values registered in the solutions represented in the top and middle radar charts, those changes are in fact not noteworthy. Notice that, in reference to the values of case C1, the decrease in installed capacity is accompanied by a smaller redistribution of products. Therefore KPI *%Storage* that concerns unused storage capacity is in case C5 indistinct of case C1. KPI *%Waste*, like KPI *%CO2* on the other hand show a modest improvement over the performance of case C1. The most perceptible improvement is verified in KPI *%Investment*. Yet, even for this KPI that is the main target of this case, the comparison with the neutral case reveals only minor differences.

Observing that larger areas correspond to worst performances of the solution in relation the other solutions, Figure F.2 presents the relative results of the six solutions in terms of each KPI.

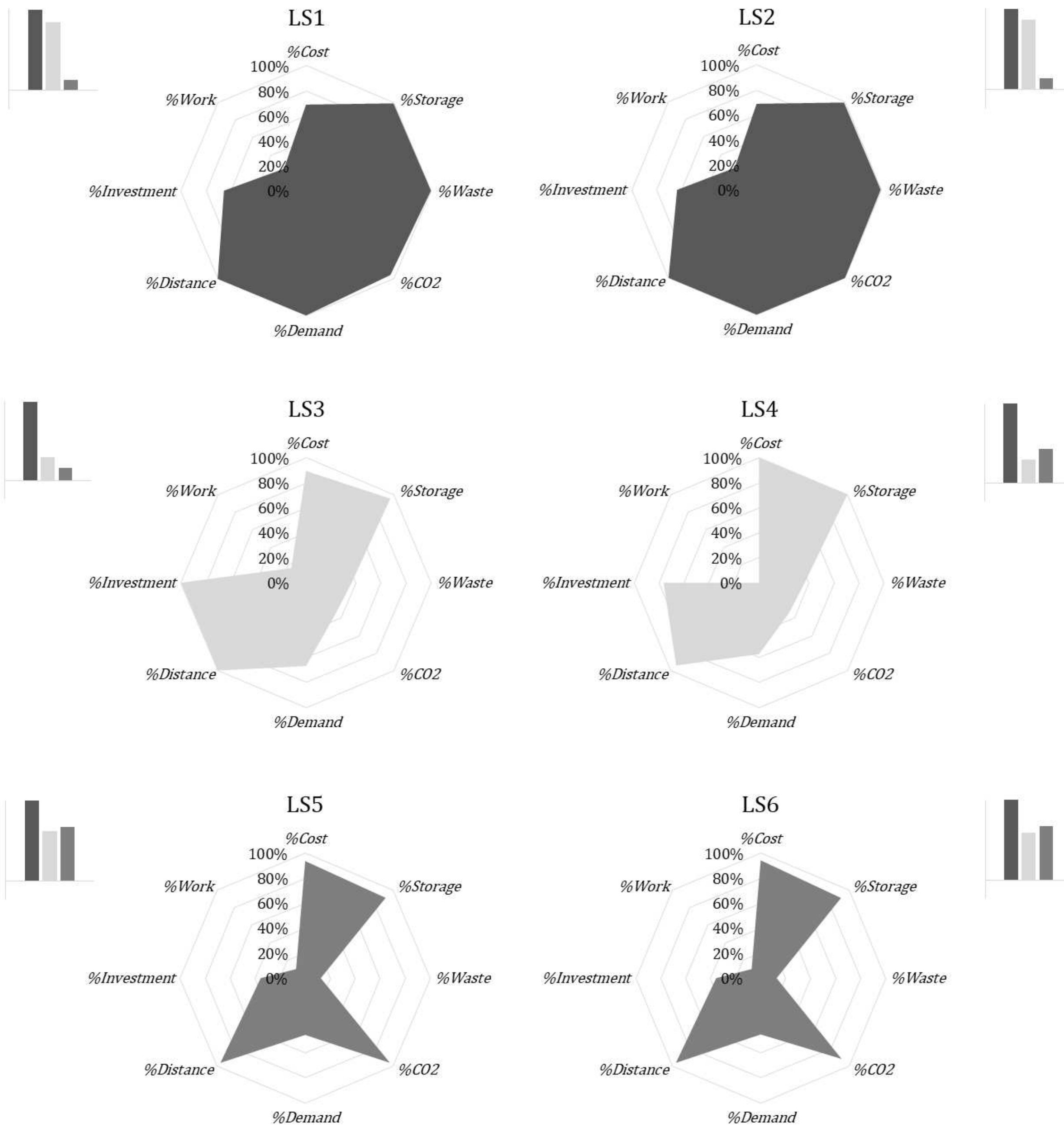


Figure F.1: Comparison of selected KPIs per lexicographic solution

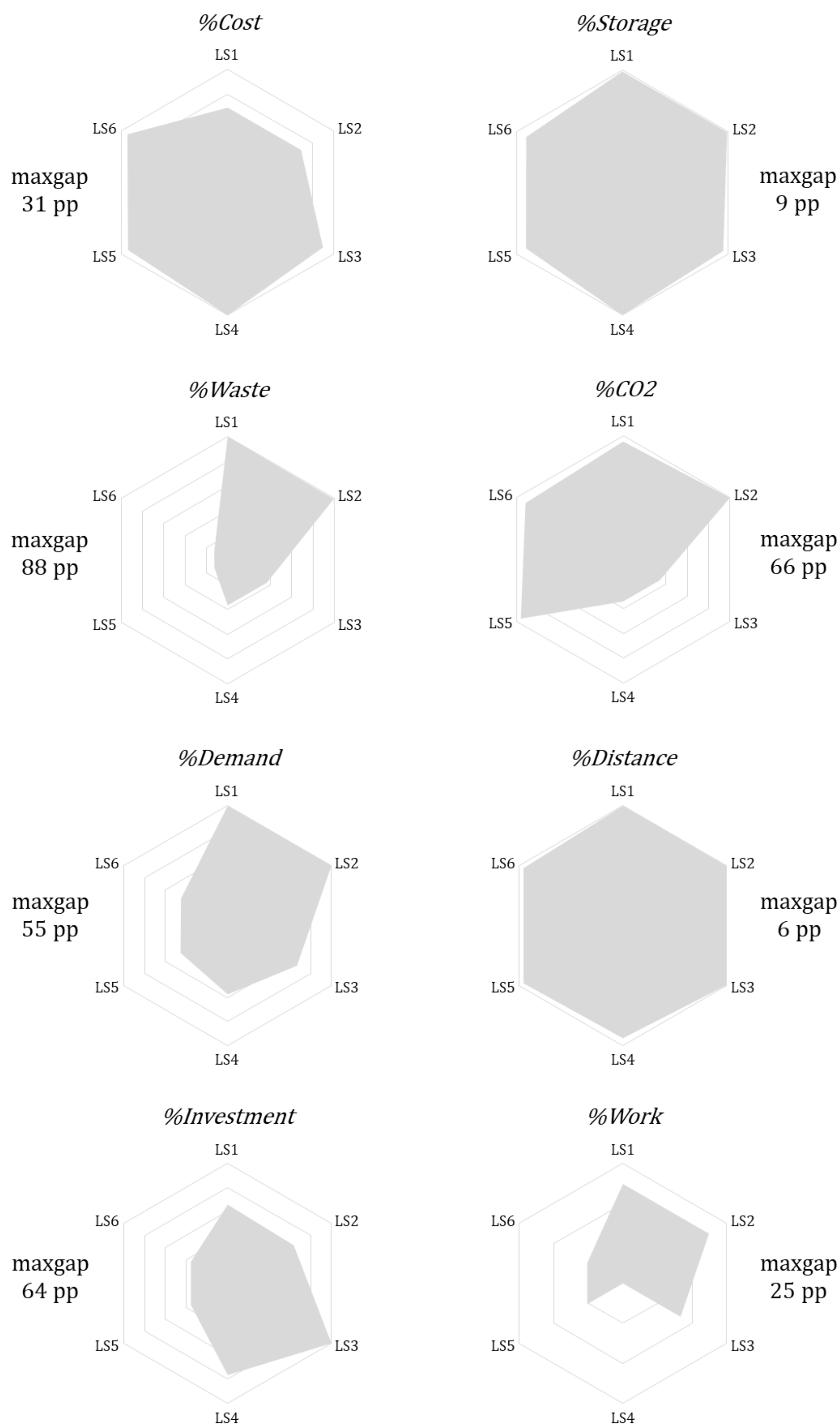


Figure F.2: Comparison of lexicographic solutions per selected KPI

Appendix G

Case C6: Work value

Choosing to benefit the creation of social work value is represented by the weighting options of case C6. In this case the third term of the social objective function has the highest importance corresponding to a weight factor of $\alpha_7 = 0.4$. The remaining social terms are included with an associated weight of 0.15 each. In addition, the decision keeps a neutral positioning in regard to the environmental factors that are weighted at 0.5 each.

Table G.1 presents the results obtained for the lexicographic solutions of this case.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective functions values						
Economic (m.u.)	6,690.3	6,690.3	8,694.0	9,833.0	9,377.8	9,418.5
Environmental (k€)	462.9	474.7	166.8	166.8	348.5	340.5
Social	-66.0	-64.6	4.0	120.4	183.9	183.9
Food banks						
Banks closed (#)	1.6	1.6	1.6	0.3	0.3	0.3
Banks opened (#)	0.6	0.6	0.8	0.5	-	-
Operating banks (#)	3.0	3.0	3.2	4.4	3.8	3.8
Total storage capacity added (t)	1,574.5	1,574.5	3,153.0	3,011.1	1,511.4	1,511.4
dry products	556.1	556.1	909.9	657.2	-	-
fresh products	994.2	994.2	2,182.1	2,291.6	1,474.4	1,474.4
frozen products	24.3	24.3	61.0	62.3	37.1	37.1

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total transp. capacity added (t)	90.1	81.7	303.3	304.1	55.6	55.6
dry products	-	-	67.4	67.4	-	-
fresh products	85.9	79.2	232.5	232.5	50.6	50.6
frozen products	4.2	2.5	3.4	4.2	5.1	5.1
Storage capacity utilization (%)						
dry products	18.1	18.1	22.3	17.9	22.1	22.1
fresh products	42.9	42.9	43.2	37.1	45.9	46.3
frozen products	22.2	22.2	25.7	24.2	32.2	32.3
Transport capacity utilization (%)						
dry products	11.6	12.1	6.4	4.8	10.6	10.3
fresh products	30.6	31.1	15.1	12.4	31.1	30.9
frozen products	13.5	15.4	4.8	1.4	13.8	14.1
Flow between food banks (t)	2.7	2.7	-	-	184.3	170.2
Charities						
Included (#)	-	-	1.8	2.8	3.0	3.0
Included (%)	-	-	60.0	93.3	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	80.5	78.9	82.7	82.8
of served charities HC	-	-	49.3	67.8	80.8	81.1
of served charities C	69.9	69.9	79.9	78.3	82.4	82.6
of all charities HC	-	-	30.1	65.0	80.8	81.1
of all charities C	59.1	59.1	72.7	76.7	82.4	82.6
Max. unsatisfied demand (δ^t)	2.7	2.7	1.5	0.7	0.5	0.5
Min. assigned to a bank (#)	2.4	2.4	3.1	1.5	1.7	1.7
Max. assigned to a bank (#)	10.5	10.5	9.2	8.8	10.3	10.1
Changes in assignments banks-charities (#)	-	-	1.9	0.9	-	-
Assignments (#) to						
food bank 1	0.3	0.3	1.5	2.2	2.2	2.2
food bank 2	1.5	1.4	1.8	3.0	2.4	2.4
food bank 3	2.9	2.9	4.1	4.0	4.4	4.5
food bank 4	10.0	10.0	7.0	7.3	10.1	10.0
food bank 5	1.4	1.5	2.9	2.1	-	-

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Max. distance to an assigned bank (d.u.) (ε^t)	236.8	236.1	235.5	213.8	222.1	222.1
Donations						
Total food donations (k€)	11,019.7	11,019.7	13,675.7	14,382.6	15,373.2	15,411.2
Total food donations (t)	13,774.3	13,774.3	16,940.2	17,852.2	19,131.3	19,178.2
from donors DD (%)	76.3	76.1	85.2	80.8	74.6	74.8
from donors CD (%)	22.0	22.4	11.0	10.4	16.7	16.4
from donors FD (%)	1.7	1.5	3.8	8.7	8.7	8.8
Unused financial donations (k€)	1,059.3	1,063.9	706.7	-	6.5	-
Unused financial donations (%)	79.4	80.0	54.1	-	0.4	-
Network flows						
Flows donors-food banks (#)	129.8	134.0	139.8	181.0	178.4	178.0
from donors DD (%)	72.8	73.6	84.3	78.2	67.0	67.3
from donors CD (%)	21.3	20.8	6.7	5.5	15.9	15.5
from donors FD (%)	6.0	5.6	9.0	16.3	17.1	17.2
Flows between food banks (#)	0.2	0.2	-	-	4.6	4.5
Flows food banks-charities (#)	387.5	388.1	434.1	470.0	478.5	475.5
Environmental indicators						
Total food waste (k€)	278.6	276.9	102.9	102.9	27.7	26.4
Total food waste (t)	4,362.5	4,337.1	1,613.0	1,612.9	430.7	409.2
Total food waste (%)	24.4	24.3	8.9	8.9	2.0	1.9
donors DD share (%)	90.0	91.1	0.2	0.2	38.8	23.4
donors CD share (%)	10.0	8.9	99.8	99.8	61.2	76.6
of donors DD offer (%)	27.9	28.1	-	-	0.9	0.5
of donors CD offer (%)	8.8	6.6	53.0	53.0	4.5	6.3
Total CO_2 emissions ((k€)	647.2	672.5	230.8	230.8	669.2	654.6
Total CO_2 (t-d.u.)	746,089.2	773,318.9	265,194.1	265,200.0	769,902.2	753,519.9
Social indicators (others)						
Total social work (k€)	2,077.5	2,077.5	2,305.3	2,832.3	2,538.4	2,538.4

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total investment capital required (% of reference budget)	42.3	41.9	65.0	51.7	25.1	25.1
Periods with investment (#)	1.1	1.1	1.3	1.2	1.0	1.1
Periods over budget (#)	0.9	0.9	1.1	0.9	0.6	0.6

Table G.1: Characteristics of the lexicographic solutions: average over 20 instances. Case C6

Figure G.1 shows the performance of each solution in terms of the main KPIs selected for their characterization. The description of these KPIs is presented in Section 7.2.3. The bar charts illustrate the values of the objective functions for each solution. For representation purposes, the value of the economic objective is depicted in a scale 1:10.

Stressing the contribution of the food bank supply chain to the generation of social work value, as conveyed by the value of human resources required to manage it, and measured on the basis of the total storage capacity available in the network, leads to results that are indistinguishable from those of case C1. The six radar charts of Figure G.1, particularly the bottom two that concern the social results, are identical to representation of the results obtained for the neutral case (cf. Figure 7.14 on page 165).

Observing that larger areas correspond to worst performances of the solution in relation the values registered by other solutions, Figure G.2 presents the relative results of the six instances in terms of each KPI.

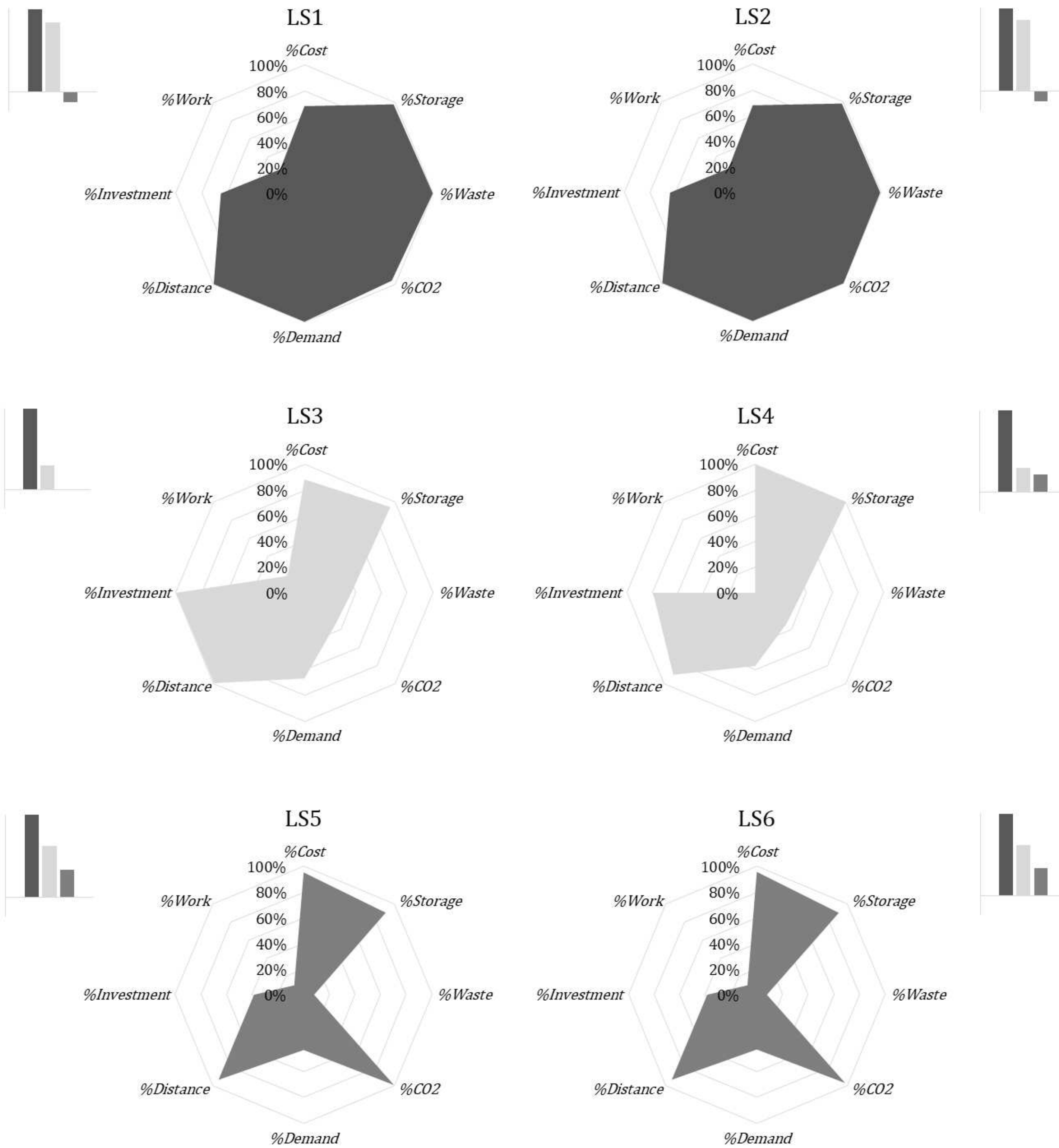


Figure G.1: Comparison of selected KPIs per lexicographic solution

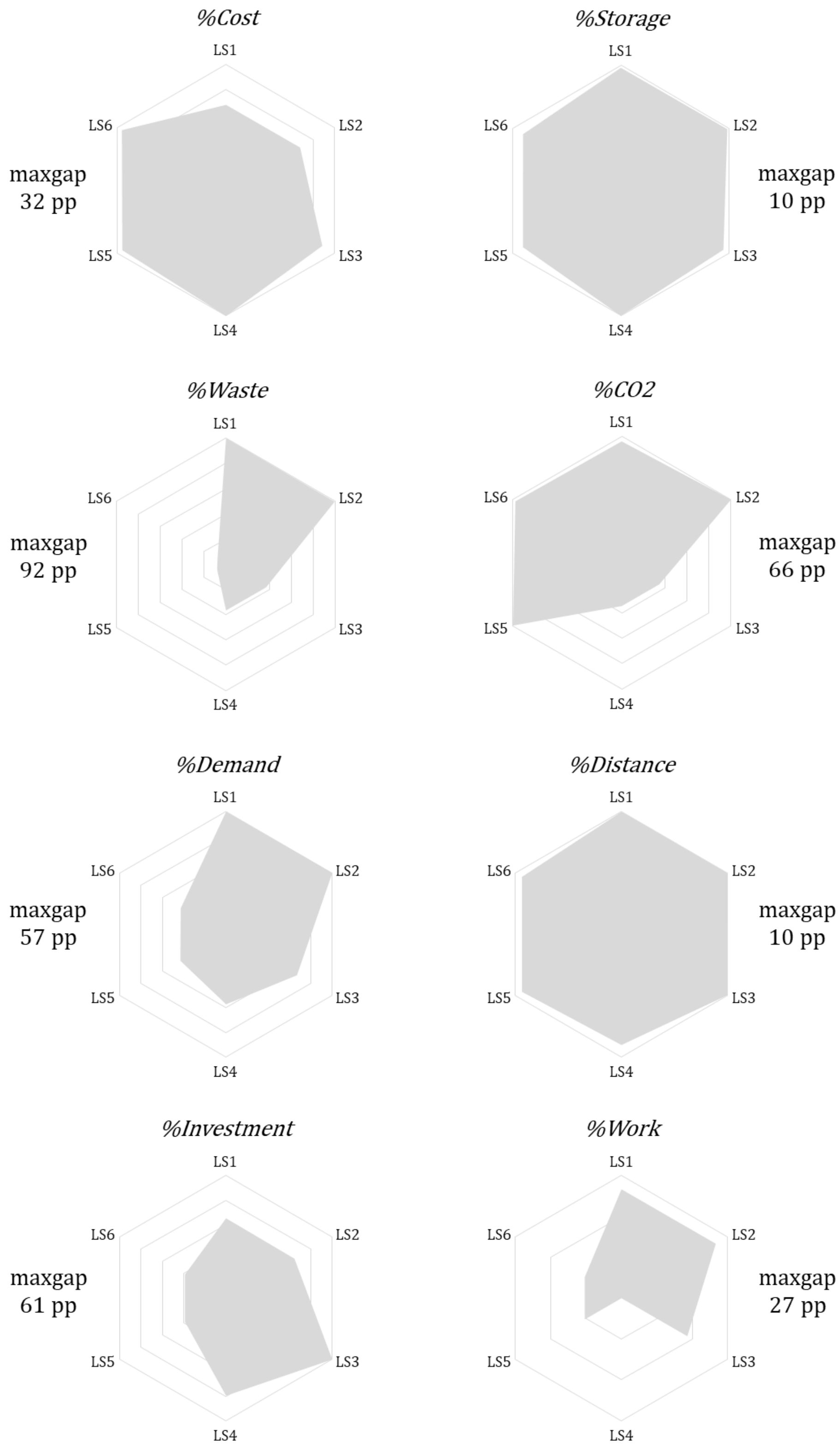


Figure G.2: Comparison of lexicographic solutions per selected KPI

Appendix H

Case C7: Proximity

The intention of decision maker represented by the weighting options of case C7 is to redesign the food bank supply chain favoring the proximity of charities to the assigned food banks. To that end, the weight factor associated with the term that identifies the maximum distance between served charities and the corresponding food banks (α_8) has the largest value of all social weight factors (0.4). The remaining weights of the social objective function have the value 0.15. No preference is expressed concerning the two environmental factors. Accordingly each one is weighted at 0.5.

Table H.1 presents the results obtained for the lexicographic solutions of this case.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective functions values						
Economic (m.u.)	6,690.3	6,690.3	8,688.9	9,767.5	9,771.2	9,802.1
Environmental (k€)	463.3	477.2	166.8	166.8	337.2	330.5
Social	-191.6	-189.6	-121.0	8.8	72.7	72.7
Food banks						
Banks closed (#)	1.6	1.6	1.6	0.5	0.4	0.4
Banks opened (#)	0.6	0.6	0.8	0.6	0.3	0.3
Operating banks (#)	3.0	3.0	3.2	4.3	3.9	3.9
Total storage capacity added (t)	1,574.5	1,574.5	3,153.0	3,037.4	2,119.7	2,119.7
dry products	556.1	556.1	909.9	758.3	252.8	252.8
fresh products	994.2	994.2	2,182.1	2,215.8	1,819.8	1,819.8

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
frozen products	24.3	24.3	61.0	63.4	47.2	47.2
Total transp. capacity added (t)	91.8	88.5	303.3	304.1	59.0	59.0
dry products	-	-	67.4	67.4	-	-
fresh products	87.6	85.9	232.5	232.5	50.6	50.6
frozen products	4.2	2.5	3.4	4.2	8.4	8.4
Storage capacity utilization (%)						
dry products	18.1	18.1	22.3	18.2	21.5	21.4
fresh products	42.9	42.9	43.2	37.4	43.6	43.7
frozen products	22.2	22.2	25.7	24.2	30.3	30.3
Transport capacity utilization (%)						
dry products	11.6	12.1	6.4	4.9	10.4	10.3
fresh products	30.6	31.2	15.1	12.4	30.0	29.5
frozen products	13.5	15.4	4.8	2.4	14.3	14.3
Flow between food banks (t)	2.7	2.7	-	-	91.4	84.1
Charities						
Included (#)	-	-	1.8	2.8	3.0	3.0
Included (%)	-	-	60.0	93.3	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	80.4	78.9	83.3	83.3
of served charities HC	-	-	50.3	67.9	81.8	81.8
of served charities C	69.9	69.9	79.9	78.3	83.1	83.1
of all charities HC	-	-	30.5	65.0	80.3	80.3
of all charities C	59.1	59.1	72.7	76.7	82.8	82.9
Max. unsatisfied demand (δ^t)	2.7	2.7	1.5	0.7	0.4	0.4
Min. assigned to a bank (#)	2.4	2.4	3.1	1.5	1.8	1.9
Max. assigned to a bank (#)	10.5	10.5	9.2	8.7	9.0	8.8
Changes in assignments banks-charities (#)	-	-	1.9	0.9	-	-
Assignments (#) to						
food bank 1	0.3	0.3	1.4	2.0	2.2	2.2
food bank 2	1.4	1.4	1.8	2.5	2.3	2.2
food bank 3	2.9	2.9	4.1	4.6	5.2	5.4
food bank 4	10.0	10.0	7.0	6.9	8.2	8.0

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
food bank 5	1.5	1.5	2.9	2.7	1.2	1.2
Max. distance to an assigned bank (d.u.) (ε^t)	236.8	236.1	236.3	208.0	195.1	195.1
Donations						
Total food donations (k€)	11,019.7	11,019.7	13,676.1	14,382.5	15,469.7	15,471.8
Total food donations (t)	13,774.3	13,774.3	16,940.5	17,852.0	19,254.1	19,257.2
from donors DD (%)	76.3	75.9	85.2	80.9	74.7	74.9
from donors CD (%)	22.0	22.6	11.0	10.4	16.5	16.4
from donors FD (%)	1.7	1.5	3.8	8.7	8.7	8.8
Unused financial donations (k€)	1,063.0	1,069.4	706.7	-	-	-
Unused financial donations (%)	79.6	80.3	54.1	-	-	-
Network flows						
Flows donors-food banks (#)	129.4	132.6	141.5	177.5	179.9	180.2
from donors DD (%)	73.1	73.5	84.5	77.7	67.6	67.9
from donors CD (%)	21.1	20.9	6.6	5.6	16.7	16.3
from donors FD (%)	5.8	5.6	8.9	16.7	15.7	15.7
Flows between food banks (#)	0.2	0.2	-	0.1	3.2	3.3
Flows food banks-charities (#)	387.0	388.1	440.7	465.9	474.7	474.5
Environmental indicators						
Total food waste (k€)	278.3	276.5	102.9	102.9	21.2	21.4
Total food waste (t)	4,358.0	4,330.3	1,613.0	1,612.9	330.1	333.8
Total food waste (%)	24.4	24.2	8.9	8.9	1.5	1.6
donors DD share (%)	90.1	91.9	0.2	0.2	13.6	4.7
donors CD share (%)	9.9	8.1	99.8	99.8	86.4	95.3
of donors DD offer (%)	27.9	28.3	-	-	0.3	0.1
of donors CD offer (%)	9.0	6.2	53.0	53.0	4.7	5.7
Total CO_2 emissions ((k€)	648.2	677.9	230.8	230.8	653.2	639.5
Total CO_2 (t-d.u.)	747,283.0	779,454.9	265,194.1	265,196.2	751,518.5	735,906.6
Social indicators (others)						

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Total social work (k€)	2,077.5	2,077.5	2,305.3	2,785.5	2,638.5	2,638.5
Total investment capital required (% of reference budget)	42.7	42.0	65.0	53.5	34.5	34.5
Periods with investment (#)	1.1	1.1	1.3	1.1	1.0	1.0
Periods over budget (#)	0.9	0.9	1.1	1.0	0.8	0.8

Table H.1: Characteristics of the lexicographic solutions: average over 20 instances. Case C7

Figure H.1 shows the performance of each solution in terms of the main KPIs selected for their characterization. The description of these KPIs is presented in Section 7.2.3. The bar charts illustrate the values of the objective functions for each solution. For representation purposes, the value of the economic objective is depicted in a scale 1:10.

Endorsing the proximity of charities to the assigned serving facilities as the main social objective results in two chief differences from the case whereby the decision maker has a neutral positioning in regard to the social objectives. As noted in Section 7.2.5, and identified in the two bottom charts of Figure H.1, preferring the proximity factor allows an improvement of KPI *%Distance*, but also demands a deterioration of KPI *%Investment* in relation to the performance registered in the neutral case. Otherwise, the impacts in the other KPIs are not significant enough to further change the shape of the area depicted in the radar charts pertaining to solutions LS5-LS6.

Observing that larger areas correspond to worst performances of the solution in relation to the values registered by other solutions, Figure H.2 presents the relative results of the six solutions in terms of each KPI.

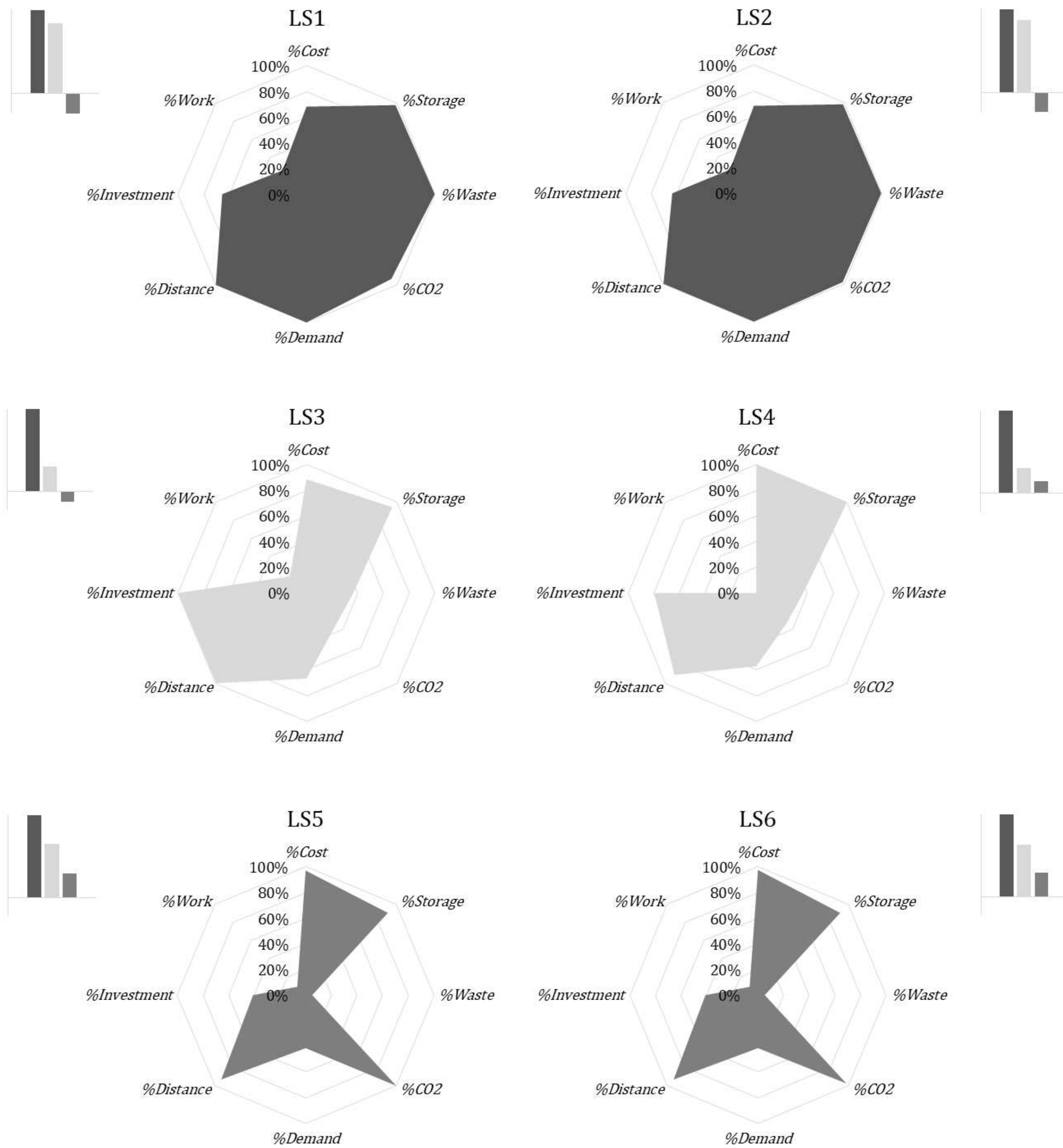


Figure H.1: Comparison of selected KPIs per lexicographic solution

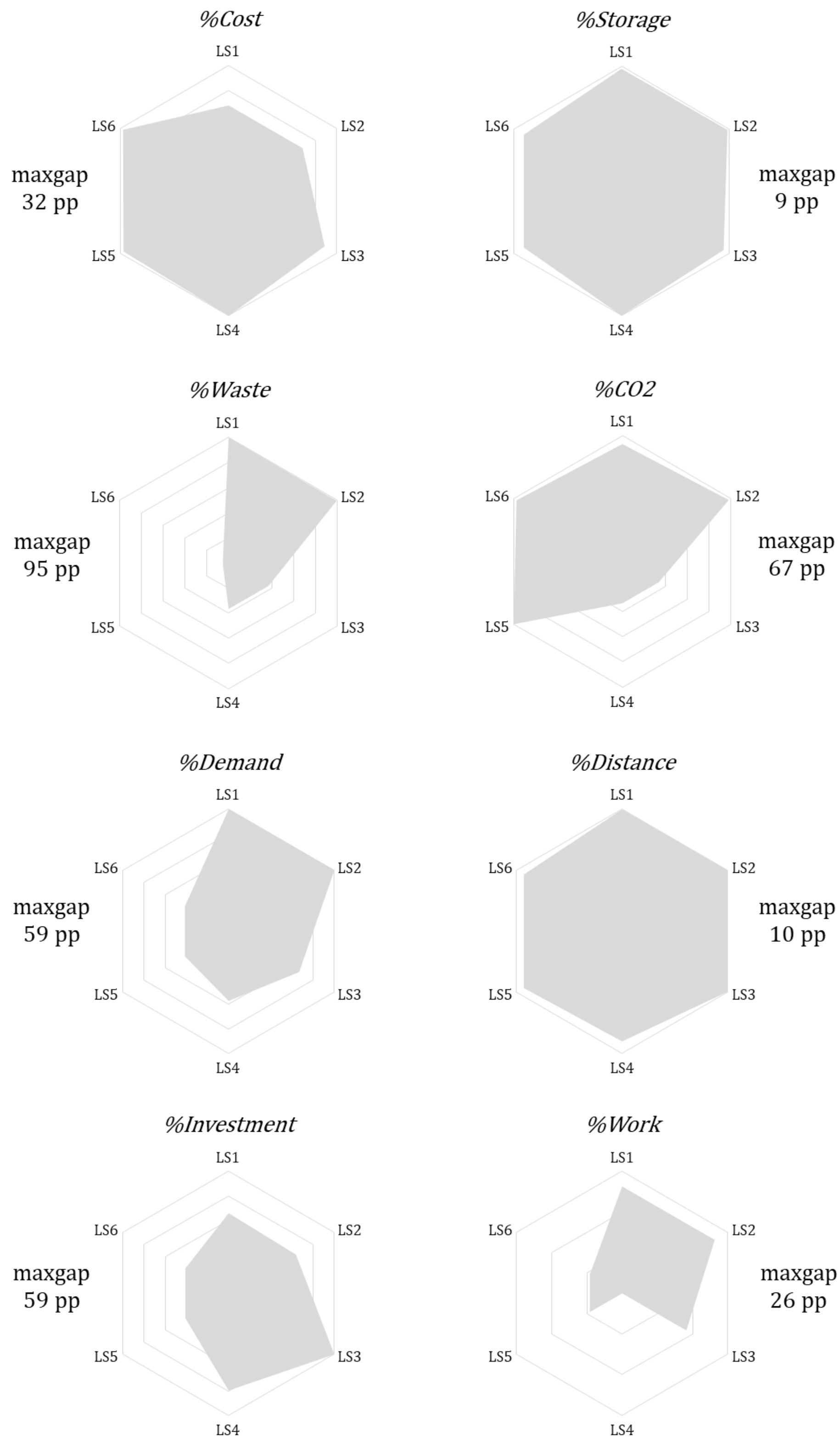


Figure H.2: Comparison of lexicographic solutions per selected KPI

Appendix I

Case C8: Equity

The objective of the decision maker of case C8 is to benefit primarily the balanced redistribution of products among the charities served by the supply chain. Focusing on the level of equity ensured by the institution corresponds to weighting the five social criteria in favor of the last term of the social objective function. Thus, in case C8 this last term in weighted with $\alpha_9 = 0.40$, and the other social terms are included with an associated weight of 0.15 each. Following a neutral positioning in regard to the environmental criteria, each term in the environmental objective function is weighted at 0.5.

Table I.1 presents the results obtained for the lexicographic solutions of this case.

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Objective functions values						
Economic (m.u.)	6,690.3	6,690.3	8,694.0	9,803.0	9,521.1	9,566.5
Environmental (k€)	463.0	477.2	166.8	166.8	355.4	346.5
Social	-206.1	-202.8	-73.9	80.5	159.0	159.0
Food banks						
Banks closed (#)	1.6	1.6	1.6	0.3	0.3	0.3
Banks opened (#)	0.6	0.6	0.8	0.5	-	-
Operating banks (#)	3.0	3.0	3.2	4.3	3.8	3.8
Total storage capacity added (t)	1,574.5	1,574.5	3,153.0	3,004.0	1,582.9	1,582.9
dry products	556.1	556.1	909.9	657.2	-	-

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
fresh products	994.2	994.2	2,182.1	2,283.2	1,541.8	1,541.8
frozen products	24.3	24.3	61.0	63.7	41.1	41.1
Total transp. capacity added (t)	91.8	86.8	303.3	304.1	71.6	71.6
dry products	-	-	67.4	67.4	-	-
fresh products	87.6	84.3	232.5	232.5	64.0	64.0
frozen products	4.2	2.5	3.4	4.2	7.6	7.6
Storage capacity utilization (%)						
dry products	18.1	18.1	22.3	18.0	22.3	22.2
fresh products	42.9	42.9	43.2	37.2	45.4	45.4
frozen products	22.2	22.2	25.7	24.2	32.3	32.4
Transport capacity utilization (%)						
dry products	11.6	12.1	6.4	4.8	10.7	10.6
fresh products	30.6	31.1	15.1	12.4	31.3	31.1
frozen products	13.5	15.4	4.8	2.4	14.3	14.6
Flow between food banks (t)	2.7	2.7	-	-	197.3	176.3
Charities						
Included (#)	-	-	1.8	2.8	3.0	3.0
Included (%)	-	-	60.0	93.3	100.0	100.0
Avg. satisfied demand (%)						
of all charities SC	69.9	69.9	80.5	78.9	83.3	83.4
of served charities HC	-	-	49.0	67.9	81.9	81.8
of served charities C	69.9	69.9	79.9	78.3	83.1	83.1
of all charities HC	-	-	30.0	65.0	81.9	81.8
of all charities C	59.1	59.1	72.7	76.7	83.1	83.1
Max. unsatisfied demand (δ^t)	2.7	2.7	1.5	0.7	0.4	0.4
Min. assigned to a bank (#)	2.4	2.4	3.1	1.6	1.9	1.9
Max. assigned to a bank (#)	10.5	10.5	9.2	8.8	10.4	10.2
Changes in assignments banks-charities (#)	-	-	1.9	0.9	-	-
Assignments (#) to						
food bank 1	0.3	0.3	1.5	2.2	2.4	2.4
food bank 2	1.4	1.4	1.8	3.0	2.3	2.3
food bank 3	2.9	2.9	4.1	4.0	4.2	4.5

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
food bank 4	10.0	10.0	7.0	7.3	10.1	9.9
food bank 5	1.5	1.5	2.9	2.1	-	-
Max. distance to an assigned bank (d.u.) (ε^t)	236.8	236.1	235.5	213.8	220.4	220.4
Donations						
Total food donations (k€)	11,019.7	11,019.7	13,675.7	14,382.6	15,506.3	15,507.4
Total food donations (t)	13,774.3	13,774.3	16,940.2	17,853.3	19,314.0	19,315.1
from donors DD (%)	76.3	75.9	85.2	80.8	74.3	74.3
from donors CD (%)	22.0	22.6	11.0	10.4	17.0	16.9
from donors FD (%)	1.7	1.5	3.8	8.7	8.8	8.8
Unused financial donations (k€)	1,063.0	1,069.5	706.7	-	-	-
Unused financial donations (%)	79.6	80.3	54.1	-	-	-
Network flows						
Flows donors-food banks (#)	129.1	132.5	139.8	179.6	178.3	178.7
from donors DD (%)	73.1	73.7	84.1	78.5	67.9	67.5
from donors CD (%)	21.1	20.8	6.7	5.5	15.8	15.6
from donors FD (%)	5.8	5.5	9.2	16.1	16.3	17.0
Flows between food banks (#)	0.2	0.2	-	0.1	4.9	4.7
Flows food banks-charities (#)	387.0	388.1	433.4	471.6	476.0	476.1
Environmental indicators						
Total food waste (k€)	278.3	276.5	102.9	102.9	18.4	18.8
Total food waste (t)	4,358.0	4,330.3	1,613.0	1,612.9	285.8	291.7
Total food waste (%)	24.4	24.2	8.9	8.9	1.3	1.3
donors DD share (%)	90.1	91.9	0.2	0.2	32.3	29.4
donors CD share (%)	9.9	8.1	99.8	99.8	67.7	70.6
of donors DD offer (%)	27.9	28.3	-	-	0.5	0.5
of donors CD offer (%)	8.8	6.1	53.0	53.0	2.8	3.2
Total CO_2 emissions ((k€)	647.6	677.9	230.8	230.8	692.4	674.2
Total CO_2 (t-d.u.)	746,581.7	779,429.8	265,194.1	265,198.9	796,614.6	775,907.0

Features	Lexicographic solutions					
	Economic-centric		Environmental-centric		Social-centric	
	LS1	LS2	LS3	LS4	LS5	LS6
Social indicators (others)						
Total social work (k€)	2,077.5	2,077.5	2,305.3	2,818.6	2,559.8	2,559.8
Total investment capital required (% of reference budget)	42.7	41.4	65.0	51.8	26.6	26.6
Periods with investment (#)	1.1	1.0	1.3	1.2	1.0	1.0
Periods over budget (#)	0.9	0.9	1.1	0.9	0.6	0.6

Table I.1: Characteristics of the lexicographic solutions: average over 20 instances. Case C8

Figure I.1 shows the performance of each solution in terms of the main KPIs selected for their characterization. The description of these KPIs is presented in Section 7.2.3. The bar charts illustrate the values of the objective functions for each solution. For representation purposes, the value of the economic objective is depicted in a scale 1:10.

In Section 7.2.5, impacts of favoring the equity objective include an increase in demand satisfaction level, reduction of food waste and larger carbon footprint cost, and other marginal changes in relation to case C1. However, the two bottom charts of Figure I.1 do not exhibit noticeable differences from the corresponding charts of Figure 7.14 on page 165 that illustrates the neutral case. It is therefore concluded that, in relation to the other solutions of case C8, the characterization of solutions LS5-LS6 on the basis of the selected KPIs is identical to case C1.

Observing that larger areas correspond to worst performances of the solution in relation the values registered by other solutions, Figure I.2 presents the relative results of the six solutions in terms of each KPI.

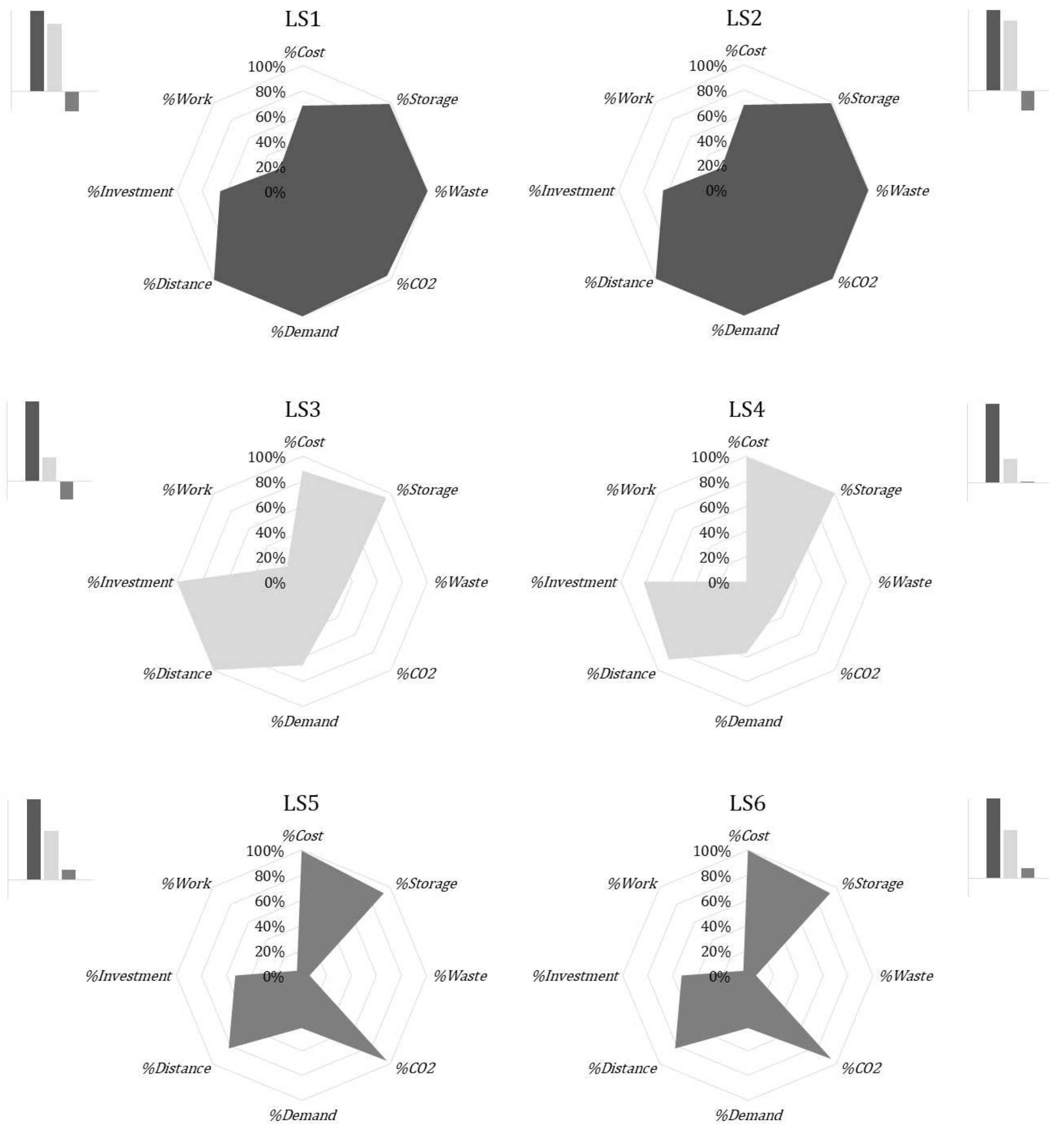


Figure I.1: Comparison of selected KPIs per lexicographic solution

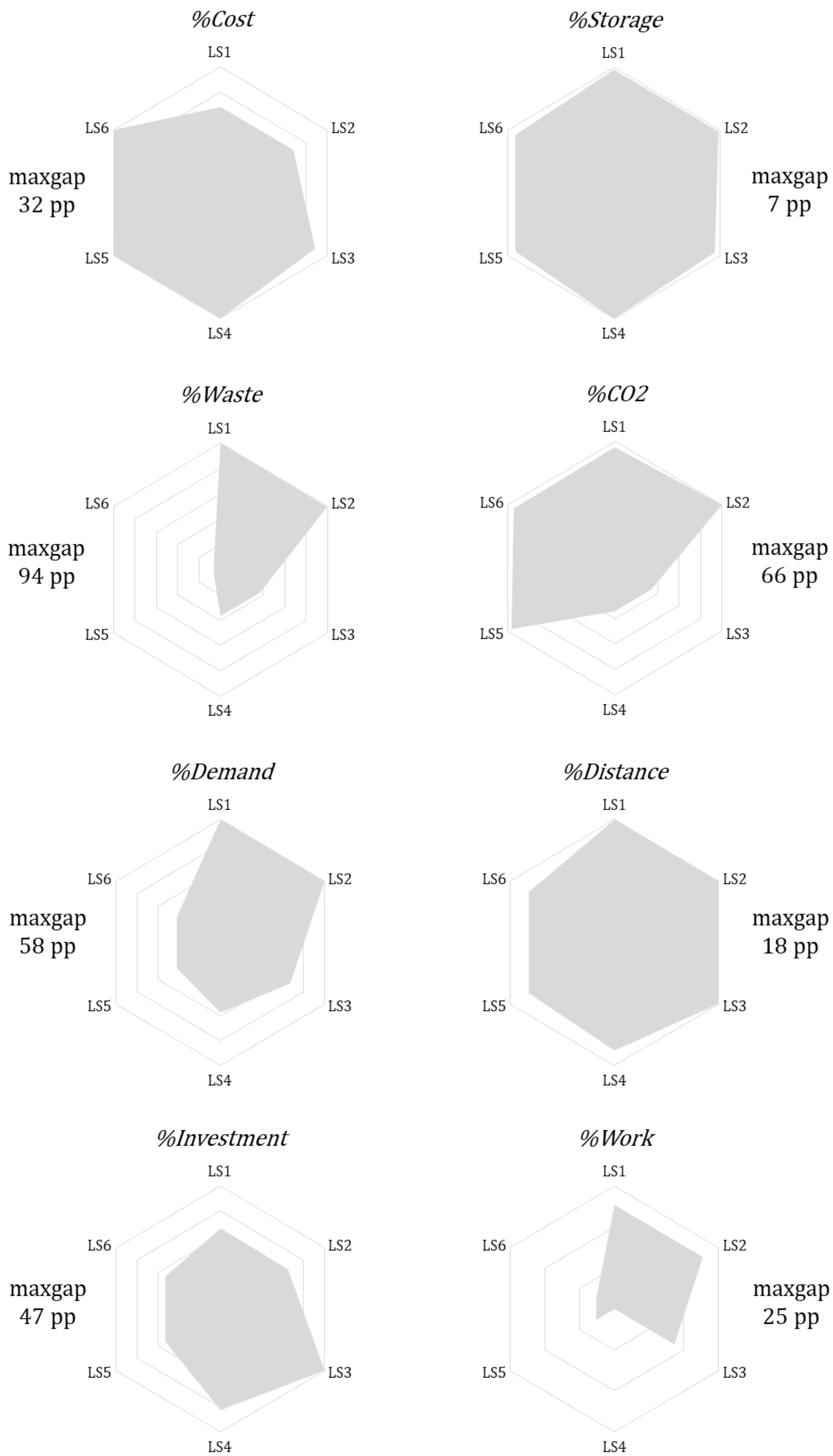


Figure I.2: Comparison of lexicographic solutions per selected KPI

Appendix J

Results with constraints (5.29)–(5.30)

Table J.1 presents the results obtained for the 20 regional instances running the MO-MILP model with constraints (5.29) and (5.30). Results concern the objective function values of the six lexicographic solutions, and respective CPU time in seconds. For each instance, results obtained in the second run are expressed in percent of the values obtained in the first run (Dif. (%)).

One run (for one instance) is understood as corresponding to one solving cycle of the MO-MILP on the basis of the solving algorithm, which involves solving 15 single objective MILP problems.

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 1									
1st run	6,946.32	328.02	-31.47	6,946.32	331.32	-28.34	8,985.09	124.25	-22.09
2nd run	6,946.32	322.64	-31.47	6,946.32	331.32	-28.16	8,985.09	124.25	-22.02
Dif. (%)	-	-1.64	-	-	-	-0.64	-	-	-0.32
Instance 2									
1st run	5,649.64	531.74	-151.83	5,649.64	543.05	-150.69	7,901.94	185.55	-24.24
2nd run	5,649.64	531.74	-151.83	5,649.64	543.05	-150.69	7,901.94	185.55	-24.24
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 3									
1st run	5,508.80	469.31	-133.36	5,508.80	477.54	-132.29	9,058.42	175.41	25.21
2nd run	5,508.80	469.31	-133.36	5,508.80	477.54	-132.29	9,058.42	175.41	25.19
Dif. (%)	-	-	-	-	-	-	-	-	-0.08
Instance 4									
1st run	7,917.26	584.50	-91.71	7,917.26	629.03	-82.55	10,912.57	322.19	-63.74
2nd run	7,917.26	584.50	-91.71	7,917.26	629.03	-82.55	10,912.57	322.19	-63.85
Dif. (%)	-	-	-	-	-	-	-	-	0.17
Instance 5									
1st run	7,927.27	360.79	-84.99	7,927.27	375.16	-84.80	9,535.98	168.14	23.89
2nd run	7,927.27	360.79	-84.99	7,927.27	375.16	-84.80	9,535.98	168.14	23.89
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 6									
1st run	7,300.28	291.43	-6.42	7,300.28	300.07	-6.37	9,020.60	120.35	3.94
2nd run	7,300.28	291.43	-6.42	7,300.28	300.07	-6.37	9,020.60	120.35	5.49
Dif. (%)	-	-	-	-	-	-	-	-	39.34
Instance 7									
1st run	6,801.58	324.42	-46.94	6,801.58	333.76	-46.88	7,769.32	130.96	32.66
2nd run	6,801.58	324.42	-46.94	6,801.58	333.76	-46.88	7,769.32	130.96	32.66
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 8									
1st run	8,906.57	418.17	-98.05	8,906.57	424.73	-82.09	12,120.36	181.80	12.99
2nd run	8,906.57	418.17	-98.05	8,906.57	424.73	-82.09	12,120.47	181.79	12.62
Dif. (%)	-	-	-	-	-	-	-	-	-2.85
Instance 9									
1st run	6,845.02	467.73	-125.02	6,845.02	477.41	-123.87	9,327.95	192.67	27.95
2nd run	6,845.02	467.73	-125.02	6,845.02	477.41	-123.87	9,327.95	192.67	27.95
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 10									
1st run	6,600.57	783.65	-39.86	6,600.57	800.41	-39.57	8,941.97	140.58	-80.15
2nd run	6,600.57	783.65	-39.86	6,600.57	800.41	-39.57	8,941.97	140.58	-80.02
Dif. (%)	-	-	-	-	-	-	-	-	-0.16

Continues on page 292

LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
10,281.92	124.25	235.01	9,668.88	288.19	267.66	9,670.22	287.99	267.66	865.23
10,281.92	124.25	235.01	9,668.88	288.19	267.66	9,670.22	287.99	267.66	771.67
-	-	-	-	-	-	-	-	-	-10.81
8,520.69	185.55	40.54	9,609.98	305.57	229.36	9,614.99	305.21	229.36	5,900.14
8,520.69	185.55	40.54	9,609.98	305.57	229.36	9,614.99	305.21	229.36	5,877.23
-	-	-	-	-	-	-	-	-	-0.39
10,675.22	175.41	165.99	9,906.36	280.25	252.61	9,906.53	280.23	252.61	435.14
10,675.22	175.41	165.99	9,906.36	280.25	252.61	9,906.53	280.23	252.61	454.80
-	-	-	-	-	-	-	-	-	4.52
11,669.62	322.19	82.17	10,213.39	661.47	172.08	10,230.10	647.35	172.08	1,336.02
11,669.62	322.19	82.17	10,213.39	661.47	172.08	10,230.10	647.35	172.08	1,681.13
-	-	-	-	-	-	-	-	-	25.83
10,364.08	168.14	125.60	9,718.57	235.83	229.17	10,017.16	182.82	229.17	958.92
10,364.08	168.14	125.60	9,718.57	235.83	229.17	10,017.16	182.82	229.17	951.44
-	-	-	-	-	-	-	-	-	-0.78
10,161.85	120.35	173.59	9,695.52	200.45	246.26	9,697.18	200.41	246.26	1,344.31
10,161.85	120.35	173.59	9,695.52	200.45	246.26	9,697.18	200.41	246.26	1,384.05
-	-	-	-	-	-	-	-	-	2.96
9,190.82	130.96	194.27	9,485.96	190.85	213.11	9,551.10	190.48	213.11	2,031.47
9,190.82	130.96	194.27	9,485.96	190.85	213.11	9,551.10	190.48	213.11	2,483.84
-	-	-	-	-	-	-	-	-	22.27
13,661.71	181.80	117.48	12,114.90	363.49	219.50	12,167.02	363.39	219.50	788.20
13,661.66	181.79	117.47	12,114.90	363.49	219.50	12,167.02	363.39	219.50	818.42
-	-	-0.01	-	-	-	-	-	-	3.83
10,661.84	192.67	218.37	10,423.18	284.19	243.18	10,443.63	275.17	243.18	6,302.28
10,661.84	192.67	218.37	10,423.18	284.19	243.18	10,443.63	275.17	243.18	5,901.67
-	-	-	-	-	-	-	-	-	-6.36
9,433.66	140.58	112.53	8,483.91	672.46	265.52	8,486.92	672.21	265.52	831.53
9,433.66	140.58	112.53	8,483.91	672.46	265.52	8,486.92	672.21	265.52	916.89
-	-	-	-	-	-	-	-	-	10.27

Continues on page 293

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 11									
1st run	5,646.06	366.01	-106.25	5,646.06	373.57	-105.47	7,575.69	171.12	53.51
2nd run	5,646.06	366.01	-106.25	5,646.06	373.57	-105.47	7,575.69	171.12	53.51
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 12									
1st run	7,362.24	707.64	-146.56	7,362.24	730.34	-145.95	8,454.39	212.76	3.46
2nd run	7,362.24	707.64	-146.56	7,362.24	730.34	-145.95	8,454.39	212.76	3.46
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 13									
1st run	6,395.30	221.38	-85.19	6,395.30	222.25	-85.07	8,214.31	95.57	57.70
2nd run	6,395.30	221.38	-85.19	6,395.30	222.25	-85.07	8,214.31	95.57	57.70
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 14									
1st run	6,080.13	450.71	-96.51	6,080.13	462.90	-95.51	6,922.53	170.51	2.73
2nd run	6,080.13	450.71	-96.51	6,080.13	462.90	-95.51	6,922.53	170.51	2.69
Dif. (%)	-	-	-	-	-	-	-	-	-1.47
Instance 15									
1st run	6,094.42	505.57	-82.61	6,094.42	529.95	-75.57	7,527.19	142.14	63.95
2nd run	6,094.42	505.57	-82.61	6,094.42	529.95	-75.57	7,527.19	142.14	64.16
Dif. (%)	-	-	-	-	-	-	-	-	0.33
Instance 16									
1st run	5,342.73	384.29	-85.39	5,342.73	399.58	-84.34	6,410.27	152.04	-58.74
2nd run	5,342.73	384.29	-85.39	5,342.73	399.58	-84.34	6,410.27	152.04	-58.69
Dif. (%)	-	-	-	-	-	-	-	-	-0.09
Instance 17									
1st run	7,710.26	719.37	-79.79	7,710.26	731.50	-79.59	9,782.74	206.12	27.73
2nd run	7,710.26	719.37	-79.79	7,710.26	731.50	-79.59	9,782.74	206.12	27.73
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 18									
1st run	6,018.74	546.19	-200.95	6,018.74	562.22	-200.24	9,720.90	157.10	90.20
2nd run	6,018.74	546.19	-200.95	6,018.74	562.22	-200.24	9,720.90	157.10	89.38
Dif. (%)	-	-	-	-	-	-	-	-	-0.91
Instance 19									
1st run	6,448.16	516.35	-68.83	6,448.16	531.57	-68.14	6,808.57	185.85	-71.22
2nd run	6,448.16	516.35	-68.83	6,448.16	531.57	-68.14	6,808.57	185.85	-71.09
Dif. (%)	-	-	-	-	-	-	-	-	-0.18
Instance 20									
1st run	6,305.45	293.27	-72.95	6,305.45	307.73	-71.81	8,787.94	101.37	-60.49
2nd run	6,305.45	293.27	-72.95	6,305.45	307.73	-71.81	8,787.94	101.37	-60.49
Dif. (%)	-	-	-	-	-	-	-	-	-
Average									
1st run	6,690.34	463.53	-91.73	6,690.34	477.20	-89.46	8,688.94	166.82	2.26
2nd run	6,690.34	463.26	-91.73	6,690.34	477.20	-89.45	8,688.94	166.82	2.30
Dif. (%)	-	-0.06	-	-	-	-0.01	-	-	1.72

Table J.1: Lexicographic solutions and CPU time: two runs on opportunistic mode

LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
8,145.29	171.12	145.24	9,164.29	229.00	234.69	9,165.88	227.87	234.69	1,241.92
8,145.29	171.12	145.24	9,164.29	229.00	234.69	9,165.88	227.87	234.69	1,075.39
-	-	-	-	-	-	-	-	-	-13.41
9,683.90	212.76	145.26	8,979.74	597.44	246.32	8,980.17	597.32	246.32	346.63
9,683.90	212.76	145.26	8,979.74	597.44	246.32	8,980.17	597.32	246.32	564.44
-	-	-	-	-	-	-	-	-	62.84
10,136.71	95.57	241.78	9,224.48	113.94	270.99	9,288.32	103.18	270.99	1,052.28
10,136.71	95.57	241.78	9,224.48	113.94	270.99	9,288.32	103.18	270.99	1,036.80
-	-	-	-	-	-	-	-	-	-1.47
8,159.10	170.51	230.42	8,274.38	233.18	241.33	8,374.08	223.97	241.33	1,148.47
8,159.10	170.51	230.42	8,274.38	233.18	241.33	8,374.08	223.97	241.33	1,250.83
-	-	-	-	-	-	-	-	-	8.91
8,825.47	142.14	181.24	8,183.38	390.08	275.67	8,208.06	370.39	275.67	1,249.59
8,825.47	142.14	181.24	8,183.38	390.08	275.67	8,208.06	370.39	275.67	1,686.61
-	-	-	-	-	-	-	-	-	34.97
7,385.47	152.04	182.58	7,672.68	388.46	243.88	7,690.66	373.08	243.88	5,268.47
7,385.47	152.04	182.58	7,672.68	388.46	243.88	7,690.66	373.08	243.88	3,931.73
-	-	-	-	-	-	-	-	-	-25.37
10,990.92	206.12	159.39	10,124.98	558.34	218.66	10,125.92	558.29	218.66	868.77
10,990.91	206.12	159.39	10,124.98	558.34	218.66	10,125.92	558.29	218.66	944.69
-	-	-	-	-	-	-	-	-	8.74
10,264.92	157.10	161.38	8,035.88	458.57	261.83	8,100.82	439.68	261.83	1,479.64
10,264.89	157.10	161.38	8,035.88	458.57	261.83	8,100.82	439.68	261.83	1,374.72
-	-	-	-	-	-	-	-	-	-7.09
8,498.75	185.85	237.50	10,001.46	338.36	261.67	10,005.53	338.05	261.67	615.27
8,498.75	185.85	237.50	10,001.46	338.36	261.67	10,005.53	338.05	261.67	667.67
-	-	-	-	-	-	-	-	-	8.52
9,310.74	101.37	-22.75	8,581.38	179.85	236.32	8,646.88	173.75	236.32	1,279.69
9,310.74	101.37	-22.75	8,581.38	179.85	236.32	8,646.88	173.75	236.32	1,204.44
-	-	-	-	-	-	-	-	-	-5.88
9,801.13	166.82	156.38	9,378.17	348.50	241.49	9,418.56	340.54	241.49	1,767.20
9,801.13	166.82	156.38	9,378.17	348.50	241.49	9,418.56	340.54	241.49	1,748.92
-	-	-	-	-	-	-	-	-	-1.03

Appendix K

Proof of Lemma 7.2

Regarding initially open food banks $b \in OB$, constraints (5.4) state that if closed, then they can not re-open until the end of the planning horizon. Constraints (5.7) declare that storage capacity of any size, and for any type of product family may only be expanded once throughout the planning horizon, provided the food bank does not close in some period t. Constraints (5.14) limit the quantity of products received by an initially open bank in period t to the departing storage capacity and possible expansions that may have occurred in that facility until that period (inclusive).

Single assignment constraints (5.17), for initially served charities $c \in SC$, and (5.18), for awaiting charities $c \in HC$, limit to one (impose in case $c \in SC$) the largest number of food banks to which charities can be assigned to, in every planning period.

Minimum supply quantities are set by constraints (5.23) for charities $c \in SC$, and by constraints (5.24) for charities $c \in HC$. Moreover, constraints (5.25) state that charities can only be served (in quantities not greater than their demand) by the food bank(s) to which they are assigned to in each period t. Lastly, constraints (5.31) determine that food banks can only (must) distribute, to charities or other food banks, a quantity of every product $p \in P$ equal to the volume received from suppliers or other food banks in each period $t \in T$. Constraints (5.32) define, concerning variables z_{bc}^t and y_b^t, that they can either assume the value zero or the value one.

If all these conditions are verified, i.e. assuming constraints (5.4), (5.7), (5.14), (5.17) and (5.18), (5.23) and (5.24), (5.25), (5.31), and (5.32), hold, then forcibly, in every period $t \in T$, charities $c \in C$ can only be assigned to initially open food banks $b \in OB$ that have not closed until that period, which is the condition established by constraints (5.30). In this case, as posited by Lemma 7.2, constraints (5.30) are rendered redundant.

The contrapositive of Lemma 7.2 states that if $z_{bc}^t \nleq 1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}$ (or $z_{bc}^t > 1 - \sum_{\tilde{t}=1}^{t} y_b^{\tilde{t}}$), then at least one of the constraints (5.4), (5.7), (5.14), (5.17) and (5.18), (5.23) and (5.24), (5.25), (5.31), and (5.32) does not hold.

The following proof appeals to the domain conditions established for parameters β_2, β_3, X^0_{pc} and R^t_{pc} (see Table 5.3 and following comments on page 77).

Lemma 7.2 revisited. *Constraints* (5.30) *are redundant.*

Proof. Assuming domain constraints (5.32) hold for variables z^t_{bc}, then $z^t_{bc} = 0$ or $z^t_{bc} = 1$ for all $b \in OB$, $c \in C$, and $t \in T$. Hence, proof will be made separately for the two cases.

If (5.32) holds for variables z^t_{bc} and $z^t_{bc} = 0$, then (5.32) does not hold regarding variables y^t_b.

If (5.32) holds for variables z^t_{bc} and $z^t_{bc} = 1$, then (5.32) only holds regarding variables y^t_b if $\sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b = 1$, so that $1 = z^t_{bc} > 1 - \sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_b = 0$. This means that in order for charity $c \in C$ to be assigned to initially open food bank $b \in OB$ (henceforth denoted b') in period $t \in T$, food bank b' must be closed until that period (inclusive).

Assuming constraints (5.7) hold, then no new storage capacity can be installed in that initial food bank in any period t ($\sum_{t \in T} \sum_{\ell \in L} w^t_{\ell k b'} \leq 1 - \sum_{t \in T}^{t} y^t_{b'} = 0$). Subsequently, assuming constraints (5.14) also hold, no food products can be received at food bank b' from suppliers or other food banks ($\sum_{p \in P_k} \sum_{i \in D \cup B \setminus \{b'\}} x^t_{pib'} \leq \overline{M}_{kb'} \left(1 - \sum_{\tilde{t}=1}^{t} y^{\tilde{t}}_{b'}\right) + \sum_{\ell \in L} M_{\ell k} \sum_{\tilde{t}=1}^{t} w^{\tilde{t}}_{\ell k b'} = 0$). Notice that in this case, besides not being able to expand capacity throughout the planning period, the initial capacity of the food bank ($\overline{M}_{kb'}$) is removed in period t when food bank closed.

Further assuming that constraints (5.31) hold, i.e. the quantity of product distributed by food bank b' to charities is integrally sourced from suppliers or other food banks (no other product origins), then no products are delivered by the food bank ($\sum_{i \in D \cup B \setminus \{b'\}} x^t_{pib'} = \sum_{j \in C \cup B \setminus \{b'\}} x^t_{pb'j} = 0$).

Whether c is an initially served charity, or an awaiting charity, assumption that constraints (5.17), for $c \in SC$, and (5.18), for $c \in HC$, hold, signify that charity c cannot be served by food banks other than bank b', and therefore $z^t_{bc} = 0$ for all food banks $b \in B$ if $b \neq b'$. It also signifies that $\sum_{b \in B} z^t_{bc} = z^t_{b'c}$. Assuming constrains (5.25) hold, then, for all food banks $b \in B$ and $b \neq b'$, no products are delivered to charity c ($x^t_{pbc} \leq R^t_{pc} z^t_{bc} = 0$). Moreover, as established earlier, no products are delivered by food bank b'. Thus, $\sum_{b \in B} x^t_{pbc} \leq 0$ for all food banks $b \in B$, including b'.

If $c \in SC$, based on the conditions over parameters β_2 and X^0_{pc}, then constraints (5.23) do not hold. Otherwise, if $c \in HC$, based on the conditions over parameters β_3 and R^t_{pc}, then constraints (5.24) do not hold (recall that $\sum_{b \in B} z^t_{bc} = z^t_{b'c}$). In both cases, it is not possible to satisfy the minimum demand volumes of served charities $c \in C$, if those charities are assigned to (can only be served by) an initially open food bank b' that does not have any products to distribute because it has been closed by period t. □

Appendix L

Results without constraints (5.29)–(5.30)

Table L.1 presents the results obtained for the 20 regional instances running the NO-MILP model without constraints (5.29) and (5.30). Results concern the objective function values of the six lexicographic solutions, and respective CPU time in seconds. For each instance, results obtained in the second, and third runs are expressed in percent of the values obtained in the first run (respectively, Dif. 1st-2nd (%) and Dif. 1st-3rd (%)). Similarly, results obtained in the third run are presented in percent of the values referring to the second run (Dif. 2nd-3rd (%)).

One run (for one instance) is understood as corresponding to one solving cycle of the MO-MILP on the basis of the solving algorithm, which involves solving 15 single objective MILP problems.

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 1									
1st run	6,946.32	328.02	-31.47	6,946.32	331.32	-28.34	8,985.09	124.25	-22.02
2nd run	6,946.32	328.02	-31.47	6,946.32	331.32	-28.34	8,985.09	124.25	-22.02
3rd run	6,946.32	328.02	-31.47	6,946.32	331.32	-28.34	8,985.09	124.25	-22.02
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-
Instance 2									
1st run	5,649.64	531.74	-151.83	5,649.64	543.05	-150.69	7,901.94	185.55	-24.24
2nd run	5,649.64	520.74	-151.83	5,649.64	542.14	-125.45	7,901.94	185.55	-24.24
3rd run	5,649.64	531.74	-151.83	5,649.64	543.05	-150.69	7,901.94	185.55	-24.24
Dif. 1st-2nd (%)	-	-2.07	-	-	-0.17	-16.75	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	2.11	-	-	0.17	20.12	-	-	-
Instance 3									
1st run	5,508.80	469.31	-133.36	5,508.80	477.54	-132.29	9,058.42	175.41	25.19
2nd run	5,508.80	469.31	-133.36	5,508.80	477.54	-132.29	9,058.42	175.41	25.19
3rd run	5,508.80	469.31	-133.36	5,508.80	477.54	-132.29	9,058.42	175.41	25.19
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-
Instance 4									
1st run	7,917.26	584.50	-91.71	7,917.26	629.03	-82.55	10,912.57	322.19	-63.99
2nd run	7,917.26	584.50	-91.71	7,917.26	629.03	-82.55	10,826.79	322.20	-85.74
3rd run	7,917.26	584.50	-91.71	7,917.26	629.03	-82.55	10,826.79	322.20	-85.53
Dif. 1st-2nd (%)	-	-	-	-	-	-	-0.79	-	33.99
Dif. 1st-3rd (%)	-	-	-	-	-	-	-0.79	-	33.66
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-0.24
Instance 5									
1st run	7,927.27	360.79	-84.99	7,927.27	375.16	-84.80	9,535.98	168.14	23.89
2nd run	7,927.27	360.79	-84.99	7,927.27	375.16	-84.80	9,535.98	168.14	23.89
3rd run	7,927.27	360.79	-84.99	7,927.27	375.16	-84.80	9,535.98	168.14	23.89
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-
Instance 6									
1st run	7,300.28	291.43	-6.42	7,300.28	300.07	-6.37	9,020.60	120.35	5.51
2nd run	7,300.28	288.32	-6.42	7,300.28	300.07	-6.35	9,020.60	120.35	5.47
3rd run	7,300.28	287.84	-6.42	7,300.28	300.07	-6.34	9,020.60	120.35	5.47
Dif. 1st-2nd (%)	-	-1.07	-	-	-	-0.31	-	-	-0.73
Dif. 1st-3rd (%)	-	-1.23	-	-	-	-0.47	-	-	-0.73
Dif. 2nd-3rd (%)	-	-0.17	-	-	-	-0.16	-	-	-

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LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
10,281.92	124.25	235.01	9,668.88	288.19	267.66	9,670.22	287.99	267.66	1,082.02
10,281.92	124.25	235.01	9,668.88	288.19	267.66	9,670.22	287.99	267.66	885.16
10,281.92	124.25	235.01	9,668.88	288.19	267.66	9,670.22	287.99	267.66	902.31
-	-	-	-	-	-	-	-	-	-18.19
-	-	-	-	-	-	-	-	-	-16.61
-	-	-	-	-	-	-	-	-	1.94
8,520.69	185.55	40.54	9,609.98	305.57	229.36	9,614.99	305.21	229.36	5,509.11
8,520.69	185.55	40.54	9,609.98	305.57	229.36	9,614.99	305.21	229.36	4,723.91
8,520.69	185.55	40.54	9,609.98	305.57	229.36	9,614.99	305.21	229.36	5,363.13
-	-	-	-	-	-	-	-	-	-14.25
-	-	-	-	-	-	-	-	-	-2.65
-	-	-	-	-	-	-	-	-	13.53
10,675.20	175.41	165.99	9,906.36	280.25	252.61	9,906.53	280.23	252.61	580.14
10,675.20	175.41	165.99	9,906.36	280.25	252.61	9,906.53	280.23	252.61	495.75
10,675.20	175.41	165.99	9,906.36	280.25	252.61	9,906.53	280.23	252.61	547.69
-	-	-	-	-	-	-	-	-	-14.55
-	-	-	-	-	-	-	-	-	-5.59
-	-	-	-	-	-	-	-	-	10.48
11,669.62	322.19	82.17	10,213.39	661.47	172.08	10,230.10	647.35	172.08	2,137.86
11,669.82	322.20	82.18	10,213.39	661.47	172.08	10,230.10	647.35	172.08	1,625.63
11,669.82	322.20	82.18	10,213.39	661.47	172.08	10,230.10	647.35	172.08	1,744.25
-	-	0.01	-	-	-	-	-	-	-23.96
-	-	0.01	-	-	-	-	-	-	-18.41
-	-	-	-	-	-	-	-	-	7.30
10,364.08	168.14	125.60	9,718.57	235.83	229.17	10,017.16	182.82	229.17	1,106.17
10,364.08	168.14	125.60	9,718.57	235.83	229.17	10,017.16	182.82	229.17	768.97
10,364.08	168.14	125.60	9,718.57	235.83	229.17	10,017.16	182.82	229.17	852.45
-	-	-	-	-	-	-	-	-	-30.48
-	-	-	-	-	-	-	-	-	-22.94
-	-	-	-	-	-	-	-	-	10.86
10,161.84	120.35	173.59	9,695.52	200.45	246.26	9,697.18	200.41	246.26	1,728.20
10,161.84	120.35	173.59	9,695.52	200.45	246.26	9,697.18	200.41	246.26	1,328.23
10,161.85	120.35	173.59	9,695.52	200.45	246.26	9,697.18	200.41	246.26	1,378.36
-	-	-	-	-	-	-	-	-	-23.14
-	-	-	-	-	-	-	-	-	-20.24
-	-	-	-	-	-	-	-	-	3.77

Continues on page 301

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 7									
1st run	6,801.58	324.42	-46.94	6,801.58	333.76	-46.88	7,769.32	130.96	32.66
2nd run	6,801.58	324.42	-46.94	6,801.58	333.76	-46.88	7,769.32	130.96	32.66
3rd run	6,801.58	324.42	-46.94	6,801.58	333.76	-46.88	7,769.32	130.96	32.66
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-
Instance 8									
1st run	8,906.57	418.17	-98.05	8,906.57	424.73	-82.09	12,120.47	181.79	12.95
2nd run	8,906.57	418.17	-98.05	8,906.57	424.73	-82.09	12,120.47	181.79	13.44
3rd run	8,906.57	418.17	-98.05	8,906.57	424.73	-82.09	12,120.47	181.79	11.80
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	3.78
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-8.88
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-12.20
Instance 9									
1st run	6,845.02	467.73	-125.02	6,845.02	477.41	-123.87	9,327.95	192.67	27.95
2nd run	6,845.02	467.73	-125.02	6,845.02	477.41	-123.87	9,327.95	192.67	27.95
3rd run	6,845.02	467.73	-125.02	6,845.02	477.41	-123.87	9,267.93	192.68	32.15
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-0.64	0.01	15.03
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-0.64	0.01	15.03
Instance 10									
1st run	6,600.57	783.65	-39.86	6,600.57	800.41	-39.57	8,941.97	140.58	-79.84
2nd run	6,600.57	783.65	-39.86	6,600.57	800.41	-39.57	8,941.97	140.58	-80.31
3rd run	6,600.57	783.65	-39.86	6,600.57	800.41	-39.57	8,941.97	140.58	-79.79
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	0.59
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-0.06
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-0.65
Instance 11									
1st run	5,646.06	366.01	-106.25	5,646.06	373.57	-105.47	7,575.69	171.12	53.51
2nd run	5,646.06	366.01	-106.25	5,646.06	373.57	-105.47	7,575.69	171.12	53.51
3rd run	5,646.06	366.01	-106.25	5,646.06	373.57	-105.47	7,575.69	171.12	53.51
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-
Instance 12									
1st run	7,362.24	707.64	-146.56	7,362.24	730.34	-145.95	8,454.39	212.76	3.47
2nd run	7,362.24	707.64	-146.56	7,362.24	730.34	-145.95	8,454.39	212.76	3.46
3rd run	7,362.24	707.64	-146.56	7,362.24	730.34	-145.95	8,454.39	212.76	3.46
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-0.29
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-0.29
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-

Continued from page 298. Continues on page 302

LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
9,190.82	130.96	194.27	9,485.96	190.85	213.11	9,551.10	190.48	213.11	2,689.66
9,190.82	130.96	194.27	9,485.96	190.85	213.11	9,551.10	190.48	213.11	2,675.52
9,190.82	130.96	194.27	9,485.96	190.85	213.11	9,551.10	190.48	213.11	2,353.30
-	-	-	-	-	-	-	-	-	-0.53
-	-	-	-	-	-	-	-	-	-12.51
-	-	-	-	-	-	-	-	-	-12.04
13,661.65	181.79	117.47	12,114.90	363.49	219.50	12,167.02	363.39	219.50	1,067.11
13,661.68	181.79	117.47	12,114.90	363.49	219.50	12,167.02	363.39	219.50	904.16
13,661.68	181.79	117.47	12,114.90	363.49	219.50	12,167.02	363.39	219.50	733.67
-	-	-	-	-	-	-	-	-	-15.27
-	-	-	-	-	-	-	-	-	-31.25
-	-	-	-	-	-	-	-	-	-18.86
10,661.85	192.67	218.37	10,423.18	284.19	243.18	10,443.63	275.17	243.18	6,021.06
10,661.85	192.67	218.37	10,423.18	284.19	243.18	10,443.63	275.17	243.18	6,140.13
10,662.50	192.68	218.39	10,423.18	284.19	243.18	10,443.63	275.17	243.18	5,288.73
-	-	-	-	-	-	-	-	-	1.98
0.01	0.01	0.01	-	-	-	-	-	-	-12.16
0.01	0.01	0.01	-	-	-	-	-	-	-13.87
9,433.66	140.58	112.53	8,483.91	672.46	265.52	8,486.92	672.21	265.52	1,310.52
9,433.66	140.58	112.53	8,483.91	672.46	265.52	8,486.92	672.21	265.52	1,133.84
9,433.66	140.58	112.53	8,483.91	672.46	265.52	8,486.92	672.21	265.52	1,001.91
-	-	-	-	-	-	-	-	-	-13.48
-	-	-	-	-	-	-	-	-	-23.55
-	-	-	-	-	-	-	-	-	-11.64
8,145.29	171.12	145.24	9,164.29	229.00	234.69	9,165.88	227.87	234.69	1,414.31
8,145.29	171.12	145.24	9,164.29	229.00	234.69	9,165.88	227.87	234.69	1,510.02
8,145.29	171.12	145.24	9,164.29	229.00	234.69	9,165.88	227.87	234.69	1,611.84
-	-	-	-	-	-	-	-	-	6.77
-	-	-	-	-	-	-	-	-	13.97
-	-	-	-	-	-	-	-	-	6.74
9,683.90	212.76	145.26	8,979.74	597.44	246.32	8,980.17	597.32	246.32	605.14
9,683.90	212.76	145.26	8,979.74	597.44	246.32	8,980.17	597.32	246.32	415.91
9,683.90	212.76	145.26	8,979.74	597.44	246.32	8,980.17	597.32	246.32	403.00
-	-	-	-	-	-	-	-	-	-31.27
-	-	-	-	-	-	-	-	-	-33.40
-	-	-	-	-	-	-	-	-	-3.10

Continued from page 299. Continues on page 303

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 13									
1st run	6,395.30	221.38	-85.19	6,395.30	222.25	-85.07	8,214.31	95.57	57.70
2nd run	6,395.30	221.38	-85.19	6,395.30	222.25	-85.07	8,214.31	95.57	57.69
3rd run	6,395.30	221.38	-85.19	6,395.30	222.25	-85.07	8,214.31	95.57	57.70
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-0.02
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	0.02
Instance 14									
1st run	6,080.13	450.71	-96.51	6,080.13	462.90	-95.51	6,922.53	170.51	2.77
2nd run	6,080.13	450.71	-96.51	6,080.13	462.90	-95.51	6,922.53	170.51	2.78
3rd run	6,080.13	450.71	-96.51	6,080.13	462.90	-95.51	6,922.53	170.51	2.74
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	0.36
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-1.08
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-1.44
Instance 15									
1st run	6,094.42	505.57	-82.61	6,094.42	529.95	-75.57	7,527.19	142.14	63.93
2nd run	6,094.42	505.57	-82.61	6,094.42	529.95	-75.57	7,527.19	142.14	63.93
3rd run	6,094.42	505.57	-82.61	6,094.42	529.95	-75.57	7,527.19	142.14	63.93
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-
Instance 16									
1st run	5,342.73	384.29	-85.39	5,342.73	399.58	-84.34	6,410.27	152.04	-58.36
2nd run	5,342.73	384.29	-85.39	5,342.73	399.58	-84.34	6,410.27	152.04	-58.58
3rd run	5,342.73	384.29	-85.39	5,342.73	399.58	-84.34	6,410.27	152.04	-58.32
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	0.38
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-0.07
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-0.44
Instance 17									
1st run	7,710.26	719.37	-79.79	7,710.26	731.50	-79.59	9,885.23	206.10	20.45
2nd run	7,710.26	719.37	-79.79	7,710.26	731.50	-79.59	9,885.16	206.11	20.45
3rd run	7,710.26	719.37	-79.79	7,710.26	731.50	-79.59	9,885.16	206.11	20.45
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-
Instance 18									
1st run	6,018.74	546.19	-200.95	6,018.74	562.22	-200.24	9,720.90	157.10	89.60
2nd run	6,018.74	546.19	-200.95	6,018.74	562.22	-200.24	9,720.90	157.10	89.84
3rd run	6,018.74	546.19	-200.95	6,018.74	562.22	-200.24	9,720.90	157.10	89.79
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	0.27
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	0.21
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-	-	-0.06

Continued from page 300. Continues on page 304

LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
10,136.71	95.57	241.78	9,224.48	113.94	270.99	9,288.32	103.18	270.99	1,392.63
10,136.71	95.57	241.78	9,224.48	113.94	270.99	9,288.32	103.18	270.99	1,150.16
10,136.71	95.57	241.78	9,224.48	113.94	270.99	9,288.32	103.18	270.99	1,122.03
-	-	-	-	-	-	-	-	-	-17.41
-	-	-	-	-	-	-	-	-	-19.43
-	-	-	-	-	-	-	-	-	-2.45
8,159.11	170.51	230.42	8,274.38	233.18	241.33	8,374.08	223.97	241.33	2,192.13
8,159.11	170.51	230.42	8,274.38	233.18	241.33	8,374.08	223.97	241.33	1,967.44
8,159.11	170.51	230.42	8,274.38	233.18	241.33	8,374.08	223.97	241.33	1,776.44
-	-	-	-	-	-	-	-	-	-10.25
-	-	-	-	-	-	-	-	-	-18.96
-	-	-	-	-	-	-	-	-	-9.71
8,825.47	142.14	181.24	8,183.38	390.08	275.67	8,208.06	370.39	275.67	2,143.63
8,825.47	142.14	181.24	8,183.38	390.08	275.67	8,208.06	370.39	275.67	1,702.03
8,825.47	142.14	181.24	8,183.38	390.08	275.67	8,208.06	370.39	275.67	1,709.75
-	-	-	-	-	-	-	-	-	-20.60
-	-	-	-	-	-	-	-	-	-20.24
-	-	-	-	-	-	-	-	-	0.45
7,385.47	152.04	182.58	7,672.68	388.46	243.88	7,690.66	373.08	243.88	5,115.22
7,385.47	152.04	182.58	7,672.68	388.46	243.88	7,690.66	373.08	243.88	5,232.14
7,385.47	152.04	182.58	7,672.68	388.46	243.88	7,690.66	373.08	243.88	5,463.14
-	-	-	-	-	-	-	-	-	2.29
-	-	-	-	-	-	-	-	-	6.80
-	-	-	-	-	-	-	-	-	4.42
10,990.86	206.10	159.39	10,124.98	558.34	218.66	10,125.92	558.29	218.66	1,448.41
10,990.87	206.11	159.39	10,124.98	558.34	218.66	10,125.92	558.29	218.66	1,176.89
10,990.87	206.11	159.39	10,124.98	558.34	218.66	10,125.92	558.29	218.66	1,081.45
-	-	-	-	-	-	-	-	-	-18.75
-	-	-	-	-	-	-	-	-	-25.34
-	-	-	-	-	-	-	-	-	-8.11
10,264.89	157.10	161.38	8,035.88	458.57	261.83	8,100.82	439.68	261.83	2,075.81
10,264.89	157.10	161.38	8,035.88	458.57	261.83	8,100.82	439.68	261.83	1,827.06
10,264.91	157.10	161.38	8,035.88	458.57	261.83	8,100.82	439.68	261.83	1,483.58
-	-	-	-	-	-	-	-	-	-11.98
-	-	-	-	-	-	-	-	-	-28.53
-	-	-	-	-	-	-	-	-	-18.80

Continued from page 301. Continues on page 305

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 19									
1st run	6,448.16	516.35	-68.83	6,448.16	531.57	-68.14	6,808.57	185.85	-71.09
2nd run	6,448.16	516.35	-68.83	6,448.16	531.57	-68.14	6,808.57	185.85	-71.09
3rd run	6,448.16	516.35	-68.83	6,448.16	531.57	-68.14	6,808.20	185.86	-71.34
Dif. 1st-2nd (%)	-	-	-	-	-	-	-	-	-
Dif. 1st-3rd (%)	-	-	-	-	-	-	-0.01	0.01	0.35
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-0.01	0.01	0.35
Instance 20									
1st run	6,305.45	293.27	-72.95	6,305.45	307.73	-71.81	8,586.19	101.37	-49.15
2nd run	6,305.45	293.27	-72.95	6,305.45	307.73	-71.81	8,787.94	101.37	-60.49
3rd run	6,305.45	293.27	-72.95	6,305.45	307.73	-71.81	8,586.19	101.37	-49.15
Dif. 1st-2nd (%)	-	-	-	-	-	-	2.35	-	23.07
Dif. 1st-3rd (%)	-	-	-	-	-	-	-	-	-
Dif. 2nd-3rd (%)	-	-	-	-	-	-	-2.30	-	-18.75
Average									
1st run	6,690.34	463.53	-91.73	6,690.34	477.20	-89.46	8,683.98	166.82	2.54
2nd run	6,690.34	462.82	-91.73	6,690.34	477.16	-88.19	8,689.77	166.82	0.89
3rd run	6,690.34	463.35	-91.73	6,690.34	477.20	-89.46	8,676.67	166.82	1.62
Dif. 1st-2nd (%)	-	-0.15	-	-	-0.01	-1.41	0.07	-	-65.04
Dif. 1st-3rd (%)	-	-0.04	-	-	-	-	-0.08	-	-36.43
Dif. 2nd-3rd (%)	-	0.11	-	-	0.01	1.43	-0.15	-	81.84

Table L.1: Lexicographic solutions and CPU time: three runs on opportunistic mode

LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
8,498.75	185.85	237.50	10,001.46	338.36	261.67	10,005.53	338.05	261.67	1,131.50
8,498.75	185.85	237.50	10,001.46	338.36	261.67	10,005.53	338.05	261.67	878.05
8,498.93	185.86	237.53	10,001.46	338.36	261.67	10,005.53	338.05	261.67	824.89
-	-	-	-	-	-	-	-	-	-22.40
-	0.01	0.01	-	-	-	-	-	-	-27.10
-	0.01	0.01	-	-	-	-	-	-	-6.05
9,255.95	101.37	35.43	8,581.38	179.85	236.32	8,646.88	173.75	236.32	3,936.70
9,310.74	101.37	-22.75	8,581.38	179.85	236.32	8,646.88	173.75	236.32	1,378.53
9,253.41	101.37	28.78	8,581.38	179.85	236.32	8,646.88	173.75	236.32	4,510.98
0.59	-	-164.21	-	-	-	-	-	-	-64.98
-0.03	-	-18.77	-	-	-	-	-	-	14.59
-0.62	-	-226.51	-	-	-	-	-	-	227.23
9,798.39	166.82	159.29	9,378.17	348.50	241.49	9,418.56	340.54	241.49	2,234.37
9,801.14	166.82	156.38	9,378.17	348.50	241.49	9,418.56	340.54	241.49	1,895.98
9,798.31	166.82	158.96	9,378.17	348.50	241.49	9,418.56	340.54	241.49	2,007.65
0.03	-	-1.83	-	-	-	-	-	-	-15.14
-	-	-0.21	-	-	-	-	-	-	-10.15
-0.03	-	1.65	-	-	-	-	-	-	5.89

Appendix M

Comparison of results with and without constraints (5.29)–(5.30)

Table M.1 compares the results obtained in the first runs of the MO-MILP model with and without constraints (5.29)–(5.30), for each regional instance. Results of the run without constraints are expressed in percent of the results obtained including the constrains (Dif.).

One run (for one instance) is understood as corresponding to one solving cycle of the MO-MILP on the basis of the solving algorithm, which involves solving 15 single objective MILP problems.

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 1									
With (5.29)–(5.30)	6,946.32	328.02	-31.47	6,946.32	331.32	-28.34	8,985.09	124.25	-22.09
Without (5.29)–(5.30)	6,946.32	328.02	-31.47	6,946.32	331.32	-28.34	8,985.09	124.25	-22.02
Dif. (%)	-	-	-	-	-	-	-	-	-0.32
Instance 2									
With (5.29)–(5.30)	5,649.64	531.74	-151.83	5,649.64	543.05	-150.69	7,901.94	185.55	-24.24
Without (5.29)–(5.30)	5,649.64	531.74	-151.83	5.649.64	543.05	-150.69	7.901.94	185.55	-24.24
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 3									
With (5.29)–(5.30)	5,508.80	469.31	-133.36	5,508.80	477.54	-132.29	9,058.42	175.41	25.21
Without (5.29)–(5.30)	5,508.80	469.31	-133.36	5,508.80	477.54	-132.29	9,058.42	175.41	25.19
Dif. (%)	-	-	-	-	-	-	-	-	-0.08
Instance 4									
With (5.29)–(5.30)	7,917.26	584.50	-91.71	7,917.26	629.03	-82.55	10,912.57	322.19	-63.74
Without (5.29)–(5.30)	7,917.26	584.50	-91.71	7,917.26	629.03	-82.55	10,912.57	322.19	-63.99
Dif. (%)	-	-	-	-	-	-	-	-	0.39
Instance 5									
With (5.29)–(5.30)	7,927.27	360.79	-84.99	7,927.27	375.16	-84.80	9,535.98	168.14	23.89
Without (5.29)–(5.30)	7,927.27	360.79	-84.99	7,927.27	375.16	-84.80	9,535.98	168.14	23.89
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 6									
With (5.29)–(5.30)	7,300.28	291.43	-6.42	7,300.28	300.07	-6.37	9,020.60	120.35	3.94
Without (5.29)–(5.30)	7,300.28	291.43	-6.42	7,300.28	300.07	-6.37	9,020.60	120.35	5.51
Dif. (%)	-	-	-	-	-	-	-	-	39.85
Instance 7									
With (5.29)–(5.30)	6,801.58	324.42	-46.94	6,801.58	333.76	-46.88	7,769.32	130.96	32.66
Without (5.29)–(5.30)	6,801.58	324.42	-46.94	6,801.58	333.76	-46.88	7,769.32	130.96	32.66
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 8									
With (5.29)–(5.30)	8,906.57	418.17	-98.05	8,906.57	424.73	-82.09	12,120.36	181.80	12.99
Without (5.29)–(5.30)	8,906.57	418.17	-98.05	8,906.57	424.73	-82.09	12,120.47	181.79	12.95
Dif. (%)	-	-	-	-	-	-	-	-	-0.31
Instance 9									
With (5.29)–(5.30)	6,845.02	467.73	-125.02	6,845.02	477.41	-123.87	9,327.95	192.67	27.95
Without (5.29)–(5.30)	6,845.02	467.73	-125.02	6,845.02	477.41	-123.87	9,327.95	192.67	27.95
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 10									
With (5.29)–(5.30)	6,600.57	783.65	-39.86	6,600.57	800.41	-39.57	8,941.97	140.58	-80.15
Without (5.29)–(5.30)	6,600.57	783.65	-39.86	6,600.57	800.41	-39.57	8,941.97	140.58	-79.84
Dif. (%)	-	-	-	-	-	-	-	-	-0.39

Continues on page 310

LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
10,281.92	124.25	235.01	9,668.88	288.19	267.66	9,670.22	287.99	267.66	865.23
10,281.92	124.25	235.01	9,668.88	288.19	267.66	9,670.22	287.99	267.66	1,082.02
-	-	-	-	-	-	-	-	-	25.06
8,.520.69	185.55	40.54	9,609.98	305.57	229.36	9,614.99	305.21	229.36	5,900.14
8,.520.69	185.55	40.54	9,609.98	305.57	229.36	9,614.99	305.21	229.36	5,509.11
-	-	-	-	-	-	-	-	-	-6.63
10,675.22	175.41	165.99	9,906.36	280.25	252.61	9,906.53	280.23	252.61	435.14
10,675.20	175.41	165.99	9,906.36	280.25	252.61	9,906.53	280.23	252.61	580.14
-	-	-	-	-	-	-	-	-	33.32
11,669.62	322.19	82.17	10,213.39	661.47	172.08	10,230.10	647.35	172.08	1,336.02
11,669.62	322.19	82.17	10,213.39	661.47	172.08	10,230.10	647.35	172.08	2,137.86
-	-	-	-	-	-	-	-	-	60.02
10,364.08	168.14	125.60	9,718.57	235.83	229.17	10,017.16	182.82	229.17	958.92
10,364.08	168.14	125.60	9,718.57	235.83	229.17	10,017.16	182.82	229.17	1,106.17
-	-	-	-	-	-	-	-	-	15.36
10,161.85	120.35	173.59	9,695.52	200.45	246.26	9,697.18	200.41	246.26	1,344.31
10,161.84	120.35	173.59	9,695.52	200.45	246.26	9,697.18	200.41	246.26	1,728.20
-	-	-	-	-	-	-	-	-	28.56
9,190.82	130.96	194.27	9,485.96	190.85	213.11	9,551.10	190.48	213.11	2,031.47
9,190.82	130.96	194.27	9,485.96	190.85	213.11	9,551.10	190.48	213.11	2,689.66
-	-	-	-	-	-	-	-	-	32.40
13,661.71	181.80	117.48	12,114.90	363.49	219.50	12,167.02	363.39	219.50	788.20
13,661.65	181.79	117.47	12,114.90	363.49	219.50	12,167.02	363.39	219.50	1,067.11
-	-	-0.01	-	-	-	-	-	-	35.39
10,661.84	192.67	218.37	10,423.18	284.19	243.18	10,443.63	275.17	243.18	6,302.28
10,661.85	192.67	218.37	10,423.18	284.19	243.18	10,443.63	275.17	243.18	6,021.06
-	-	-	-	-	-	-	-	-	-4.46
9,433.66	140.58	112.53	8,483.91	672.46	265.52	8,486.92	672.21	265.52	831.53
9,433.66	140.58	112.53	8,483.91	672.46	265.52	8,486.92	672.21	265.52	1,310.52
-	-	-	-	-	-	-	-	-	57.60

Continues on page 311

Instance	LS1			LS2			LS3		
	Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.
Instance 11									
With (5.29)–(5.30)	5,646.06	366.01	-106.25	5,646.06	373.57	-105.47	7,575.69	171.12	53.51
Without (5.29)–(5.30)	5,646.06	366.01	-106.25	5,646.06	373.57	-105.47	7,575.69	171.12	53.51
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 12									
With (5.29)–(5.30)	7,362.24	707.64	-146.56	7,362.24	730.34	-145.95	8,454.39	212.76	3.46
Without (5.29)–(5.30)	7,362.24	707.64	-146.56	7,362.24	730.34	-145.95	8,454.39	212.76	3.47
Dif. (%)	-	-	-	-	-	-	-	-	0.29
Instance 13									
With (5.29)–(5.30)	6,395.30	221.38	-85.19	6,395.30	222.25	-85.07	8,214.31	95.57	57.70
Without (5.29)–(5.30)	6,395.30	221.38	-85.19	6,395.30	222.25	-85.07	8,214.31	95.57	57.70
Dif. (%)	-	-	-	-	-	-	-	-	-
Instance 14									
With (5.29)–(5.30)	6,080.13	450.71	-96.51	6,080.13	462.90	-95.51	6,922.53	170.51	2.73
Without (5.29)–(5.30)	6,080.13	450.71	-96.51	6,080.13	462.90	-95.51	6,922.53	170.51	2.77
Dif. (%)	-	-	-	-	-	-	-	-	1.47
Instance 15									
With (5.29)–(5.30)	6,094.42	505.57	-82.61	6,094.42	529.95	-75.57	7,527.19	142.14	63.95
Without (5.29)–(5.30)	6,094.42	505.57	-82.61	6,094.42	529.95	-75.57	7,527.19	142.14	63.93
Dif. (%)	-	-	-	-	-	-	-	-	-0.03
Instance 16									
With (5.29)–(5.30)	5,342.73	384.29	-85.39	5,342.73	399.58	-84.34	6,410.27	152.04	-58.74
Without (5.29)–(5.30)	5,342.73	384.29	-85.39	5,342.73	399.58	-84.34	6,410.27	152.04	-58.36
Dif. (%)	-	-	-	-	-	-	-	-	-0.65
Instance 17									
With (5.29)–(5.30)	7,710.26	719.37	-79.79	7,710.26	731.50	-79.59	9,782.74	206.12	27.73
Without (5.29)–(5.30)	7,710.26	719.37	-79.79	7,710.26	731.50	-79.59	9,885.23	206.10	20.45
Dif. (%)	-	-	-	-	-	-	1.05	-	-26.25
Instance 18									
With (5.29)–(5.30)	6,018.74	546.19	-200.95	6,018.74	562.22	-200.24	9,720.90	157.10	90.20
Without (5.29)–(5.30)	6,018.74	546.19	-200.95	6,018.74	562.22	-200.24	9,720.90	157.10	89.60
Dif. (%)	-	-	-	-	-	-	-	-	-0.67
Instance 19									
With (5.29)–(5.30)	6,448.16	516.35	-68.83	6,448.16	531.57	-68.14	6,808.57	185.85	-71.22
Without (5.29)–(5.30)	6,448.16	516.35	-68.83	6,448.16	531.57	-68.14	6,808.57	185.85	-71.09
Dif. (%)	-	-	-	-	-	-	-	-	-0.18
Instance 20									
With (5.29)–(5.30)	6,305.45	293.27	-72.95	6,305.45	307.73	-71.81	8,787.94	101.37	-60.49
Without (5.29)–(5.30)	6,305.45	293.27	-72.95	6,305.45	307.73	-71.81	8,586.19	101.37	-49.15
Dif. (%)	-	-	-	-	-	-	-2.30	-	-18.75
Average									
With (5.29)–(5.30)	6,690.34	463.53	-91.73	6,690.34	477.20	-89.46	8,688.94	166.82	2.26
Without (5.29)–(5.30)	6,690.34	463.53	-91.73	6,690.34	477.20	-89.46	8,683.98	166.82	2.54
Dif. (%)	-	-	-	-	-	-	-0.06	-	12.46

Table M.1: Lexicographic solutions and CPU time: comparison with and without (5.29)–(5.30)

LS4			LS5			LS6			CPU
Eco.	Env.	Soc.	Eco.	Env.	Soc.	Eco.	Env.	Soc.	
8,145.29	171.12	145.24	9,164.29	229.00	234.69	9,165.88	227.87	234.69	1,241.92
8,145.29	171.12	145.24	9,164.29	229.00	234.69	9,165.88	227.87	234.69	1,414.31
-	-	-	-	-	-	-	-	-	13.88
9,683.90	212.76	145.26	8,979.74	597.44	246.32	8,980.17	597.32	246.32	346.63
9,683.90	212.76	145.26	8,979.74	597.44	246.32	8,980.17	597.32	246.32	605.14
-	-	-	-	-	-	-	-	-	74.58
10,136.71	95.57	241.78	9,224.48	113.94	270.99	9,288.32	103.18	270.99	1,052.28
10,136.71	95.57	241.78	9,224.48	113.94	270.99	9,288.32	103.18	270.99	1,392.63
-	-	-	-	-	-	-	-	-	32.34
8,159.10	170.51	230.42	8,274.38	233.18	241.33	8,374.08	223.97	241.33	1,148.47
8,159.11	170.51	230.42	8,274.38	233.18	241.33	8,374.08	223.97	241.33	2,192.13
-	-	-	-	-	-	-	-	-	90.87
8,825.47	142.14	181.24	8,183.38	390.08	275.67	8,208.06	370.39	275.67	1,249.59
8,825.47	142.14	181.24	8,183.38	390.08	275.67	8,208.06	370.39	275.67	2,143.63
-	-	-	-	-	-	-	-	-	71.55
7,385.47	152.04	182.58	7,672.68	388.46	243.88	7,690.66	373.08	243.88	5,268.47
7,385.47	152.04	182.58	7,672.68	388.46	243.88	7,690.66	373.08	243.88	5,115.22
-	-	-	-	-	-	-	-	-	-2.91
10,990.92	206.12	159.39	10,124.98	558.34	218.66	10,125.92	558.29	218.66	868.77
10,990.86	206.10	159.39	10,124.98	558.34	218.66	10,125.92	558.29	218.66	1,448.41
-	-	-	-	-	-	-	-	-	66.72
10,264.92	157.10	161.38	8,035.88	458.57	261.83	8,100.82	439.68	261.83	1,479.64
10,264.89	157.10	161.38	8,035.88	458.57	261.83	8,100.82	439.68	261.83	2,075.81
-	-	-	-	-	-	-	-	-	40.29
8,498.75	185.85	237.50	10,001.46	338.36	261.67	10,005.53	338.05	261.67	615.27
8,498.75	185.85	237.50	10,001.46	338.36	261.67	10,005.53	338.05	261.67	1,131.50
-	-	-	-	-	-	-	-	-	83.90
9,310.74	101.37	-22.75	8,581.38	179.85	236.32	8,646.88	173.75	236.32	1,279.69
9,255.95	101.37	35.43	8,581.38	179.85	236.32	8,646.88	173.75	236.32	3,936.70
-0.59	-	-255.74	-	-	-	-	-	-	207.63
9,801.13	166.82	156.38	9,378.17	348.50	241.49	9,418.56	340.54	241.49	1,767.20
9,798.39	166.82	159.29	9,378.17	348.50	241.49	9,418.56	340.54	241.49	2,234.37
-0.03	-	1.86	-	-	-	-	-	-	26.44

Appendix N

Linear relaxation

Table N.1 compares the results obtained by the CPLEX optimizer at the first branch-and-cut node, corresponding to the linear relaxation solution, with and without the inclusion of constrains (5.29)–(5.30) in the model. As individual results of a single instance are more meaningful to identify the impact of including redundant constraints (5.29)–(5.30) in the model, results report to the illustrative instance 15. Results are also compared with the optimal value of each problem.

The objective value of the solutions obtained including constrains (5.29)–(5.30) are regularly closer to the optimal value of each problem, resulting in smaller or equal (absolute) integrality gaps than gaps obtained when the constraints are excluded from the model. In four cases (P_6, P_{11}, P_{12}, and P_{15}), the linear relaxation solution value is identical with and without constrains (5.29)–(5.30), but for the remaining cases the value provided by the model including the constraints improves between 1.62% and 16.74% over the linear relaxation value obtained excluding the constraints.

Problems	Objective value			Integrality gap (absolute)		Comparison
	Optimal	With (5.29)–(5.30)	Without (5.29)–(5.30)	With (5.29)–(5.30)	Without (5.29)–(5.30)	(%)
P_1	6,094.42	5,241.81	4,819.24	1.16	1.26	8.77
P_2	505,565.62	151,117.75	142,142.04	3.35	3.56	6.31
P_3	-75.57	226.23	229.90	2.99	3.04	1.62
P_4	-82.61	226.23	229.90	2.74	2.78	1.62
P_5	529,950.54	151,117.75	142,142.04	3.51	3.73	6.31
P_6	142,142.04	142,142.04	142,142.04	1.00	1.00	-
P_7	7,527.19	6,316.43	5,907.99	1.19	1.27	6.91
P_8	181.24	260.43	269.85	1.44	1.49	3.62
P_9	63.93	256.59	266.00	4.01	4.16	3.67
P_{10}	8,825.47	6,351.45	6,026.85	1.39	1.46	5.39
P_{11}	275.67	293.40	293.40	1.06	1.06	-
P_{12}	8,183.38	7,049.32	7,049.32	1.16	1.16	-
P_{13}	370,389.97	189,477.25	162,302.92	1.95	2.28	16.74
P_{14}	390,079.35	189,477.25	162,302.92	2.06	2.40	16.74
P_{15}	8,208.06	7,049.32	7,049.32	1.16	1.16	-

Table N.1: Comparison of linear relaxation solutions with and without (5.29)–(5.30): instance 15

Appendix O

Optimal gaps of heuristic *LA-STc*

Table O.1 shows, for every instance and problem, the gaps to the optimal value from the solutions obtained by heuristic *LA-STc*. Results concern the solutions of regional instances, for which the optimal values are known.

	Instances																				Avg.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
P_1	37.81	23.92	48.39	4.15	16.21	10.93	6.84	23.64	15.20	44.96	45.40	22.39	30.48	46.08	43.76	26.11	47.00	19.65	20.48	45.63	28.95
P_2	10.89	5.08	2.77	4.62	7.54	5.69	6.07	8.07	7.15	0.13	0.03	3.51	9.29	0.01	0.01	8.08	0.17	5.78	10.70	3.23	4.94
P_3	24.97	49.07	34.38	14.30	55.31	40.81	23.24	61.22	48.58	32.13	48.49	54.42	35.87	15.51	68.52	49.27	32.21	47.10	50.39	42.56	41.42
P_4	61.34	49.20	68.65	14.45	55.32	40.81	24.16	61.22	48.63	40.99	60.29	55.50	36.06	26.98	50.36	49.27	53.48	47.10	50.39	46.87	47.05
P_5	0.67	5.08	0.83	4.45	7.54	5.65	6.36	4.06	7.16	1.09	0.29	6.10	2.01	0.73	0.06	8.08	0.39	1.76	10.70	0.15	3.66
P_6	-	-	-	0.37	0.01	0.46	0.03	0.09	0.05	-	0.01	0.01	-	-	0.22	0.01	-	-	-	0.02	0.06
P_7	26.90	22.31	35.71	13.03	16.27	12.19	14.35	20.91	29.90	10.98	30.52	35.81	29.94	16.96	16.56	11.31	40.77	6.03	16.19	9.29	20.80
P_8	45.47	52.52	24.67	22.11	35.88	34.81	35.00	44.25	42.74	60.02	58.47	61.64	31.84	18.85	38.11	25.92	44.08	18.89	54.97	33.24	39.17
P_9	42.74	44.87	38.06	37.87	46.48	42.59	36.56	46.92	49.96	33.29	53.77	40.73	10.68	27.05	44.52	27.96	43.67	28.78	39.36	36.41	38.61
P_{10}	21.24	23.25	18.73	9.81	21.77	10.61	32.49	12.00	21.49	21.78	36.98	27.74	13.61	15.50	16.64	26.75	18.21	17.01	15.13	12.06	19.64
P_{11}	38.34	31.78	25.75	1.10	27.07	32.81	0.36	54.99	32.99	23.91	39.00	38.11	35.84	15.52	35.56	31.86	44.41	15.04	43.87	41.97	30.51
P_{12}	27.23	36.30	34.73	4.41	29.83	26.91	1.74	33.20	34.92	22.60	30.60	34.94	29.43	21.11	37.09	33.81	26.10	21.16	36.97	32.86	27.80
P_{13}	1.02	1.53	0.63	0.69	0.48	1.03	0.10	0.39	0.76	1.09	0.30	0.11	0.72	0.72	1.03	0.94	0.29	1.58	3.35	0.33	0.85
P_{14}	9.99	6.14	4.35	2.66	5.24	4.26	3.13	8.44	0.68	4.46	7.88	2.00	1.57	5.59	5.09	13.07	1.28	7.24	11.14	5.07	5.46
P_{15}	27.73	33.74	27.03	1.16	26.17	23.36	7.26	28.58	28.35	18.19	27.37	25.17	22.52	21.71	32.01	31.92	30.86	23.49	9.90	18.82	23.27
$z_1(x)$	28.18	27.90	32.92	6.51	22.05	16.80	12.54	23.67	25.97	23.70	34.17	29.21	25.20	24.27	29.21	25.98	32.59	17.47	19.73	23.73	24.09
$z_2(x)$	4.51	3.57	1.72	2.56	4.16	3.42	3.14	4.21	3.16	1.35	1.70	2.35	2.72	1.41	1.28	6.04	0.43	3.27	7.18	1.76	3.00
$z_3(x)$	42.57	45.49	38.30	17.97	44.01	38.37	23.86	53.72	44.58	38.07	52.00	50.08	30.06	20.78	47.41	36.86	43.57	31.38	47.80	40.21	39.35

$z_1(x)$: average of P_1, P_7, P_{10}, P_{12}, and P_{15}

$z_2(x)$: average of P_2, P_5, P_6, P_{13}, and P_{14}

$z_3(x)$: average of P_3, P_4, P_8, P_9, and P_{11}

Table O.1: Best bound to optimal solution gaps (%) with heuristic *LA-STc* per problem

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