Université
de Toulouse

THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par :

Institut National Polytechnique de Toulouse (INP Toulouse)

Discipline ou spécialité :

Génie des Procédés et de l'Environnement

Présentée et soutenue par :

M. MARCO AUGUSTO MIRANDA ACKERMAN
le jeudi 5 novembre 2015

Titre :

OPTIMISATION MULTI-OBJECTIF POUR LA GESTION ET LA CONCEPTION D'UNE CHAINE LOGISTIQUE VERTE: APPLICATION AU CAS DE LA FILIERE AGROALIMENTAIRE DU JUS D'ORANGE

Ecole doctorale :
Mécanique, Energétique, Génie civil, Procédés (MEGeP)

Unité de recherche :
Laboratoire de Génie Chimique (L.G.C.)

Directeur(s) de Thèse :
MME CATHERINE AZZARO PANTEL
M. LUDOVIC MONTASTRUC

Rapporteurs :
M. HAMID ALLAOUI, UNIVERSITE D'ARTOIS
Mme GENEVIÈVE GESAN GUIZIOU, INRA RENNES

Membre(s) du jury :
M. ANTOINE GASET, INP TOULOUSE, Président
M. ANTONIN PONSICH, UNIVERSIDAD AUTONOMA METROPOLITANA MEXICO, Membre
M. LUDOVIC MONTASTRUC, INP TOULOUSE, Membre
Mme ANNE-LAURE CADENE, ALTRAN, Membre
Mme CATHERINE AZZARO PANTEL, INP TOULOUSE, Membre

Acknowledgement

First I would like to thank the INPT for their unconditional support throughout the thesis work. I would also like to thank CONACYT and SEP as an extension of the Mexican government for their financial support throughout my PhD work.

I graciously and humbly thank the members of the jury of my thesis defense. Firstly the president Antoine GASET for his empowering presence and openness to discussion; my external jury members, Anne-Laure CADENE for her wonderful insight and questions from an entrepreneurial point of view and her creativity in terms of developing insightful questions after many lines of questioning where already explored, as well as Antonin PONSICH for his precise questions and suggestions on optimization, and for his openness to address supply chain management topics; and not least for his efforts to join us through technological means with great patience.

I would like to give a very warm and special thanks to my rapporteurs. Geneviève GESAN-GUIZIOU for her deep immersion in my manuscript; helping me achieve a much improved final version. Indeed her series of questions during the defense where equally fruitful and targeted. I especially appreciate her wonderful insights on food production issues and details, giving me the opportunity to explain and extend many of the ideas that where outside of the core subject of the laboratory, mainly agro-industrial topics. Key to my manuscript and to my defense experience was my second reviewer Hamid ALLAOUI. I thank him and I am so very lucky to have had the chance to meet him and that he accepted the role of rapporteur. He provided a fundamental balance to the defense experience with his extensive experience, having worked in the same subject field, with knowledge of the tools and paradigms being integrated as if his own. His mere presence and first questions gave me confidence in the subject matter of my thesis.

I would like to thank the contribution made by Ludovic and Serge, especially at the beginning of the thesis work, challenging and helping me to find and define the core of the subject matter and for being always there for me - be it - to answer questions or to consistently have programed meetings. Ludovic I have learned many things through our working relationship and I am grateful for your interest and openness.

I would also like to thank Alberto and Gregorio with who I am in debt for all the help – before and during – my thesis work; and for allowing me to be part of the team even when I was so far away.

Catherine…I thank you the most. You gave me the opportunity to fulfill a dream and accepted me with a smile and candor. You always gave me the space and the pace of work I needed, and helped me find my way. You were always available and had a very natural way to understanding everything I wanted to explain. Always open to new ideas and interested in my subject matter, and having a brilliant capacity to learn and teach me new things, always sending interesting and timely publications and links that made the research work so much more interesting and engaging. I cannot explain how much I am grateful for the dedication and consistency you gave, especially at the critical moments. You are my true benchmark…I am forever grateful, and hopeful this is only the beginning of work to come. You and the things I learned from you are the hallmark of my thesis.

I would like to mention my gratitude to those who left a mark that helped me throughout my thesis work. Beira G., Mario A., Mortera, Guillermo C., Constantino M., Magno G. and all my teachers that built the steps towards my thesis.

Secondly, I would like to thank all of my friends who I had a chance to share and lean from, especially from the Lab: Guillermo, Raul, Fernando, Jesus, Jose Luis, Eduardo (y Denisse), who helped me land on my feet when I arrived in Toulouse. Also the people who thought me about France from a foreigner's pint of view: Ali, Wey Fang, Laszlo. I also appreciate the friendship shared with the current team: Ahmed, Stephane, Manuel, Phuong-Anh, Jesus, Ségolène, Guillaume W. and everyone else that has been a part of this experience.

I have a special appreciation for the unexpected friendship and working relationship that grow with Antonio and Sofia, thanks for always listening to what I needed to share and always having insightful feedback.

I always had the idea that I would have very interesting and harebrained conversation during my PhD studies, thanks to Philip, Marie B., Guillaume B. and Laszlo for all the wonderful debates and interchange of ideas.

Rene and Lety, at a different level of gratitude and surprise, you have serendipitously become part of my family history and have been with us from beginning to end of this journey. I am so happy to have met you and happy we will always be friends.

I thank my parents Blanca and Carlos for always stimulating and rewording curiosity over everything else; and my brothers Roberto, Jacobo and Marcel, and extended sister Karina - forming the base of stability and family.

Above all I thank my wife Alejandra…I thank you for all the patience, help and love. I thank you for making being a parent and PhD student easy and fun. I thank you for being the best wife in the world, and for always…always believing in my vision and helping me reach it.

Dedicated to my son Maatiaak, may your childhood dreams become a reality.

Résumé

La gestion de la chaîne logistique a gagné en maturité depuis l'extension de son champ d'application qui portait sur des problématiques opérationnelles et économiques s'est élargi à des questions environnementales et sociales auxquelles sont confrontées les organisations industrielles actuelles. L'addition du terme «vert» aux activités de la chaîne logistique vise à intégrer une conscience écologique dans tous les processus de la chaîne d'approvisionnement. Le but de ce travail est de développer un cadre méthodologique pour traiter la gestion de la chaîne logistique verte (GrSCM) basée sur une approche d'optimisation multi-objectif, en se focalisant sur la conception, la planification et les opérations de la chaîne agroalimentaire, à travers la mise en œuvre des principes de gestion et de logistique de la chaîne d'approvisionnement verte. L'étude de cas retenu est la filière du jus d'orange. L'objectif du travail consiste en la minimisation de l'impact environnemental et la maximisation de la rentabilité économique pour des catégories de produits sélectionnés. Ce travail se concentre sur l'application de la GrSCM à deux questions stratégiques fondamentales visant les chaînes d'approvisionnement agroalimentaire. La première est liée au problème de la sélection des fournisseurs en produits « verts » (GSS) pour les systèmes de production agricole et à leur intégration dans le réseau globalisé de la chaîne d'approvisionnement. Le second se concentre sur la conception globale du réseau de la chaîne logistique verte (GSCND). Ces deux sujets complémentaires sont finalement intégrés afin d'évaluer et exploiter les caractéristiques des chaînes d'approvisionnement agro-alimentaire en vue du développement d'un éco-label. La méthodologie est basée sur le couplage entre analyse du cycle de vie (ACV), optimisation multi-objectifs par algorithmes génétiques et technique d'aide à la décision multicritère (de type TOPSIS). L'approche est illustrée et validée par le développement et l'analyse d'une étude de cas de la chaîne logistique de jus d'orange, modélisée comme une chaîne logistique verte (GrSC) à trois échelons composés de la production d'oranges, de leur transformation en jus, puis de leur distribution, chaque échelon étant modélisé de façon plus fine en sous-composants.

D'un point de vue méthodologique, le travail a démontré l'intérêt du cadre de modélisation et d'optimisation de GrSC dans le contexte des chaînes d'approvisionnement, notamment pour le développement d'un éco-label dans le domaine de l'agro-alimentaire. Il peut aider les décideurs pour gérer la complexité inhérente aux décisions de conception de la chaîne d'approvisionnement agroalimentaire, induite par la nature multi-objectifs multi-acteurs multi-périodes du problème, empêchant ainsi une prise de décision empirique et segmentée. D'un point de vue expérimental, sous les hypothèses utilisées dans l'étude de cas, les résultats du travail soulignent que si l'on restreint l'éco-label "bio" à l'aspect agricole, seule une faible, voire aucune amélioration sur la performance environnementale de la chaîne d'approvisionnement n'est atteinte. La prise en compte des critères environnementaux pertinents sur l'ensemble du cycle de vie s'avère être une meilleure option pour les stratégies publiques et privées afin de tendre vers des chaînes agro-alimentaires plus durables.

Abstract

Supply chain and operations management has matured from a field that addressed only operational and economic concerns to one that comprehensively considers the broader environmental and social issues that face industrial organizations of today. Adding the term "green" to supply chain activities seeks to incorporate environmentally conscious thinking in all processes in the supply chain. The aim of this work is to develop a Green Supply Chain (GrSC) framework based on a multi-objective optimization approach, with specific emphasis on agrofood supply chain design, planning and operations through the implementation of appropriate green supply chain management and logistics principles. The case study is the orange juice cluster. The research objective is the minimization of the environmental burden and the maximization of economic profitability of the selected product categories. This work focuses on the application of GrSCM to two fundamental strategic issues targeting agro food supply chains. The former is related to the Green Supplier Selection (GSS) problem devoted to the farming production systems and the way they are integrated into the global supply chain network. The latter focuses on the global Green Supply Chain Network Design (GSCND) as a whole. These two complementary and ultimately integrated strategic topics are framed in order to evaluate and exploit the unique characteristics of agro food supply chains in relation to eco-labeling. The methodology is based on the use of Life Cycle Assessment, Multi-objective Optimization via Genetic Algorithms and Multiple-criteria Decision Making tools (TOPSIS type). The approach is illustrated and validated through the development and analysis of an Orange Juice Supply Chain case study modelled as a three echelon GrSC composed of the supplier, manufacturing and market levels that in turn are decomposed into more detailed subcomponents. .

Methodologically, the work has shown the development of the modelling and optimization GrSCM framework is useful in the context of eco-labeled agro food supply chain and feasible in particular for the orange juice cluster. The proposed framework can help decision makers handle the complexity that characterizes agro food supply chain design decision and that is brought on by the multi-objective and multi-period nature of the problem as well as by the multiple stakeholders, thus preventing to make the decision in a segmented empirical manner. Experimentally, under the assumptions used in the case study, the work highlights that by focusing only on the "organic" eco-label to improve the agricultural aspect, low to no improvement on overall supply chain environmental performance is reached in relative terms. In contrast, the environmental criteria resulting from a full lifecycle approach is a better option for future public and private policies to reach more sustainable agro food supply chains.

CONTENTS

General Introduction

Green Supply Chain Management (GrSCM) has arisen as a philosophical and technical management framework derived from the well-known and proven effective Supply Chain Management (SCM) model. GrSCM synergy integrates the environmental pillar of sustainable development through Environmental Assessment (EA) within the taxonomy provided by SCM: all links in the supply chain have to be viewed in the context of an integrated system, providing the necessary framework to take a Life Cycle Approach to product and process design and improvement.

GrSCM means to answer fundamental tactical, operational and strategic business issues with the goal of optimizing multiple criteria simultaneously, mainly related to economic, operational and environmental performance. This approach has started to be applied in many sectors of the economy but is still in its initial development and adoption stage.

One sector that could benefit from this approach is the food industry. Food production has evolved through human history. Technological advancements have allowed civilization to overcome the Malthusian vision of limited resource and demographic expansion. But as food production systems have become more industrialized and globally distributed, allowing humanity to have a food plentiful epoch, they have also contributed in great measure to the negative effects on the natural ecosystems , accounting for a large share of the emission to the air, water and soil, through the production and use of synthetic chemicals such as fertilizers and pesticides, the use of fossil and other fuels for energy-intensive processing and transportation systems, along with other environmentally harmful practices.

Fueled by demographic and economic policies that promote growth and a consumer economy, the demand for sustainable food systems within nations and throughout the world has become imperative. Moreover, scientific advancement and social awareness have shifted political and business policies towards sustainable development goals, encouraging businesses and policy makers to find new ways to transform current systems through the scope of environmental awareness.

In that context, this work focuses on the application of GrSCM to two fundamental strategic questions targeting agro food supply chains. The former is related to the Green Supplier Selection (GSS) problem devoted to the farming production systems and the way they are integrated into the global supply chain network. The latter focuses on the global Green Supply Chain Network Design (GSCND) as a whole. These two complementary and ultimately integrated strategic topics are framed in order to evaluate and exploit the unique characteristics of agro food supply chains in relation to *organic* eco-labeling.

Eco-labeling is a marketing and policy tool that promotes the environmental improvement of production systems through the valorization of business efforts to design and implement better environmentally performing product lifecycles. In the case of the agrofood industry this is limited to the agricultural practices used to obtain raw materials, denominated as *organic certification*.

In order to illustrate and validate the feasibility and potential of the approach, an orange juice supply chain case study is developed. The general modelling strategy is exemplified in terms of a real system to facilitate its understanding. Furthermore, the case study is also developed numerically through historical and scientific literature data in order to implement and evaluate the feasibility and effectiveness of the proposed methodological framework. The obtained results are then analyzed and discussed.

The objective of this work is twofold: methodologically, the aim is to show that the implementation of GrSCM in the context of eco-labeled agro food supply chains is not only feasible but provides insights that would not otherwise be reached. Experimentally, under the assumptions used in the model, the goal is to highlight that with a single environmental criterion in the context of *organic* eco-labeled agro food supply chain network design, low to no improvement on environmental performance is reached by implementing *organic* eco-labeled marketing and pricing strategies. Both aspects are converging to demonstrate that a full lifecycle approach is a better option than the current single-level approach promoted by the *organic* eco-labeling scheme (centered only on the agricultural issue). Going forward, policies should change accordingly in order to capture the full *greening* potential that lies within the agro food supply chain.

The doctoral research presented in this thesis was conducted from September 2011 to September 2015 at the Laboratory of Chemical Engineering, LGC UMR CNRS 5503 INPT/UPS as part of the research area “Multi-objective optimization for the eco-design of industrial systems and processes” in the Design, Optimization and Process Scheduling Team (COOP – Conception, Optimization et Ordonnancement des Procédes) of the “Process Systems Engineering” (PSE) department.

The PhD scholarship was financially supported by the Mexican National Scientific and Technology Council (CONACYT), and by the Mexican Ministry of Public Education (SEP). This work stemmed from a larger research project that was initiated during my Master carried out at Instituto Tecnológico de

Orizaba (Mexico) under the master's thesis supervision of Alberto A. Aguilar Lasserre in collaboration with Gregorio Fernandez Lambert from Instituto Tecnológico Superior de Misantla (Mexico). During my PhD, this cooperation led to several publications that are related to this subject thesis and that are listed below (Fernandez Lambert et al., 2015, 2014; Miranda-Ackerman et al., 2014). The direct publications derived from the thesis work are also listed (Miranda-Ackerman et al., 2015, 2013a, 2013b).

The PhD manuscript is organized into six chapters. A brief description of the content of each chapter is presented hereafter. A more detailed presentation will be given at the end of the first chapter.

Chapter 1 *Motivation for the Study and State of the Art.* This first chapter gives an introduction to the motivations for targeting this research topic and the background of this PhD work. It provides key definitions and descriptions that serve throughout the manuscript.

Chapter 2 *Tools and Methods for Green Supply Chain Design.* The aim of this chapter is to present the tools and methods that are used to tackle the problems. It includes descriptions and procedures that are used and shared at the later chapters.

Chapter 3 *Supplier Selection through Partnership for Sustainability.* Modelling and optimization of the Supplier Selection Problem is developed through a theoretical framework and a case study serves as a test bench. It introduces the concept of Partnership for Sustainability that forms a part of the wider network design approach described in later chapters.

Chapter 4 *Modelling and Optimization Framework for Green Supply Chains.* The theoretical and mathematical framework for Green Supply Chain Network Design through Multi-objective Optimization dedicated to agro food supply chains is presented. A case study is used to illustrate the approach.

Chapter 5 *Solution Strategy for Green Supply Chain Network Design Problem.* A set of solution strategies that explore different pricing policies and objective function definitions is presented. A Multicriteria Decision Making approach is presented in order to evaluate and define the best solution alternatives. Lastly, results and conclusion are given on the optimization simulation outcomes.

Chapter 6 *Conclusions and Perspectives.* The main outcomes of the methodology developed and the observations made through its application to the case study are reviewed. In addition, some limitations to the work and perspectives are discussed as a gateway to further research.

Chapter 1 Motivation for the Study and State of the Art

Résumé

Ce chapitre souligne l'importance de trouver de nouvelles voies respectueuses de l'environnement pour concevoir et mettre en œuvre des chaînes logistiques. Il présente en particulier le contexte de l'industrie agroalimentaire en considérant les aspects économiques, sociétaux et environnementaux.

La valorisation des efforts réalisés pour accroître la qualité écologique d'un produit peut ainsi se manifester à travers le développement d'écolabels, signes de reconnaissance pour le consommateur final.

La philosophie de gestion d'une chaîne logistique est présentée dans ce chapitre introductif, notamment à travers le problème de la sélection des fournisseurs et de la conception du réseau de la chaîne logistique. Les différents outils d'évaluation environnementale pour compléter les objectifs exclusivement économiques et opérationnels de la gestion traditionnelle de la chaîne d'approvisionnement sont ensuite présentés. Leur intégration donne lieu au paradigme de la gestion de la chaîne logistique « verte ». La mise en parallèle du champ de l'Analyse du Cycle de Vie (ACV) et de la SCM montre le recouvrement des domaines, suggérant le recours à l'ACV comme outil d'analyse environnementale. Le problème de sélection des fournisseurs de produits « verts » et celui de la conception du réseau de la chaîne logistique « verte » sont décrits ainsi que leur adaptation au cas de du secteur agroalimentaire. Le cas d'étude de la filière du jus d'orange retenu dans le cadre du travail est justifié..

Abstract

This chapter emphasizes the importance of finding new ways to environmentally friendly design and implement supply chains. It also presents the agro food industry background and motivations for the study from an economic, societal and environmental viewpoint.

Environmental awareness of consumers can be promoted especially in the agro food industry as a means to differentiate products through "organic" eco-labeling. The Supply Chain Management (SCM) philosophy is presented along with some of its more important applications, mainly the Supplier Selection Problem and Supply Chain Design Problem. The different environmental assessment tools that exist to complement the exclusively economic and operational goals of traditional Supply Chain Management are then presented, their integration leading to the Green Supply Chain Management paradigm. The parallels of LCA and SCM are highlighted with the framing of the product life cycle, suggesting to select LCA as an environmental assessment tool. The Green Supplier Selection problem and the Green Supply Network Design problem are described as well as their adaptation to the specific scope of this study. The case study of the orange juice cluster is then justified.

Acronyms

AHP	Analytic Hierarchical Process
ANP	Analytic Network Process
DEA	Data Envelopment Analysis
GA	Genetic Algorithms
GrSCM	Green supply chain management
GSCND	Green supply chain network design
GSS	Green Supplier Selection
GWP	Global warming potential
INLP	Integer nonlinear program
KEPI	Key environmental performance indicators
KPI	Key performance indicators
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life cycle inventory assessment
MCDM	Multiple Criteria decision Making
MOO	Multi-objective optimization
MS	Multiple strength
M-TOPSIS	Modified Technique for Order of Preference by Similarity to Ideal Solution
NFCOJ	Not From Concentrate Orange Juice
NLP	Nonlinear program
NPV	Net present value
NSGA	Non-dominated sorting genetic algorithms
PfS	Partnership for Sustainability
SA	Simulated Annealing
SC	Supply Chain
SCM	Supply Chain Management

1.1 INTRODUCTION

Supply Chain Management (SCM) has provided in the last 30 years many advances in the scientific management of operations. It has allowed for managers and engineers to take a holistic approach to production and service systems. In general terms, it is a management paradigm that focuses on the flow of information, resources and money through the lifecycle of a product, and aims to optimize the performance of these flows. In the past, this optimization was limited to economic and operational objectives, but has now extended to include other important issues such as social and environmental ones. Current research has shown that in many industries, synergy can be obtained by integrating environmental performance into the SCM model. This has been facilitated by new strategies to measure and improve productions systems that have been developed. Some of the most widely studied are: (1) closed-loop supply chain management that focuses on waste integration between different production systems as raw materials and to the natural ecosystem, (2) reverse logistics - integrating the recovery of waste after products and intermediate products go through the product life cycle (e.g. bottles, pallets, e-waste, etc.) (3) Green Supply Chain Management that integrates environmental measurements as Key Performance Indicators to assess and optimize the overall performance of the SC.

This last approach is a promising strategy given that it provides a theoretical and practical framework for production systems integrating Supply Chain Management (SCM) and Environmental Assessment (EA). The former provides an outline to quantify and improve the economic and operational performance of productive systems by modelling the flow of materials, information and money, throughout the links in the production chain, with the end objective of economic profit. The latter (EA) involves techniques that allow measuring all or some key production stages in terms of environmental emissions and human health. It also provides a framework that translates measured emissions from production (e.g. tons of CO_2 emissions to the atmosphere) into their potential effects on the environment (e.g. Global Warming Potential). One of the most widely used technique is Life Cycle Assessment (LCA) to aid in the decision making process by providing a means to evaluate the impacts on human health, the ecosystem and the natural resource depletion at some or all the stages in the life span of a product, service or system (Jolliet et al., 2010a). By integrating these two approaches, the scope of SCM is extended to include key criteria offered by EA, thus allowing for the classical economic and operational objectives to be evaluated at the same time as social and environmental issues, when trying to holistically design or improve the overall performance of a production system in a sustainable viewpoint.

Although much progress has been made in this field, some of the key advantages and possible applications of the SCM model have not yet or only scarcely been included in GrSCM body of research (Eskandarpour et al., 2015): especially, the development of efficient multi-objective models that adequately addresses the different dimensions of sustainable development is considered as a cornerstone to tackle the problem. Concerning solution techniques, standard and powerful solvers have been the most widely used tools to solve the resulting models. However, the size and particularly the number of binary variables in practical supply chain problems often leads to difficulties for solving the model in a reasonable amount of time. This issue is even more crucial for adequately solving non-linear, stochastic or multi-objective models. Moreover, the coordination of the different levels of decisions involved in the SCM has been almost ignored in the sustainable SCND literature. Special emphasis is then placed in this work to consider the nonlinear and multi-objective nature of the GrSCM problem.

Moreover, the literature concentrates on specific rich models focused on a particular real-life application. For general industrial companies, there is a need to develop generic models. Although this issue is an important motivation, it is yet difficult to embed in a generic formulation all the peculiarities of various industrial fields. This work is devoted to the development of GrSCM concepts in the agro food cluster. The aim of the proposed framework is the optimization of the agrofood supply chain design, planning and operations through the implementation of appropriate green supply chain management and logistics principles. Some works such as (Bloemhof et al., 2015) have described the potential and different strategies that could be taken, as described hereafter.

Society has currently evolved to understand that the human activities, including food production, are damaging the natural environment. According to (Vermeulen et al., 2012), 19%-29% of global emissions of greenhouse gases come from agriculture and food production systems. Looking closer to the European Union this same pattern stands - where agriculture and food production are main contributors to emissions related to global warming potential (GWP). Furthermore, agriculture is the main contributor to other important environmental impacts, noticeably eutrophication with roughly a 50% share (Tukker and Jansen, 2006). Modern agricultural production systems use agrochemicals like fertilizers and pesticides, and fossil fuels for power machinery that have increased the environmental footprint of food production. Further, energy and water demand for food processing systems also play an important part. In addition, food production is setup as a globally distributed network of suppliers, manufacturers and consumers. Transportation of the raw materials and food products around the world in order to satisfy global demands has also played a large role on the environmental impact. These factors combine to form the economic and environmental profile of most food products consumed.

Most of the research works on improving the environmental performance of agro food productions systems has been done by parts, this is to say, many LCA studies have been performed to measure and study alternatives in the agricultural and food manufacturing process designs (Roy et al., 2009). Other studies have been carried out comparing scenarios or technological alternatives from an environmental point of view. Moreover, economic and operational improvements have been studied extensively from tactical, operational and strategic point of views for agro food SCs (Miranda-Ackerman et al. 2014). This work extends the studies carried out at the Instituto Tecnológico de Orizaba in Mexico, devoted to an integrated supply chain design approach through multi-objective optimization for the fresh fruit industry, where only operational and economic objectives are considered: it cemented the base of the modelling approach that is the core of this doctoral thesis.

Our work uses GrSCM as a platform to propose a modelling and optimization framework targeting agro food supply chains through the integration of SCM problems on Supplier Selection and ultimately Supply Chain Network Design with LCA principles.

It must be highlighted that there is a great emphasis to GrSCM for agro food industry, e.g. the first international conference on Agrofood Supply Chain and Green Logistics was held in Greece in May 2015. Many products and industries have adopted the use of eco-labelling as a means to promote and market products in terms of environmental impact process improvements, which has been especially significant in the case of the agro food industry. One of the most important eco-labels in the food industry is the "*Organic*" label, referring to the limited use of agrochemicals during the production process. Through the integration of the GrSCM concepts and their adaptation to the agro food SC characteristics, including *organic* eco-labelling, the objective of this PhD work is to contribute to the related body of knowledge and to extend the current approaches.

In this introduction chapter, a review of the state of the art - branching from green supply chain management is offered. Firstly, we present the Supply Chain Management paradigm with its main components and uses. In order to introduce the Green Supply Chain Management model that takes from SCM and refocuses it to include environmental issues, an introduction to Environmental Assessment (EA) and the current state of the art are proposed. The green component of the GrSCM approach is developed with focus on the LCA approach. The integration of SCM and EA into a single GrSCM framework is then proposed, leading to the two main issues that are tackled in this work, that are Green Supplier Selection and Green Supply Chain Network Design problems from a decision modelling and optimization viewpoint. It is trailed by an introduction into the importance of the agro food industry and its need for better and greener supply chain designs. Particular attention is given to the peculiarities that food supply chains have since raw materials sourcing is fundamental for agricultural systems. It also highlights the principles and use of *organic* eco-labelling in the food product industry. It finalizes with the introduction of the orange juice case study, the reasoning behind its illustrative selection and the possible ramifications of the technique to similar cases.

1.2 SUPPLY CHAIN MANAGEMENT

Current industrial enterprises are typically composed of multiples sites operating in different regions and countries satisfying a globally distributed clientele. Thus planning, coordination, cooperation and responsiveness between nodes in the network, made up by the different stakeholders are of essence in order to remain competitive and grow. The need for integrated and systematic strategies for plant coordination and operation is driven by the need to minimize capital and operating costs, improving output and maintaining market response flexibility, thus leading to the development of the Supply Chain Management paradigm (Hugos, 2003).

The "Supply Chain Management" term started to be used in the late 1980s and was popularized in the 1990s. Before SCM the terms *logistics* and *operations management* were used instead. In order to understand what SCM is - first one needs to define what a Supply Chain is:

> *"A supply chain consists of all stages involved, directly or indirectly, in fulfilling a customer request. The supply chain not only includes the manufacturer and suppliers, but also transporters, warehouses, retailers, and customers them-selves."*
>
> *-(Chopra and Meindl, 2001)*

Thus the concept of supply chain can be derived 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."*
>
> -(Mentzer et al., 2001)

It must be emphasized that currently SCM and logistics differ as concepts; the latter refers to activities within the boundaries of a single organization while the former refers to a network of companies that work together and coordinate their actions to provide products and services to markets. The companies that make up the SC network must make decisions individually and collectively on three levels (illustrated in Figure 1-1):

1. Strategic level: these are decisions with a long-term time horizon mainly related to long-term partnerships and capital investment projects. Some of the issues that are formulated are related to, e.g. the number, location, and capacity of warehouses and manufacturing plants and the flow of material through the SC network.
2. Tactical level: these are decisions with a medium-term time horizon mostly related to issues on purchasing, production planning, inventory planning, transportation, marketing and distribution policies and strategies.
3. Operational level: these are decisions on a day-by day-basis related to issues on weekly and monthly scheduling, planning, response to customer feedback, materials routing, information flow and collection.

The scope of this research focuses on strategic level decision making dealing with two main problems, i.e., supplier selection and supply chain network design.

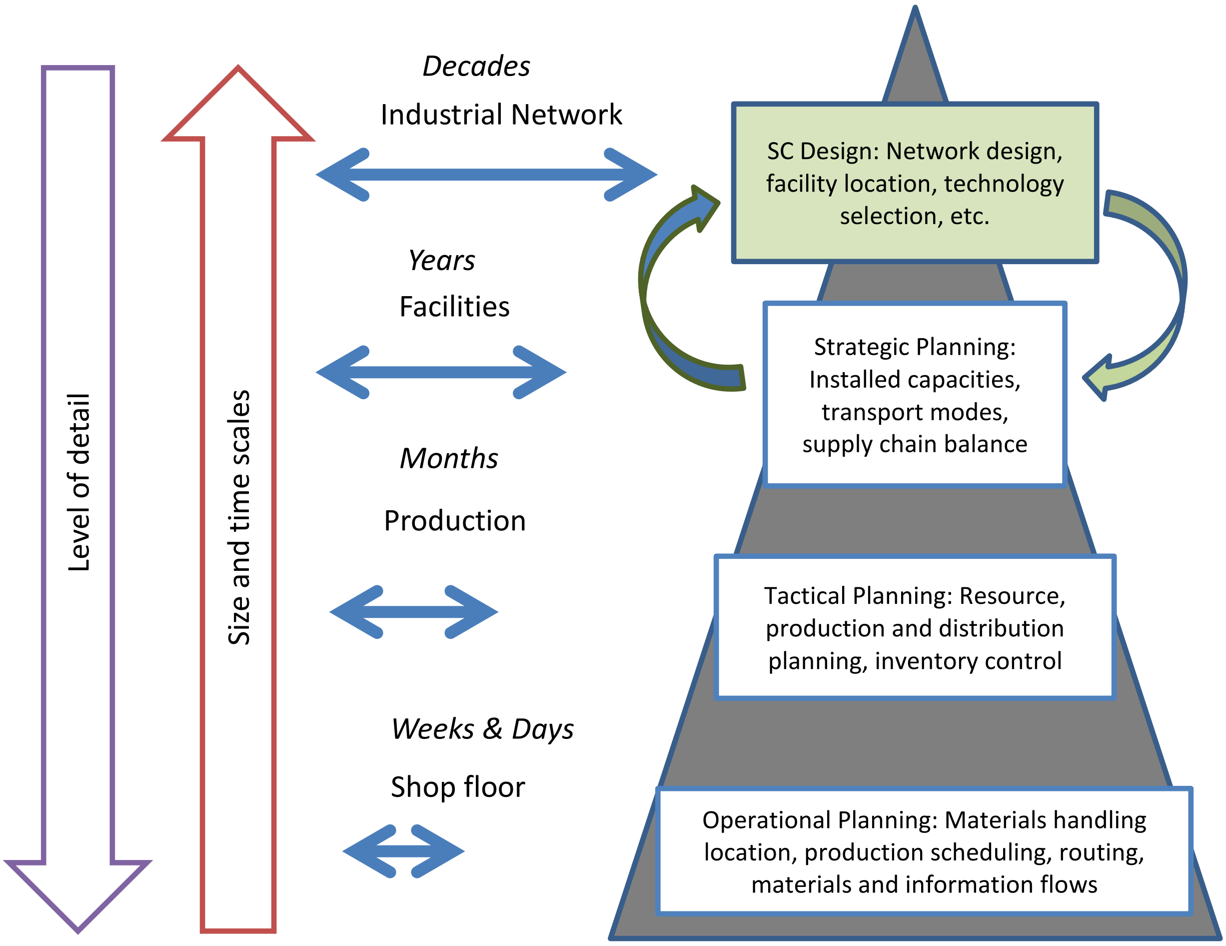


FIGURE 1-1 DIFFERENT LEVELS OF SUPPLY CHAIN MANAGEMENT PLANNING CATEGORIES ADAPTED FROM (GARCIA AND YOU, 2015)

1.2.1 SUPPLIER SELECTION PROBLEM

The role of purchasing has increased in significance as organizations are more dependent on suppliers having direct influence on performance of the whole supply chain. Suppliers provide the materials necessary for the Focal Company (FC) to manage the flow of products and services. According to (Seuring and Muller, 2008), the FC is characterized by being the designer or owner of the product or service offered, governing the supply chain, and having contact with all SC stakeholders. A key component to the FC's activities is the Procurement task.

Traditionally, the procurement was driven by the sole objective of minimizing cost by buying raw materials from the lowest cost supplier that could be found (Hugos, 2003). Procurement (that will also be referred interchangeably with "sourcing" throughout the manuscript) plays an essential role in all organizations; it consists of the activities to obtain the inputs needed in order for the organization to function. Two main types of products are managed through procurement: (1) direct or strategic materials, i.e. materials needed to produce the products the FC sells to its customers; (2) indirect or MRO (maintenance, repair and operations) products that are needed for daily operations. The indirect products are selected and bought based on short term goals, and do not influence the quality of the final product directly. The scope of this work is limited to the first type of products i.e. strategic materials, this is because they form a part of the product and in the case of agro food they can define the quality and perception the consumer has when purchasing.

According to (Hugos, 2003) procurement functions include: purchasing, consumption management, supplier selection, contract negotiation and contract management. The scope of this research mainly focuses on the Supplier Selection function, given its strategic importance in the context of agro food supply chains and *organic* eco-labeling strategies.

In order to guarantee that production planning goals can be met, suppliers have to be selected and contracted based on their characteristics in relation to the needs of the SC network. According to (Nyaga et al., 2010) strategic long-term partnerships "create unique value that neither partner can create independently". Through these partnerships, manufacturers aim to protect resources and technologies, develop suppliers' know-how, and ultimately improve quality and efficiency. Our work, developed in detail as a standalone supplier selection problem in Chapter 3 and part of a GSCND framework in Chapters 5 and 6, use this partnership advantage principle as the base of the problem formulation and solution strategy.

The Supplier Selection problem has mostly been formulated as a multiple criteria decision-making process. Some of the most important criteria being evaluated are related to price, quality, delivery time, responsiveness, historical performance, capacities, and geographical location, among many others (Degraeve et al., 2000). Many different approaches to solving this problem have been proposed mainly through quantitative methods. Some of the most important approaches have been through the use of technics such as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Fuzzy set techniques (Fuzzy-AHP, Fuzzy-ANP, etc.), Data Envelopment Analysis (DEA), Linear and Nonlinear Programing, Multi-objective Optimization (MOO), Metaheuristics (Genetic Algorithms (GA, Simulated Annealing (SA), etc.) (Ware et al., 2012).

MOO and Metaheuristics present some specific advantages over the other methods. Because they encompass a "black-box" mathematical modelling framework (Azzaro-Pantel et al., 2013), the evaluation of many criteria and different types of decision variables can be accommodated. This is especially important given that the supplier selection problem formulation that is proposed is formulated under the assumption that it is a component of a larger Supply Chain Network Design decision formulation. Under these two decisions, e.g. Supplier Selection and SC design, MOO solved through Metaheuristic methods like GA provide the power of efficiency of finding Pareto optimal trade-off solutions without the restriction on modelling and variable type that the other techniques hold. This is why the combination of MOO and GA is a significant factor of selection in the modelling and optimization strategy presented in this work. The supplier selection is presented as a black box multi-objective mathematical model that integrates different items of interest to the FC within a framework that uses a Genetic Algorithm optimization as an outer optimization loop. Through this formulation antagonistic objectives are considered, and many different factors that add complexity to the model, such as environmental performance measurement (that will be developed further down) can be integrated.

1.2.2 SUPPLY CHAIN NETWORK DESIGN

Supply Chains are viewed as networks of elements that involve suppliers, manufacturers, distributors among other stakeholders and reflect materials, information and economic flows. They are physically constructed of natural resource extraction facilities, processing facilities, manufacturing plants, trucks, sea vessels, warehouses, etc…, that are located in different locations around the world. Supply Chain Network Design (SCND) involves a decision and model framework that searches *"through one or a variety of metrics, for the "best" configuration and operation of all of these (SC network) elements"* (Garcia and You, 2015).

Some of the most important challenges that SCND holds reflect the issues that complex real systems face including for example decisions at multiple scales, multiple levels, multiple periods, multiple objectives and undoubtedly multiple stakeholders.

SCND consists in formulating the SC network as nodes and arcs that connect, featured in layers for each echelon that constructs the SC of interest (see Figure 1-2). In each layer, several alternatives are presented that can represent differences in modes of transport, technologies used, geographical locations of sites, among many other choices, while the arcs may represent attributes and criteria of interest such as distances, costs, time periods, etc. The process of optimizing the SCND is to find the best configuration of the network, this is to say, the best route of arcs and nodes that fulfil the single or multiple objectives that are of interest to the decision maker.

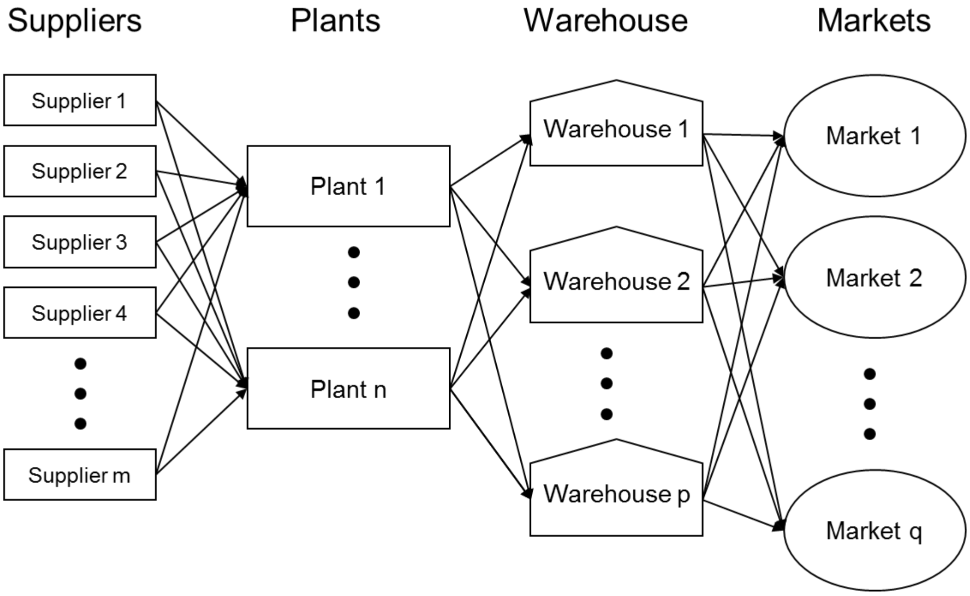


FIGURE 1-2 SUPPLY CHAIN NETWORK EXAMPLE

1.3 GREEN SUPPLY CHAIN MANAGEMENT

GrSCM is one of a few sets of approaches that try to harness the potential of SCM paradigms to counteract the poor environmental performance of production supply chains. Among some of the most well-known and developed techniques are:

Reverse Logistics (RL) is defined according to the American Reverse Logistics Executive Council as "the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" (Rogers and Tibben-Lembke, 1998). It focuses on the recovery of waste after final or intermediate product consumption to recover useful or valuable materials. Depending on the type of design of the product, this strategy can be used to guide product and manufacturing process design in order recycle, remanufacture, repair or dispose of more easily. In many states like the EU and the US have adopted this approach into policies. In the EU, e.g. the European end of life (ELV) directive and the

Waste Electrical and Electronic Equipment (WEEE) directive and in the US the Electronics Recycling laws, have been implemented under the principals of RL (Qiang, 2015). In the case of food products RL have played a large role, where mostly packing and packaging materials have been recovered through the history of the use of wooden boxes and pallets, as well as, glass and metal, and more currently plastic bottling containers.

Close-Loop Supply Chain Management (CLSC) is defined as "the design, control and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time" (Govindan et al., 2015). CLSC partially stems from Reverse Logistics, integrating both forward and reverse supply chains simultaneously. Resulting in networks that have closed loops of materials flows. Similar to the Industrial Ecology paradigm where the waste of one enterprise is the raw material of another, CLSC develop waste materials flow into by-products, that are recovered at different stages in the product lifecycle. This is to say, that material waste from the manufacturing process, distribution, and consumption can be included within the SC structure. Through this approach many externalities related to waste and emissions are internalized by design.

Green Supply Chain Management (GrSCM) is a fusion of Supply Chain Management (SCM) and Environmental Assessment (EA). The former provides a framework to visualize and improve the economic and operational performance of productive systems by modelling the flow of materials, information and money, throughout the links in the production chain, with the end objective of economic profit (Hugo and Pistikopoulos, 2005). The latter (EA), is a technique to aid in the decision making process by providing a system wide approach to evaluate the environmental impacts (EI) of a project or, of some or all the stages in the life cycle of a product (Jolliet et al., 2010a). By integrating both approaches the economic and operational objectives can be set side by side with sustainability objectives when trying to make decisions on design or improvements of the overall performance of a production system (see Figure 1-3).

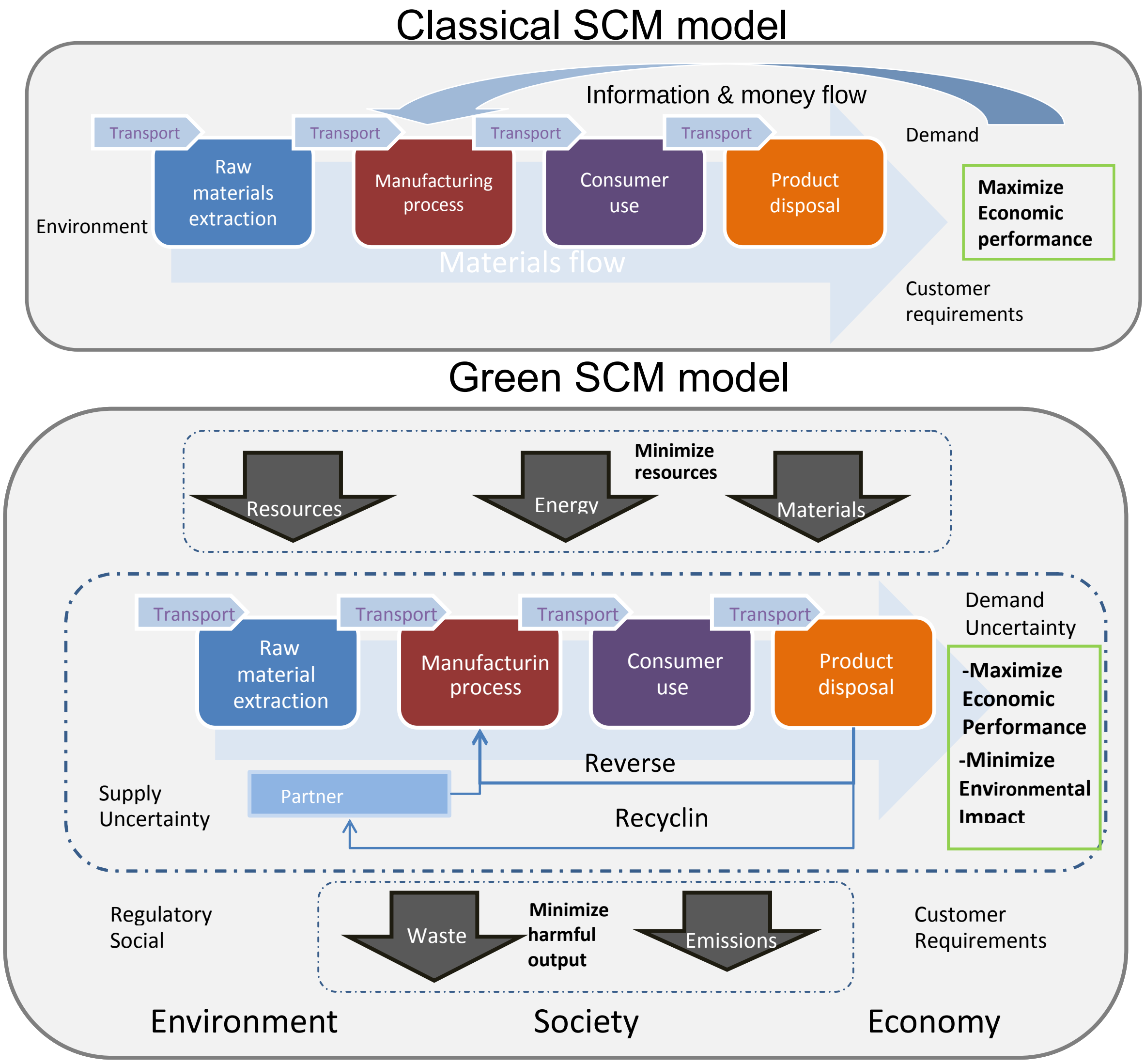


FIGURE 1-3 CONTRAST BETWEEN CLASSICAL SCM AND GRSCM MODELS

The main principle of this approach is that Key Performance Indicators, that are classically reserved for operational and economic evaluations, are extended to include Key Environmental Performance Indicators (Doublet et al., 2014). By applying this measurement strategy, emission *hotspots* can be identified and minimized or eliminated through strategic, operational or tactical design decision making.

While RL and CLSC schemes are well suited for products that have materials flows that produce valuable waste that can be reconstituted into valuable resources (e.g. consumer electronics, household appliances, vehicles, etc.), the situation is different in the case of agro food chains. There has been work done exploring the application of RL and CLSC to agro food chains. Some examples are issues related to packaging (e.g. bottles, containers, etc.) and packing (e.g. boxing, bagging, palletizing, etc…), as well as, biomass and other organic waste byproducts use as fertilizers and raw materials for bioreactors are among the more well-known and developed.

Having said that, the modelling approach explored in this work is limited to GrSCM, more specifically to the Green Supplier Selection Problem and Green Supply Chain Network Design Problem, respectively. Moreover, the focus on agro food SCs is made with the goal of evaluating various design strategies, as well as, pricing policies related to labeling that culminate in a highly complex modelling and optimization scheme. Nevertheless, the possibility of aggregating RL and CLSC into the proposed framework will constitute a potential extension of the proposed work as it will be highlighted in Chapter 6.

1.3.1 ORGANIC ECO-LABEL FACTOR IN GRSCM

The GrSCM model that is proposed in this work includes environmental performance - as a quality characteristic of the product alongside the traditional ones (qualitative and quantitative). This makes for a novel approach to understand and evaluate the effect that being "Green" has over supply chain decisions given that *greening* of the product adds market value (Loureiro et al., 2002; Oakdene Hollins Research and Consulting, 2011; Roheim et al., 2011). Furthermore, this is proposed in the context of agro food supply chains instead of looking at the problem merely from a marketing point of view. Agro food SCs are special because they provide food for human consumption and thus require special attention to attributes related to sensorial, health safety and environmental quality. In additions, these systems integrate agricultural systems into the SC network given that strategic raw materials sourcing are mainly from agricultural production. These agricultural systems act as the raw materials suppliers that define a large part of the quality of the final product. Because of this a large part of the value the customer gives the product depends on the quality the strategic material sourcing.

Market demand for higher quality, safe and more environmentally friendly products is now applying pressure on the production companies (Bougherara and Combris, 2009). New market niches that are willing to pay for higher priced products (Eco-label premium price) should be evaluated when designing and improving production systems (Roheim et al., 2011).

Consider then that a new product quality attribute is now being attached to environmentally produces/processed products. This new attribute is marketed through eco-labels such as: *organic, bio, green, eco-friendly, etc*. More specifically eco-labels in the scope of this research are limited to the rules and regulations of the EU.

The concept of “EU Eco-labels” is highly restrictive and limits its use to certain products. Food products are not included in the EU Eco-label scheme. Nevertheless an eco-label (in the wider sense of the term) can be used under the Organic certification scheme.

EU Organic certification eco-label scheme aims at improving environmental impact of production and consumption of agricultural products. This certification scheme is regulated by *EC Council regulation No 834/2007 on organic production and labelling of organic products and repealing Regulation ‘EEC) No 20029/9.* In summery promotes the use of natural means to obtain agricultural products that limit the use of agrochemicals and other farm management practices that are known to have a negative effect on the environment.

These new *green* attributes changes the market value and pricing of the *organic* eco-label products. Although this type of labelling has been widely used since the 1990’s in the US and 1980’s in France (Dobbs et al., 2003), and has continued to be implemented to many food products in many other countries around the world (Grunert et al., 2014; Upham et al., 2011); little research has been performed to include their effects on the supply chain modelling and optimization process.

Indeed, this gap in the scientific literature provides an interesting research subject. This is to say, the methodological approach tackled in this work has the objective to consider this eco-friendly preference and marketing trends born from eco-labeling, and to integrate them within the current GrSCM modelling and optimization methods. The typical issues that are addressed in this manuscript in terms of the relationship between *organic* eco-labeling and SCM are the following ones:

- Production design problem: which agricultural practices should be used to add *green* value to the product at the raw material production stage e.g. optimal use of pesticides, fertilizers, gasoline powered machine, etc. or which technologies should be chosen e.g. sorters, centrifuges, container, chillers, etc. to green the processing process?
- Product mix problem: which should quantity of each quality-type orange juice be produced (e.g. organic or non-organic)?
- Location-allocation problem: which region and how many orchards should produce environmentally friendly oranges and which and how many orchards should use intensive agricultural? Where should bottling site be located and what kind of technology should be used?
- Sourcing decisions: which suppliers to buy from? How much to buy? Which criteria to use to evaluate supplier performance? What agro practices should be used?

- Pricing policies: “What if” the market paid a premium on an *organic* eco-labelled product, what environmental improvement could be made to the supply chain to maintain or improve profit margins? What is the breakeven point market-price needed to reduce X% of EI while maintaining profitability?

This PhD work proposed to answer these questions through a multi-objective optimization approach as described in chapters 3 through 5.

1.3.2 GREEN SUPPLIER SELECTION

In the field of supplier selection, there is a wide body of publications looking at many different aspects such as formulation, method and application (Amin and Zhang, 2012), including recent works on green or sustainable supplier selection. Although Green Supplier Selection (GSS) has been named in different ways such as Green Vender, Green Purchasing, Environmental Purchasing, most definitions in general coincide in its reach. In (Zsidisin and Siferd, 2001) the authors define GSS as *“… the set of purchasing policies held, actions taken and relationships formed in response to concerns associated with the natural environment.*” It goes on to clarify that “*These concerns relate to the acquisition of raw materials, including supplier selection, evaluation and development…*”. This integration is promoted because of the benefits that the interaction of the different members of the supply chain produces not only on sustainability issues but also on economic and operational performance (Walton et al., 1998). A recent review on green supplier selection has highlighted some interesting research challenges (Tate et al., 2012). According to these authors, the integration of Life Cycle Assessment in the definition and measurement of environmental criteria offers an interesting methodological framework, since it involves a system wide approach for environmental impact evaluation. Some other examples of GSS have been published for industries such as electronic and consumer goods, (Humphreys et al., 2003; Lee et al., 2009). A study on the effectiveness of a large scale Sustainable Supplier program in Mexico by (van Hoof and Lyon, 2012) showed how this Green Supplier Selection strategy can be implemented.

Following a similar strategy, this work suggests the incorporation of specific elements of LCA in the multi-objective decision making process in selecting suppliers that will eventually become SC partners. Furthermore, intrinsic characteristics of agro food supply chain hold an especially challenging decision formulation. This is because elements such as *organic* eco-labels based on supplier agro practice and globally distributed processing stages of production add complexity. The advantage of using this approach is that it can be coupled with other strategic decision-making processes such as those that GSCND searches to answer.

1.3.3 GREEN SUPPLY CHAIN NETWORK DESIGN

Green Supply Chain Network Design (GSCND) integrates the environmental impact measurements as additional criteria to be considered at earlier design stage, encompassing the location and allocation of production and resource capacities, transportation network between locations, technology selection (e.g. equipment, work practices, etc.). GSCND gives an emphasis on characterizing the use of resource such as energy and materials as sources of pollution, and may consider their impact on natural environment and human health. The case study will show that the optimal solutions for each single objective, either economic or environmental are different and exhibit antagonist behaviour. As suggested by (Eskandarpour et al., 2015), LCAs have been widely used in their full form or used to calculate one or more LCA indicators in order to integrate the criteria into optimization models. Indeed, due to limited resources businesses have to manage and operate, a full LCA implementation is not always feasible. But because social and economic pressures are converging industry towards environmentally sound production processes and products, gradual integration of environmental assessments is currently underway. By using partial environmental assessment, logistics and supply chain issues can improve current SCND decision processes (Eskandarpour et al., 2015). This philosophy guided the work that is presented in the body of this thesis, taking into consideration only the Key Environmental Performance Indicators (KEPI) that are needed to reflect the environmental preference of the stakeholders and decision makers in the orange juice application.

1.4 ENVIRONMENTAL ASSESSMENT

According to Sadler (Sadler, 1996), environmental assessment is defined as "*a systematic process for evaluating and documenting information on the potentials, capacities and functions of natural systems and resources in order to facilitate sustainable development planning and decision making in general, and to anticipate and manage the adverse effects and consequences of proposed undertakings in particular*". There are many different procedures and methods to assess the environmental issues or impacts of plans, projects and programs. Among the most important and widely used are:

1) **Materials Flow Analysis (MFA)** is relative to family of methods that focus on materials flows emphasising on inputs. Three examples of this method category are the Total Materials Requirement, Materials Intensity per Unit Service and Substance Flow Analysis.
2) **Input-Output Analysis (IOA)** consists in an analytical tool within economics and systems of national accounts that define the scope and objective of study in terms of nations and regions. It mainly focuses on the trade between industries, applying environmental impact evaluation through substitution of monetary measurements of input-outputs in economic

terms to physical materials flows. These are mostly applied to specific industrial sectors and broad product families.

3) **Environmental Impact Assessment (EIA)** is a mature tool used to assess environmental impact of projects. It is mainly applied to a site specific scope, where the EIA are used to evaluate alternative locations for projects in terms of environmental emissions.
4) **Life Cycle Assessment (LCA)** is a tool to assess the environmental impacts and resource use throughout a product or service lifecycle. Its scope can vary depending on the objectives of the study but mostly reflect the full lifecycle from raw materials acquisition through to product or service use and disposal.

Each method has its own advantages and disadvantages related to scope, applicability, maturity, feasibility, among other criteria. Among these, LCA is one of the most well-known and powerful tools (Finnveden et al., 2009; Heijungs et al., 2011; Manuilova et al., 2009). Although there is no single tool or approach to address all the problems of environmental management, it provides an especially useful framework to integrate with SCM paradigm. The parallels of LCA and SCM are related with the framing of the product life cycle: in both methodologies, each step is strongly connected to the previews and forward links through the exchange of material flows. Furthermore, the scope that characterizes LCA, i.e. raw materials through consumption, is shared by the SCM model. SCM taxonomy allows for LCA to be used seamlessly without any adaptation or limitation. This explains, among other reasons that are presented in detail along the thesis, why LCA was selected as the best Environmental Assessment tool for the problem being studied.

1.4.1 LIFE CYCLE ASSESSMENT

As abovementioned, Life cycle assessment (LCA) evaluates the environmental impacts of products, processes and services. The results of LCA can identify major emissions, thereby enabling detection and measurement to target and verify improvements.

LCA evaluates the material and energy flows involved in the whole life cycle of the product, and can be classified as follows:

- Elementary flows: consist of flows that each process exchanged with the ecosphere: *primary resources* as water, fuels, minerals..., and *waste emissions* as solid waste, effluents and gaseous emissions.
- Intermediate flows: material or energy flows between the different stages of the life cycle.

For an adequate interpretation of the results that will be generated by an LCA, the goal must be appropriately defined and will guide the LCA operator to manage and focus the efforts to collect the information that best suit the purpose and interpret the outcomes appropriately.

According to (Jolliet et al., 2010b), LCA evaluates the environmental impact of a product, service or system related to a particular function, considering all stages of its life cycle. It identifies all the points on which a product can be improved, thus contributing to the development of new products.

From the LCA investigations that were already implemented and mentioned in numerous studies, (Jolliet et al., 2010b) for instance, several strengths of the LCA methodology can be highlighted.

- In eco-design, LCA can help to take into account environmental criteria during the design phase of a new product or product improvement already created. This is typically one of the first motivations of this work.
- In the evaluation and improvement of product, LCA can identify critical areas on which it is possible to focus to optimize the environmental performance and to compare different manufacturing processes.
- LCA can also be useful to support decision for the implementation of either industrial (choice of design, product improvement, selection of procedures, etc.) or public policies (choice of recovery processes, eco-labelling criteria, etc.).

The objective of this study is to use the information that is provided by the LCA tool for agro food production systems.

Two main advantages can be found by using LCA for agro food supply chains:

1. When using LCA, the system can be optimized from an environmental viewpoint taking key performance indicators endogenous to agricultural and food processing systems into account, for instance by measuring acidification and eutrophication related to agricultural practices and CO_2 emissions related production, transportation and other stages in the agro food SC.
2. The second advantage is comparability. When comparing different agricultural practices, processing technologies, facility location, etc. (e.g., evaluating the installation of electric or gas energy consuming food processing technologies), LCA can provide quantitative results, thereby enabling comparison of each technology on an equal footing.

The application of LCA requires a protocol defined by the International Organization for Standardization (ISO) that has developed and formalized a series of standards for the Environmental

Management. These standards include the ISO-14040 (International Standard Organization, 1997), which describes the principles and framework for LCA and ISO-14044 (International Standard Organization, 2000), which explains the requirements and guidelines of LCA. The guidelines of the LCA approach are outlined in Chapter 2.

1.4.2 LCA SOFTWARE TOOLS

Nowadays, many LCA software tools have been developed based on the LCA methodology. Most of them include a certain number of databases and impact assessment methods.

These tools facilitate the estimation of total emissions and extraction for the LCI as well as the calculation of characterization, damage and normalized score. Some of them generate a report with the results obtained through graphs. Evaluation of scenarios and sensitivity analysis are other optional features of these software tools. Some of the LCA software tools currently available on the market are: TEAM (Ecobilan-PriceWaterhouseCooper), GaBi Software (PE INTERNATIONAL,) Umberto (IFU Hamburg GmbH), SimaPro (PRé Consultants). Each software tool has advantages and disadvantages mainly related to flexibility and ease of use, data base inclusion and pricing

Most environmental impact indicators needed for the model parameters were obtained from published LCA studies that will be mentioned in the dedicated sections of the manuscript. Partial environmental assessment factors were evaluated and information obtained through the SimaPro software (see Chapter 2) that was available in our research team and is one of the most widely used LCA software in academia and industry.

The environmental impact results are available through graphs or tables that can be exported. Several processes or scenarios can be compared leading to the development of representative key environmental performance indicators for alternatives in each set in the supply chain model detailed in Chapters 2, 3 and 5.

1.5 AGRO FOOD INDUSTRY

1.5.1 IMPORTANCE OF GRSCM IN AGRO FOOD CHAINS

Agro food industry has two main and highly linked facets that demand research attention: economic and environmental issues at the macro level. During the second half of the past century global food supply and distribution developed rapidly in order to keep up with demographic growth, leading to improvements in affordability, reliably and food safety in many regions (Vermeulen et al., 2012). These gains have led to the depletion of natural resources such as fresh water, land soil, forest, and oceans, among many others. According to (Vermeulen et al., 2012), *"Future food security for all will* *ultimately depend on management of the interaction trajectories of socioeconomic and environmental changes.”*. Food chains are constructed by activities like manufacturing and distribution of inputs like fertilizers and pesticides, agricultural production, primary and secondary processing, packaging storage, transport and distribution. In addition, materials handling is in many cases subject to “cold chains” this is to say (energy demanding) refrigerated materials handling and storage. Each and all of these factors contribute to the environmental impact that the natural environment and ultimately society are facing.

According to European commission website on Enterprise and Industry (http://ec.europa.eu/enterprise/sectors/food/index_en.htm), the food industry is the second largest manufacturing sectors in Europe; roughly 15% of the manufacturing turnover is estimated at €917 billion. This is driven by economic and social policies that promote continuous population and economic growth at unsustainable rates. Furthermore, popularity for standard food products and food commodities has promoted consumption patterns that could be judged as inefficient, e.g. having fresh oranges available around the world year round.

The research presented here limits its scope of application to food production systems that exhibit similar characteristics to the case study, i.e., orange juice supply chain. Data collection and analysis of this case study was initiated in my Master’s Degree thesis work. It focused on Mexican lime fresh fruit supply chains that addresses an important share of the global economic and environmental impact related to human consumption of goods.

Furthermore, according to (Beske et al., 2014) *“…consumers are becoming more concerned with the (food) products they consume, including their origin, the inputs used during production, the labor standards implemented, e.g. by farmers and food corporations, the treatment of animals, and the environmental impact of production.”.* Stating this as a main source of scrutiny by society that requires attention, the abovementioned study highlights that organic food along with fair trade initiatives are of special importance. The work we present follows this belief and centers special attention on organic production.

The food logistics structure is evolving towards integrated systems (Cristina Gimenez, 2006). Different logistics structures are used in food SC made up by producers, distribution centres, central nodes (in hub and spoke systems), and retailer, among others. These network designs are important given the sources of environmental impact related to materials handling and transportation that is estimated to account for 13.5% of global greenhouse gases, made up of the “food mile” concept that refers to the total distance the components of food products travel to reach consumers (Ala-Harja and Helo, 2014). Modern food industry has become industrialized mass producing and distributing at a global scale (Beske et al., 2014). According to (Beske et al., 2014) "*Globalization along with changing marketing techniques, consumption trends, and modern technology has simultaneously raised concerns in regards to the economy, society, and the environment.*". These observations make the use of GSCND in agro food industry essential going forward.

1.5.2 ORANGE JUICE CLUSTER

The **orange juice case study** that is used and developed throughout the thesis holds good properties as a test bench. First, orange juice industry is globally distributed, where the European Union (EU) is the top consumer market with approximately 11 275 million litres consumed every year according to the "AIJN 2012 Liquid Fruit Market Report", and where between 75% (for Non From Concentrate orange juice) and ~90% (From Concentrate orange juice) comes from outside the EU, mostly from warm and humid countries like Brazil and Mexico (Aintzane Esturo, 2013). One is that it is a very well-known and studied case from different research perspectives. From a process design many studied on the more important unit operations processes and related equipment have be well studied from economic, energetic and operational point of view (Alves and Coelhoso, 2006; Charles-Rodríguez et al., 2007; Ho and Mittal, 2000; Jesus et al., 2007; Mújica-Paz et al., 2011; Sampedro et al., 2013); more importantly and recently from an Environmental impact point of view. Research from (Doublet et al., 2013; Dwivedi et al., 2012) has provided sound reference for the environmental impact assessment overview of the standard orange juice production system. While (Knudsen et al., 2011) provides environmental impact insight that extends and focuses on the globally distributed aspect of an orange juice production system, in particular Brazilian export to Denmark. Lastly (Beccali et al., 2010) provides a detailed outlines for multiple products related to citrus production, including orange juice. The development and scope definition laid out in this manuscript was inspired by this last study. Based on this fruitful body of documental research accessibility, the importance of the fruit juice industry worldwide and previews research experience within the citrus fruit family made the orange juice case study an ideal test subject for the approach. It is introduces and described in detail in Chapter 2 through 5.

1.6 CONCLUSION

Green Supply Chain Management provides an integrated systems approach to improving food supply chains, that are important given socioeconomic drivers and environmental imperatives. Since food supply chains depend largely on their supplier network, and due to the foreseen widespread use of the eco-labeling, concerning especially *organic certificated* food products, the GrSCM issue constitutes a research challenge. The integration of all the elements presented in Chapter 1 constitutes the basis of the methodological framework that will be presented in Chapters 2 to 5.The outline of the thesis manuscript is presented in Figure 1-4.

- Chapter 1 gives a brief overview of the organizational and modelling GrSCM paradigm in order to frame the research issue that is tackled in this work. In addition, the scope of application of the method is described and the case study is introduced.
- Chapter 2 presents the concepts, methods and tools that will be used to develop an integrated framework to overcome the challenges faced by the agro food industry. These include the Environmental Assessment methods, the description of the process steps within the scope of the research, the modelling and solution strategies, as well as a review of multicriteria decision-making methods used.
- Chapter 3 formulates and solves the Green Supplier Selection problem through a case study. It provides philosophical and practical requirements to develop a Partnership for Sustainability between the suppliers and the focal company.
- Chapter 4 develops a theoretical and mathematical framework to integrate many key strategic decisions into a Green Supply Chain Network Design problem, and illustrates its application in the agro food industry through the orange juice cluster.
- Chapter 5 presents the solution strategies proposed to solve the problem formulation that was the core of Chapter 4 and provides numerical results.
- Finally, Chapter 6 presents some general conclusions related to the proposed strategy as well as prospective for future work that derives from these findings.

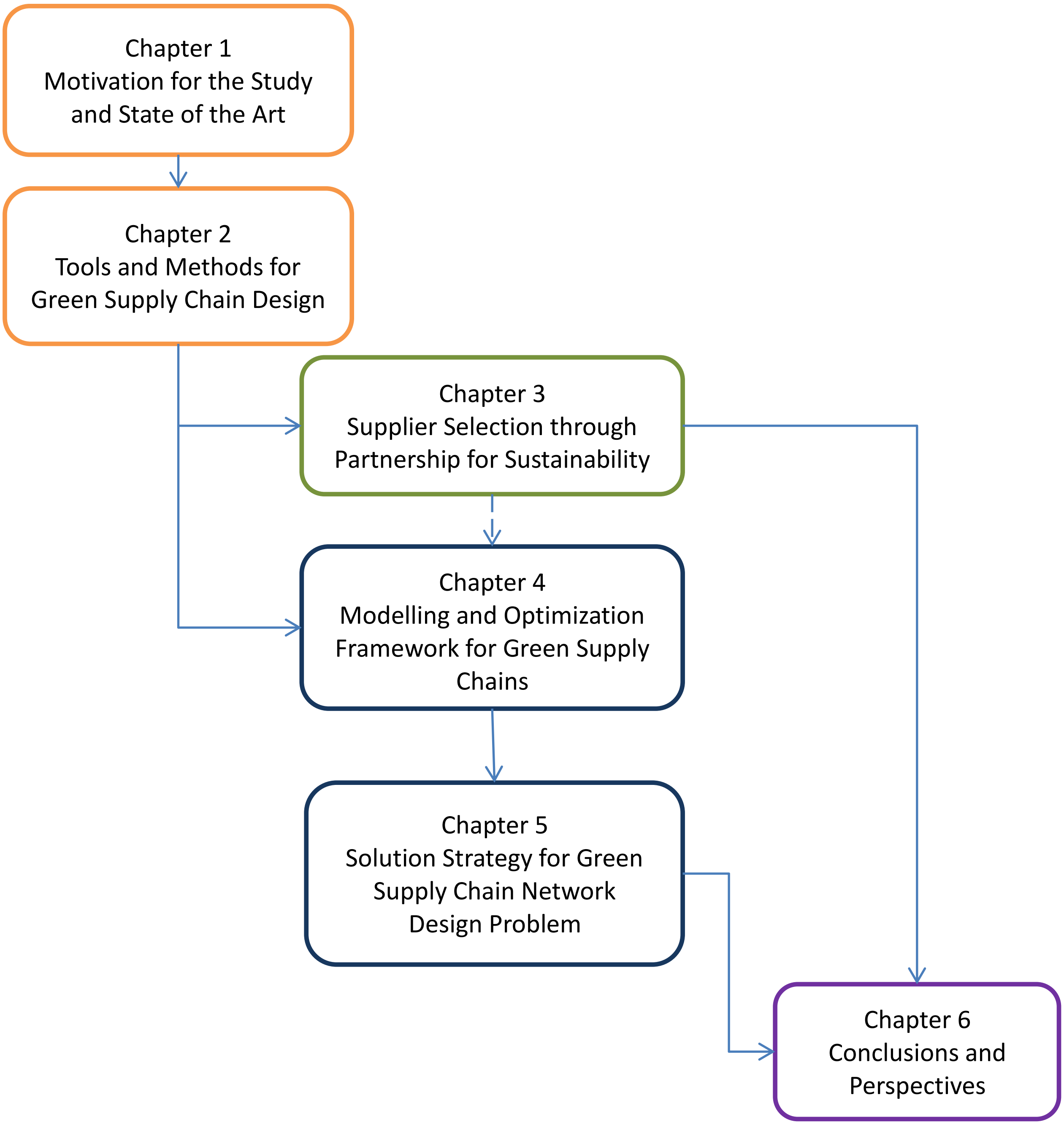


FIGURE 1-4 SCHEMATIC DESCRIPTION OF THE MANUSCRIPT

Chapter 2 Methods and Tools for GrSCD

Résumé

Ce deuxième chapitre présente de façon détaillée les principales méthodes et techniques adaptées et mises en œuvre pour résoudre les problèmes liés à la conception et à la gestion de la chaîne logistique « verte » dans le secteur agroalimentaire, notamment pour le cas de la filière du jus d'orange. Il souligne l'intérêt de l'utilisation de l'ACV comme méthode systémique d'analyse environnementale et la similitude de certains concepts avec ceux de la modélisation de la chaîne logistique verte. Les pratiques agricoles et les procédés industriels du cas d'étude sont décrits. Ces concepts forment la base de la formulation des différentes décisions relatives à la conception du réseau de la chaîne, incluant les choix logistiques, les pratiques agricoles et les alternatives technologiques des procédés. Ces choix sont importants car ils ont un effet sur les performances du réseau global. Le cadre d'optimisation multi-objectif basé sur des algorithmes génétiques et l'outil d'aide à la décision M-TOPSIS sélectionnés et utilisés dans la thèse sont ensuite présentés.

Abstract

This second chapter presents a thorough description of the main methods and techniques that are adapted and implemented to solve the problems related to the green supply chain design and management in the agrofood sector dedicated to the orange juice cluster. It highlights LCA alignment to green supply chain management issues. A description of agricultural practices and industrial processes that make up the case study is presented. These concepts form the base to formulate the different decisions related to the alternatives the supply chain network can take, including logistical choices, agricultural practices, as well as process technology alternatives. These choices are important given their effect on the performance of the overall supply chain network. The multi-objective optimization framework based on Genetic Algorithms and the decision-making tool, M-TOPSIS that are selected and used throughout the thesis are then presented.

Acronyms

FCOJ	FROM CONCENTRATE ORANGE JUICE
GrSCM	GREEN SUPPLY CHAIN MANAGEMENT
GSCD	GREEN SUPPLY CHAIN DESIGN
GSCND	GREEN SUPPLY CHAIN NETWORK DESIGN
GWP	GLOBAL WARMING POTENTIAL
HHP	HIGH HYDROSTATIC PRESSURE
HHP	HIGH PRESSURE PROCESSING
INLP	INTEGER NONLINEAR PROGRAM
KEPI	KEY ENVIRONMENTAL PERFORMANCE INDICATORS
KPI	KEY PERFORMANCE INDICATORS
LCA	LIFE CYCLE ASSESSMENT
LCI	LIFE CYCLE INVENTORY
LCIA	LIFE CYCLE INVENTORY ASSESSMENT
MCDM	MULTIPLE CRITERIA DECISION MAKING
MOO	MULTI-OBJECTIVE OPTIMIZATION
MS	MULTIPLE STRENGTH
M-TOPSIS	MODIFIED TECHNIQUE FOR ORDER OF PREFERENCE BY SIMILARITY TO IDEAL SOLUTION
NFCOJ	NOT FROM CONCENTRATE ORANGE JUICE
NLP	NONLINEAR PROGRAM
NPV	NET PRESENT VALUE
NSGA	NON-DOMINATED SORTING GENETIC ALGORITHMS
PEF	PULSE ELECTRIC FIELD
PfS	PARTNERSHIP FOR SUSTAINABILITY
SC	SUPPLY CHAIN
SCM	SUPPLY CHAIN MANAGEMENT
SS	SINGLE STRENGTH
TOPSIS	TECHNIQUE FOR ORDER OF PREFERENCE BY SIMILARITY TO IDEAL SOLUTION

2.1 INTRODUCTION

Chapter 1 presents an overview of the current state of the art relative to Green Supply Chain Design (GSCD) in terms of the paradigms and technics that are integrated in this work. Chapter 2 develops the key elements that will be further used throughout the research work and that form the basis for all chapters hereafter. This Chapter is divided into two main sections. Section 1 is devoted to an overview of the Life Cycle Assessment method due to its key role as the *Greenness* measurement tool. Through the scope of LCA, a description of agricultural and industrial processes that make up the case study is presented. These concepts form the base to formulate the different decisions related to the alternatives the supply chain network can take, including logistical choices but also agricultural practices, as well as process technology alternatives. These choices are important given their effect on the performance of the overall supply chain network. Section 2 is then dedicated to a thorough description of the modelling, optimization and decisions analysis tools that are selected and used throughout the thesis. Each component and its integration in the global approach is presented and justified.

2.2 LIFE CYCLE ASSESSMENT AS AN ENVIRONMENTAL ASSESSMENT METHOD FOR A SUPPLY CHAIN

During the last years, climate change and other environmental threats have come more into focus by society, governments and enterprises. Nowadays, environmental considerations are integrated as an important element in the evaluation of projects and other decisions made by business, individuals, and public administrations. For this purpose, the development and use of environmental assessment and management techniques to better understand the environmental impacts have been required. These techniques aim at identifying opportunities for reducing the environmental impacts and risks of projects, processes, products, and services. Environmental management systems (EMS), life cycle assessment (LCA), industrial ecology and symbiosis, and design for the environment (DFE) or ecodesign, are all areas of study that may be closely linked to green supply chain management. Due to its normative implications, Life Cycle Assessment (LCA) method is now broadly applied in many fields including agriculture and food productions (Bloemhof et al., 2015; Brentrup et al., 2004; Cellura et al., 2012; Doublet et al., 2014; Milà i Canals et al., 2006).

LCA provides a well-developed and comprehensive framework to measure and compare different project possibilities. In additions, it matches seamlessly with the SCM paradigm. Both methodologies take a holistic approach, integrating each of the stages of the product life cycle. This is especially useful in food production because of the initial and intermediate stages food products go through that require evaluation. LCA assesses the environmental impact of products, process and services. Identifying major emissions in order to target improvements objectively. It is composed of four main phases (illustrated in Figure 2-1):

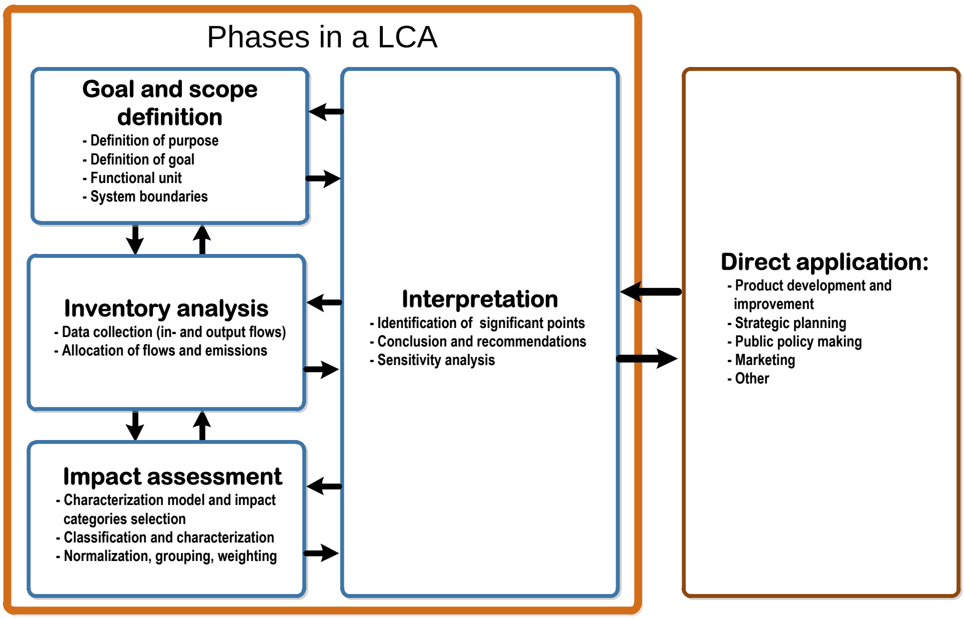


FIGURE 2-1 LCA FRAMEWORK (ISO 14040:1997)

(1) Goal and scope definition: definition of the objective and scope involved and accurate description of the study characteristics, its purpose, stakeholders and possible applications. The scope determines which product system or process will be analysed, the unit processes evaluated, functional unit, system boundaries, impact categories, data requirements, and limitations.

The *unit process* describes a stage within the life cycle and serves as a basic element of the assessment. The identification of unit processes facilitates the quantification of the inputs and outputs flows at each processing step. The group of *unit processes* makes up the *product system* that can involve production, use, and disposal of the product or service depending on the *system boundaries*. The *system boundaries* specify the unit processes that are included in the LCA. The accuracy in defining the *production system* and *system boundaries* have strong implication on the results that are obtained.

Further, it is necessary to define a reference unit to quantify the inputs and outputs flows; this is done through the Functional Unit (FU). The FU must be fully specified and measurable, and forms the basis for comparing alternative *production systems*.

(2) Inventory analysis: it Involves data collection and calculation procedures to quantify input and output flows of the product system. Data for each unit process within the system boundary includes

energy and raw materials flows, products and co-products, waste and emissions to air, water and soil (see Figure 2-2). Data for each unit process are either provided directly from industry or using an LCI database, such as Ecoinvent, European Life Cycle Database (ELCD) or US life cycle inventory database. Databases provide industrial data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services for a variety of generic unit processes that allow for the development of more complex product systems (Ecoinvent Center, 2010).

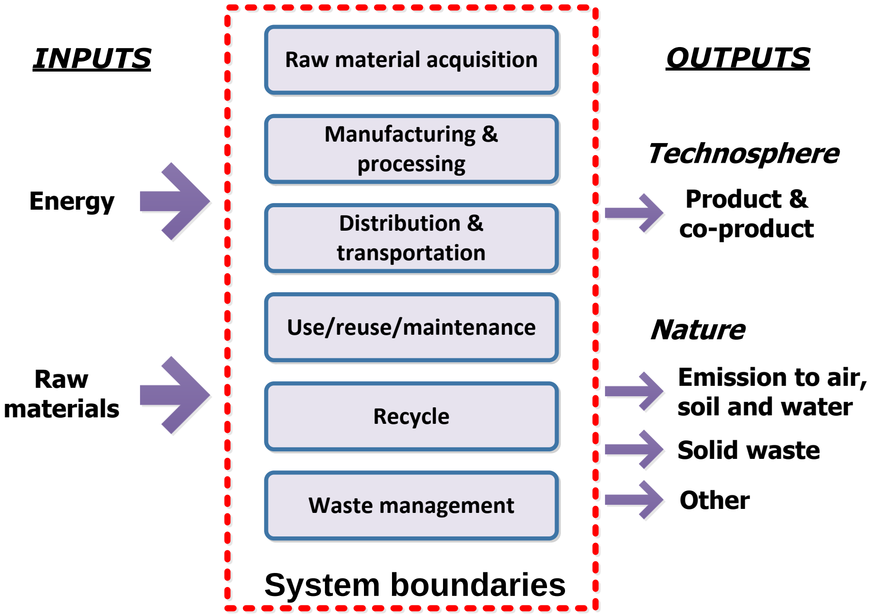


FIGURE 2-2 LIFE CYCLE INVENTORY ANALYSIS BASIC DIAGRAM

<u>(3) Impact assessment:</u> Life Cycle Impact Assessment (LCIA) stage uses the results from the LCI and evaluates its significance of potential environmental impacts. The structure is composed of mandatory and optional elements as illustrated in Figure 2-3.

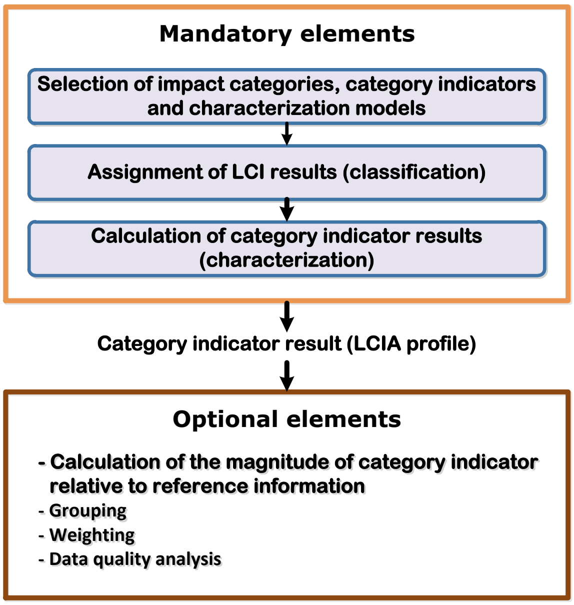


FIGURE 2-3 ELEMENTS OF LCIA (ISO 14042:2000)

This steps result in the categorization of environmental impact based on different criteria grouped into damage categories. These damage categories reflect where the impact has its effect e.g. human health, ecosystems quality, climate change, etc. For the sake of illustration, Table 2-1 features the characterization, reference substances and flow used in the IMPACT 2002+ LCIA methodology developed at the Ecole Polytechnique Fédérale de Lausanne in Switzerland (Jolliet et al., 2010a).

TABLE 2-1 CHARACTERISATION REFERENCE SUBSTANCES AND REFERENCE FLOW USED IN IMPACT 2002+ (BASED ON (MARGNI, JOLLIET, & HUMBERT, 2005))

Midpoint category	Midpoint reference flow (Kg$_{eq}$ Substance x)	Damage category	Reference flow
Human Toxicity (carcinogens + non-carcinogens)	Kg$_{eq}$ chloroethylene into air	Human health	DALY
Respiratory effects (inorganic)	Kg$_{eq}$ PM2.5 into air		
Ionizing radiation	Bq$_{eq}$ carbon-14 into air		
Ozone layer depletion	Kg$_{eq}$ CFC-11 into air		
Photochemical oxidation (Respiratory organics)	Kg$_{eq}$ ethylene into air		
Aquatic ecotoxicity	Kg$_{eq}$ triethylene glycol into water	Ecosystem quality	PDF*m²*a
Terrestrial ecotoxicity	Kg$_{eq}$ triethylene glycol into soil		
Terrestrial acid/nutria	Kg$_{eq}$ SO_2 into air		
Land occupation	M^2_{eq} organic arable land-year		
Aquatic acidification	Kg$_{eq}$ SO_2 into air		*Under development*
Aquatic eutrophication	Kg$_{eq}$ PO_4^{3} into water		*Under development*
Global warming	Kg$_{eq}$ CO_2 into air	Climate change	Kg$_{eq}$ CO_2 into air
Non-renewable energy	MJ Total primary non-renewable or kg$_{eq}$ crude oil (860kg/m^3)	Resources	MJ
Mineral extraction	MJ additional energy or kg$_e$ iron		

Ideally, the application of a multicriteria environmental assessment would involve to consider a whole set of potential impacts in order to detect the most significant ones relative to a given application field. The lack of data may make this often impracticable. The analysis of the relevant literature shows that the problem of supplier selection focusing on the agricultural practices and the orchard performance (see Chapter 3) can be tackled considering two key indicators that are Aquatic Eutrophication and Global Warming Potential (GWP). Chapters 4 and 5 consider GWP as the main environmental performance indicator given that it provides a manageable and relevant measurement of the environmental impact related to the food production in all the echelons of the SC.

<u>(4) Interpretation</u> refers to the analysis of the results based on the objectives and scope of the study previously defined. In order to find areas of opportunity for improvement that lead to decision-making process for change. Three key outcomes form the interpretation process are achieved: (1) identification of significant issues that would otherwise not be detected; (2) determination of the influence of the significant issues on the overall results, i.e., to understand how reliable and valid are the results obtained, in order to drive decision making; (3) formulation of conclusion and recommendations based on the results.

The modelling and optimization framework provided by the SCM paradigm will be coupled with the Life Cycle approach through the evaluation of some significant objectives. Some typical applications provided by LCA are presented in Figure 2-1, mainly product development and improvement, as well as strategic planning forming the bases of the Green Supply Chain Network approach that is presented in detail in Chapters 3, 4 and 5.

Indeed, LCA has been broadly used in many areas of the food production cycle (i.e. agriculture of different food products, food processing, food packaging, etc.). Food production chains are made up of two main echelons: production of the natural resource i.e. agriculture (e.g. fruit, fiber, livestock, etc.) and food processing (e.g. packaging, juice extraction, pasteurization, fermentation, etc.). Other transversal and intermediate steps are also needed which are common to all consumable products (e.g. transport, distribution, warehousing, etc.).

The concepts of supply chain management and environmental management with Life Cycle Assessment have emphasized that there is a strong relationship between the components of the studied system and its boundaries, which has been supported by the concept of green supply chain. This explains why some of the concepts of LCA are intrinsically developed with the presentation of the studied system.

2.3 SUPPLY CHAIN CASE STUDY: TECHNICAL, ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

2.3.1 STUDIED SYSTEM AND BOUNDARIES

Given the Green Supply Chain Management (GrSCM) paradigm, a less detailed but wider scope approach is proposed in terms of system modelling, i.e., the main operations that require the most resources are considered in order to capture the environmental impact via a reliable set of Key Environmental Performance Indicators (KEPI). Besides, since the GrSCM approach provides special attention to materials and information flows and other logistics issues, some operations are aggregated into higher level-black box operations in order to manage the SC scope. Indeed transportation operations are included in more detail in the proposed modelling framework than in (Beccali et al., 2010).

The studied *production system* considers the 1 L of bottled orange juice as the FU in its 4 variations (based on the labeling). The essential oil production is excluded from the scope.

Figure 2-4 presents the adapted materials flow diagram for the case study developed in Chapters 4 and 5. In contrast to the approach proposed in (Beccali et al., 2010), the model proposed here addresses many important supply chain design issues. First, two types of raw materials (i.e. organically and conventionally grown orange fruit) based on the agricultural practices applied (i.e. use of agrochemicals), are considered. These two materials flows are segregated throughout the product life cycle in order to evaluate a differentiated pricing policy based on this quality attribute. Besides, the type of agro practices that can be selected during production can range in the level of intensity with which agrochemicals are used. Four levels, ranging from organic agro practice to intensive are considered. The organic practice uses no agrochemicals. In return, the production yield per hectare is very low but is assumed as the only type of production that allows the use of *organic* eco-labels. The intensive case, and all other in-between levels, use fertilizers and pesticides in order to achieve better production yields.

In (Beccali et al., 2010), the primary process consisted in the sorting, cleaning and extraction operations, that are aggregated in the pasteurization process in our case study. The detailed study of these operations could be considered in future work but was excluded to delimit a more manageable scope in terms of data collection. Pasteurization process, concentration and bottling are considered here as the three main process steps that are the focus of the SCND problem formulation.

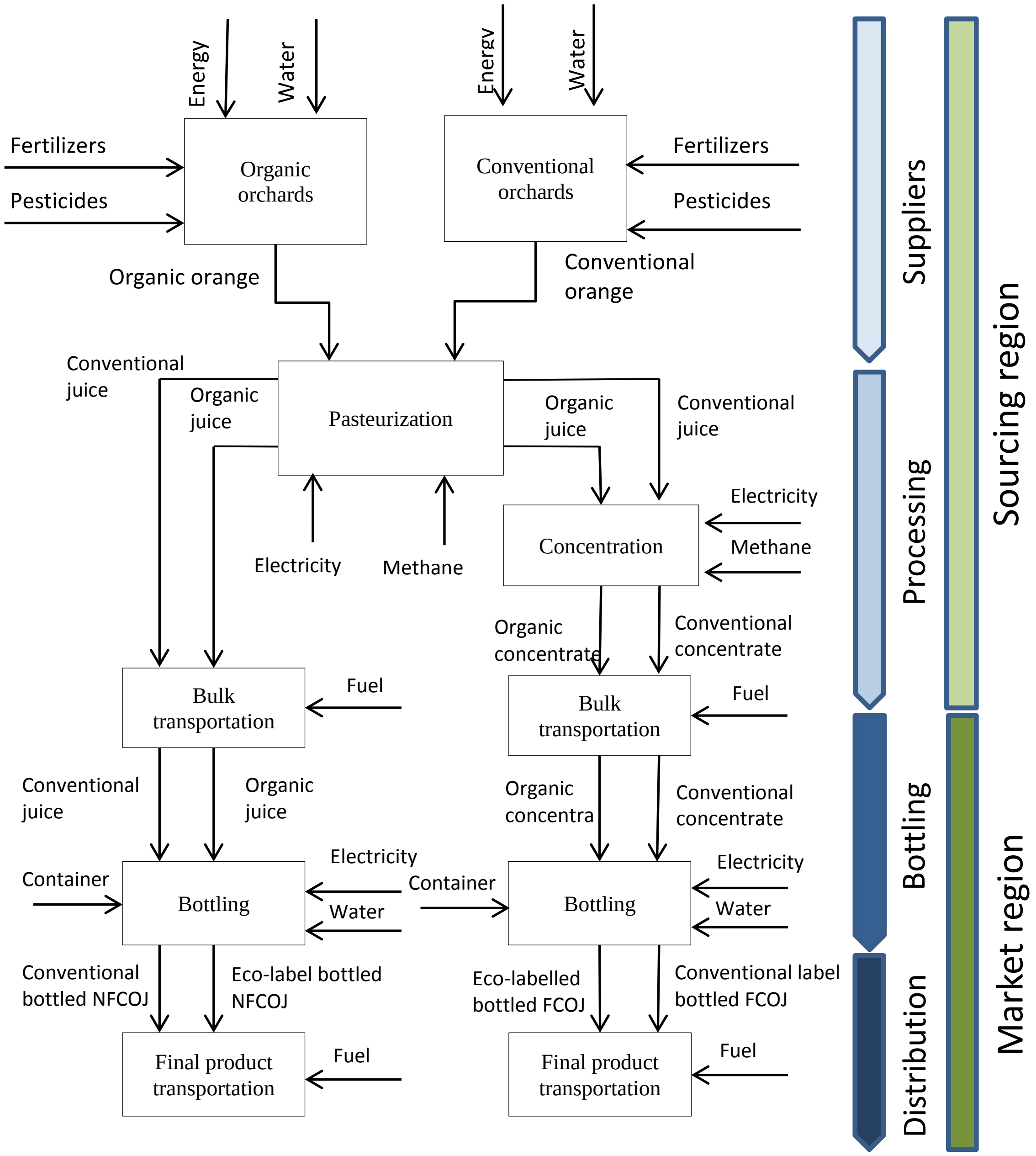


FIGURE 2-4 MATERIALS AND RESOURCE FLOWCHART FOR THE CASE STUDY

Considering **agricultural aspects** on the one hand, extensive research has been performed on the environmental effects of the production and use of agrochemicals, as wells as on the effects from resource use (e.g. land, water, etc.) (Levitan et al., 1995; Meisterling et al., 2009; Snyder et al., 2009; Viets and Lunin, 1975; Wauchope, 1978). Agrochemicals, such as pesticides and fertilizers, are used to improve the yield and quality of the agricultural system. Pesticides are used to protect and treat against invasions of pests and plant diseases. Fertilizers are materials from nature or synthetized that are applied to soil or plant tissues to supply plant nutrients needed for plant growth and to improve its output yield and quality. LCA has also evaluated the use of resources such as water and land for agricultural use and its impact through conversion and runoff (Correll, 1998; Spalding and

Exner, 1993; Wauchope, 1978). Water and land that would otherwise be part of the natural environment are needed, modified and managed to be agriculturally productive. Solid waste handling from agriculture and the other processing and transportation steps are not considered within the scope of the study. These are considered within the perspectives in the last section of the manuscript.

Food processing, on the other hand, has also been studied for many products and production systems (Andersson et al., 1994; Carlsson-Kanyama et al., 2003; Cederberg and Mattsson, 2000; Cellura et al., 2012; Doublet et al., 2014; Roy et al., 2009). Food products from agriculture can be sold and consumed in fresh form; this is to say, with little processing, mostly related to packing and labeling, or they can be processed in higher degrees. These processed food products span from basically-processed, such as packaged and labeled fruit, to highly processed foods composed of many materials and substances, such as a frozen pizza. Although there is a large variety of agro food products and thus as many productions systems, there is a set of main unit operations that are widely used and studied. Some exemplary operations are pasteurization, concentration and packaging. These types of unit operations require material and energy resources that come at an economic and environmental price. LCA helps improve environmental performance by providing a framework to evaluate different design and configuration alternatives.

In addition to the production process to obtain a final product, there are other types of operations, such as materials handling that do not transform to product itself but are required in order to get the intermediate and final products to the different location associated to each step in product life cycle. Transportation from one point to another in the supply chain is a key source of environmental impact (Ala-Harja and Helo, 2014; Bloemhof et al., 2015; Böge, 1995; McKinnon and Piecyk, 2010; Meisterling et al., 2009). This is because global food productions have a distributed production and consumer market system, this is to say that the natural resources, production processes and consumers are frequently located far apart from one another. Due to globalization and free trade policies, as well as a growing world market for standard food products, transportation systems have been developed and put in place to accommodate these globally distributed food supply chain trends. Some important elements of these operations are the consumption of the materials resources needed to construct the transport units or vessels and related infrastructures (containers, frights, boats, trains, ports, etc.), and the resources that allow them to operate, mainly energy.

In the next two sections, a detailed description of the importance of the two main stages (i.e. agriculture and food processing) as well as some logistics issues - are presented. Furthermore, the presentation is focused on their associated materials and energy flows, centering on the case study in order to form a base to illustrate the methods and tools of Chapters 3 to 5.

2.3.2 AGRICULTURE SUB-SYSTEM

Agriculture has been used to produce food by humans for millennia but not until recently have many of the modern agricultural practices been developed. Two principal developments in recent times have been mechanization of work and use of agrochemicals. On the one hand, modern fuel powered machines, such as tractors allowed the agricultural worker to prepare and harvest larger areas of land more efficiently. On the other hand, fertilizers produced a large gain in land efficiency, while before their use, natural soil nutrition cycles and natural fertilizers such as animal manure were used to produce food products. The Haber (Bosch) process allowed the production of ammonia in an industrial scale and made nitrogen fertilization possible. One main setback of this process is the large requirement of materials and energy resource, thus damaging the natural environment. Furthermore, the widespread use of chemical fertilizers has also produced many other harmful effects to the environment. Agrochemicals use pollutes ground and surface water by rain runoff causing ecosystem damage through eutrophication and acidification of water and soils. In addition to fertilizers, pesticides have also been widely used and are pervasive in most modern agricultural production systems. Similar to fertilizers, the efficiencies gained through their use have made them ubiquitous. Their environmental impact is partially due to the production phase, but also largely due to its use and its effect on the natural environments, damaging natural food chains where insects play an important role.

FIGURE 2-5 EXAMPLES OF APPLICATION OF AGROCHEMICALS IN AN ORANGE ORCHARD SETTING (EXTRACTED 06/2015 FROM SOURCE: HTTP://NATURALLYBUBBLY.COM/WP-CONTENT/UPLOADS/ORANGESPRAYING-300X199.PNG)

Focusing on the orange juice production case study related to this thesis, the literature review highlights (Doublet et al., 2014) that the sources for impact to land use, water depletion and freshwater ecotoxicity categories are predominantly from orange cultivation. This phase also contributes to acidification and freshwater eutrophication. The main sources during orange cultivation are related to energy consumption, fertilizer use and the application of pesticides as illustrated in Figure 2-5. One purpose of this work will be to quantify the impact contribution of each phase.

LCA can be used for different purposes and based on this, different levels of study and scope are defined. In the illustrative case study used throughout this thesis, i.e. orange juice production system, LCA measurements are used in order to evaluate different design scenarios. These evaluations are used for long-term strategic decisions related to the design of the supply chain network and to the selection process of some key technologies used during the product life cycle. From the point of view of Supply Chain Management (SCM) the first step in the chain is the natural resource extraction. In a similar way, LCA uses the same scope. For the case study, orange fruit orchards supply oranges to the processing plant. Each producing region (i.e. where the suppliers are located) has its own local production characteristics. These characteristics play an important role in determining the yield and quality of the fruit; some other factors that also influence performance are the agricultural practices (also referred to as agro practices) consisting of activities such as soil loosening, weeding, planting, pruning, and application of agrochemicals among others (Miranda-Ackerman et al., 2013b) as illustrated in Figure 2-6. Through these activities, the agricultural manager can influence the performance of the orchard system.

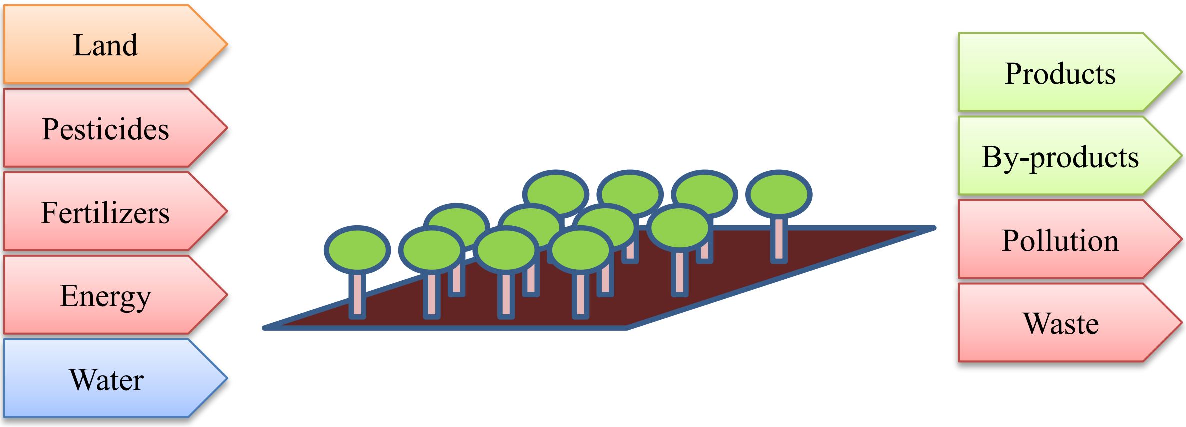


FIGURE 2-6 ILLUSTRATION OF THE INPUT AND OUTPUT FLOW IN A FRUIT ORCHARD

Some of these activities have nominal environmental impacts, but others are key to the environmental performance of the system (Doublet et al., 2014). The approach presented here concentrates on the use of fertilizers (e.g. N, P_2O_5, K_2O, etc.), pesticides (e.g. Benomyl, Diazinon, etc.) and fuel for energy (e.g. fossil fuels).

2.3.3 FOOD PROCESSING SUB-SYSTEM

According to (Doublet et al., 2014; Beccali et al., 2010), the most relevant sources of impact for the juice processing are related to electricity use and thermal energy use. The LCA study reported in (Beccali et al., 2010) was used as the base model focusing on a variety of citrus-based products, including orange juice. The scope of this research work and the case study is limited to this product line and in particular to the production of orange juice in its concentrated and non-contracted forms. Recalling Figure 2-4 the production flow to produce orange juice follows two main lines. Both start with the pasteurization process and go through different stages until the final bottled product is finished. In the following descriptions of these operations and the alternatives that are considered within the case study are reviewed.

BACTERIOLOGICAL STABILIZATION

The bacteriological stabilization process, often referred to as pasteurization[1], consists of treating food through thermal or non-thermal means in order to eliminate or neutralize microorganisms and enzymes that produce spoilage and pathogens. Its objective is to extend product shelf life and guarantee food safety for consumption. For fruit juice products, this is traditionally done through thermal methods that consist in applying heat in a range of temperature and time. One setback from these thermal methods is that they require a lot of energy in the form of heat and thus have a large environmental footprint. Further, the thermal treatment affects the gustative properties of the food, mainly color, taste and scent. For this case study, only non-thermal methods for pasteurization are evaluated, assuming that there is a market trends towards investing on technologies that produce higher quality and more competitive products (Hicks et al., 2009).

Non-thermal pasteurization processes consist in treating food through means different than from applying high temperatures. The case study evaluates two types of such processes based on High Hydrostatic Processing (HHP; aka High Pressure Processing) and Pulse Electric Field (PEF). These two

---

[1] Pasteurization in technical terms is a food conservation process invented by Louis Pasteur. It is a thermal process used for the elimination of pathogenic microbes and lowering microbial numbers to prolong the quality of beverages. In the related current literature "Pasteurization" is used to refer to processes that have similar objectives. In this manuscript we subscribe to this convention.

technologies are preselected to be included given two groups of reasons. The former is related to the problematic being targeted. The GSCND problem is formulated as a strategic long-term capacity problem to increase market share. The assumption is that current and future consumers will demand higher quality products avoiding those that are perceived to be highly processed (Heinz et al., 2003; Janssen and Hamm, 2012; Lee et al., 2015). The framework is set under the assumption that part of the production output will be in non-concentrated form. The competitive advantage is gained by avoiding thermal processes that degrade the sensorial and nutritional qualities of the food product. Many studies have shown that PEF and HHP pasteurization methods conserve higher sensorial (e.g. color and taste) qualities while reducing operation energy costs that cannot be achieved through conventional thermal methods. (Heinz et al., 2003, 2001; Hodgins et al., 2002; Ho and Mittal, 2000; Pereira and Vicente, 2010; Sampedro et al., 2013; Toepfl et al., 2006; Yuk et al., 2014).

HHP on the one hand consists in packaging the food product in plastic bag containers (final or transitory) and introducing into a vessel subjected to high levels of isostatic pressure in the order of 300-600MPa transmitted by water as illustrated in Figure 2-7. This is done in cold to ambient temperatures and result in the inactivation of vegetative flora like bacteria, virus, yeasts and other parasites present in food. (Balda et al., 2012; Heinz and Buckow, 2010; Hernando Saiz et al., n.d.)

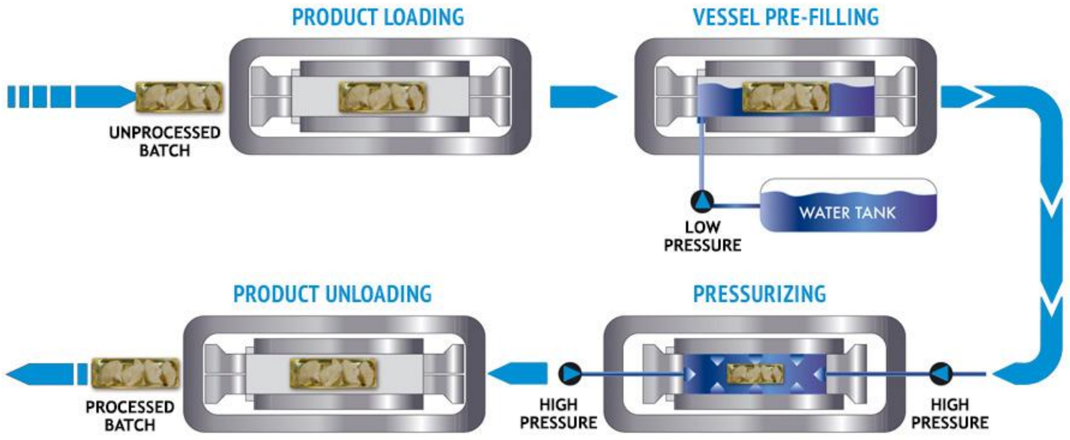


FIGURE 2-7 HHP - BASIC PROCESS FLOW DIAGRAM (EXTRACTED 06/2015 FROM SOURCE: HTTP://WWW.HIPERBARIC.COM)

PEF on the other hand uses high voltage electric pulses applied to liquid or semi-solid foods via two electrodes. Figure 2-8 shows how the basic process flow diagram (E.A. and Amer Eiss, 2012). The material flows through a chamber (where the electric pulse is applied controlled by a computer) and finally arrives at final product container. Although it is not a thermal pasteurization method, temperature changes do occur due to the high levels of energy in electric form used (temperature is yet lower than the one of thermal methods obtaining benefits in nutrient and sensorial quality preservation similar to those of the HHP.

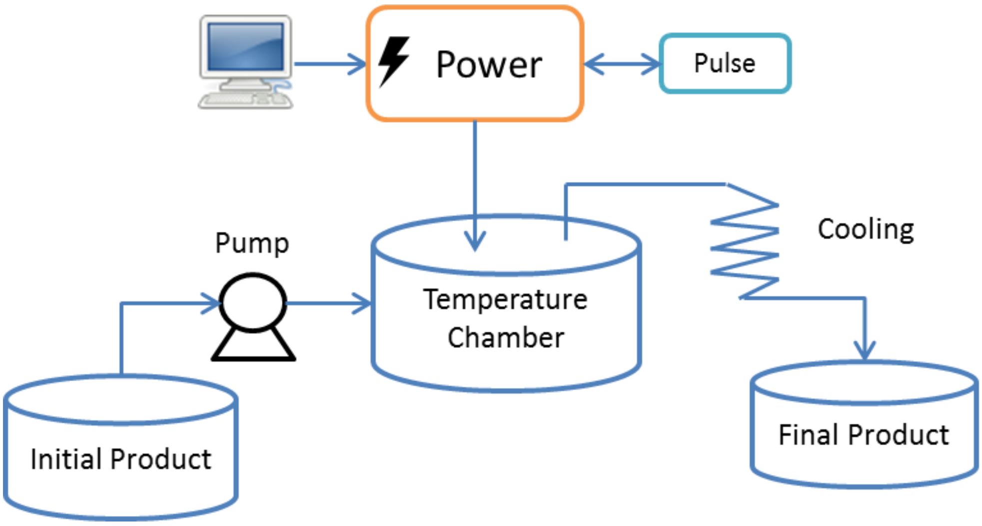


FIGURE 2-8 PEF – BASIC PROCESS FLOW DIAGRAM (E.A. AND AMER EISS, 2012)

CONCENTRATION

The process diagram in Figure 2-4 shows that pasteurization has four flows of materials, two allocated towards bulk transportation and two to concentration process. The flow to bulk transportation is for materials that are sent as is in single strength; this is to say with natural concentration level of ~11° Brix (Brix measures the quantity of solids and sugar per unit of volume). Single strength is equal to the natural concentration of juice, i.e. the content of the juice is diluted in the natural quantity of water contained in juice. By sending the material as is to the bottling plant, high quality characteristics are conserved due to less processing. The quantity of materials that has to be transported is therefore higher (due to the water content) that if it were concentrated. The second set of flows towards the concentration process consists of removing or separating some of the water contained in the juice. It will be then reconstituted at the bottling plant that is located far away. By removing some of the water, the overall quantity of materials that has to be transported is reduced and the valuable part of juice is contained in its solids and sugar contents; by concentrating these elements of the juice, a multi-strength or concentrated juice (also known as Frozen Concentrate or From Concentrate Orange Juice, FCOJ) is obtained. This presentation of juice can be at different levels of concentration that are achieved through the concentration process. The FCOJ is transported to the bottling plant where it is reconstituted into its single strength form by mixing with water and flavor packets in order to reach acceptable levels of similitude to natural single strength orange juice.

The case study considers a choice between 3 types of technologies: (1) Multi-effect evaporator ("Evaporators"), (2) Freeze concentration ("Freeze") and (3) Reverse Osmosis ("R. Osmosis"). These three alternatives were preselected to be incorporated to the case study in order to evaluate eco-design principals of finding trade-off based on energy, cost and operational capacities during the SC design process. A summary of some well-known concentration processes that can be used in orange juice concentration is presented in Table 2-2 .

TABLE 2-2 SUMMARY OF ADVANTAGES AND INCONVINEINECES FOR DIFFERENT CONCENTRATION PROCCESSES (JARIEL ET AL., 1996)

Process	Max °Brix	Juice quality obtained	Pretreatment to inactivate enzymes	Tested and commercially available equipment	Operational cost	Possibility of treating multiple products	Investments
Conventional evaporation	80	--	no	yes	0	no	0
High temperature evaporation	65-75	0	no	yes	0	no	0
Low temperature evaporation	40-60	--	yes	yes	+	no	+
Freeze concentration	30-50	++	yes	yes	+	no	+++
Reverse osmosis	20-50	++	yes	yes*	+	no	++
Direct osmosis	50	+	yes	no	+	yes	+
Membrane distillation	60-70	+	yes	no	+	yes	0
Osmotic evaporation	60-70	++	yes	no	+	yes	0

*In combination with other concentration systems. --:very weak; -: weak; +:high; ++: very high; +++:extremely high

Multi-effect evaporators are the most widely used technology for the concentration of fruit juice. As presented in Table 2-2, Freeze and R. Osmosis are commercially viable alternatives that provide interesting advantages versus evaporators mainly in terms of juice quality, energy economic and environmental cost, with limited disadvantages, mainly investment cost. Traditional thermal processing from fossil fuels is generally involved whereas electricity is the main energy used to operate mechanical power pumps that drive Freeze and R. Osmosis (Dalsgaard and Abbotts, 2003; Pereira and Vicente, 2010). Further, these alternatives create the possibility of finding a trade-off between processing technologies based on the type of energy used. Electric energy has different sources and thus different economic and environmental costs (e.g. nuclear, geothermal, coal burning electricity generation). These interdependencies and interactions between different logistical and technological issues merit their inclusion within the model framework in order to evaluate the potential improvements that can be achieved in the GSCND decision making process.

(1) **Evaporators** involve a thermal process that uses heat to remove water from the orange juice given the evaporation point difference between the water and other substances in the mixture. Passing the mixture through different geometries in multiple stages where vapor and heat are applied as well as cooling processes. Its most important advantage is its lower cost compared to alternative methods that makes it one of the best known and well developed methods of

concentration. Some disadvantages are its effect on nutrition, sensorial and physical properties of the juice, although this is out of the scope of the model framework. Figure 2-9 shows a TASTE evaporator that takes in juice at 13°Brix that is passed through 4 stages to remove the water content to achieve a 68°Brix concentration level.

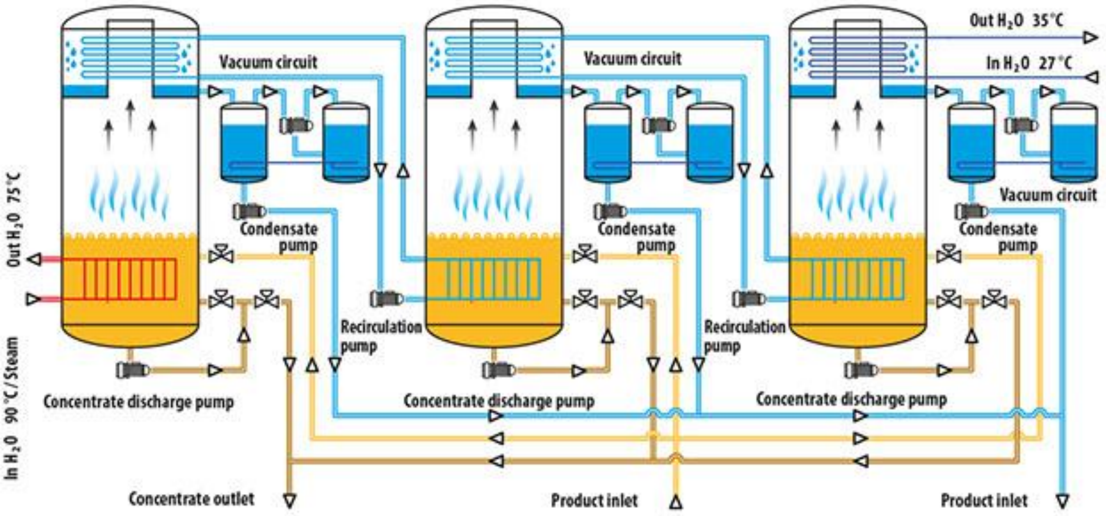


FIGURE 2-9 EVAPORATOR – BASIC PROCESS DIAGRAM (EXTRACTED 25-07-2015 FROM HTTP://WWW.PF10.IT/EN/EVAPORATORS-AND-CONCENTRATION-UNITS.HTML#EVAPORATORI_ACQUA_CALDA_VAPORE_DOPPIO_TRIPLO_EFFETTO)

(2) **Freeze concentration** is a process (also known as freeze crystallization) that removes heat from a mixture making one of the components crystallize. The crystallized substance is then physically removed, the remaining liquid is more concentrated as illustrated in Figure 2-10. One of the main advantages is its conservation of flavor and other thermally fragile compounds that form the base of the quality of the juice (Deshpande et al., 1984; Miyawaki et al., 2005). Its major disadvantage is its initial investment cost. While the sensorial quality of the product is not considered in the model, the investment and operational cost is explicitly modeled.

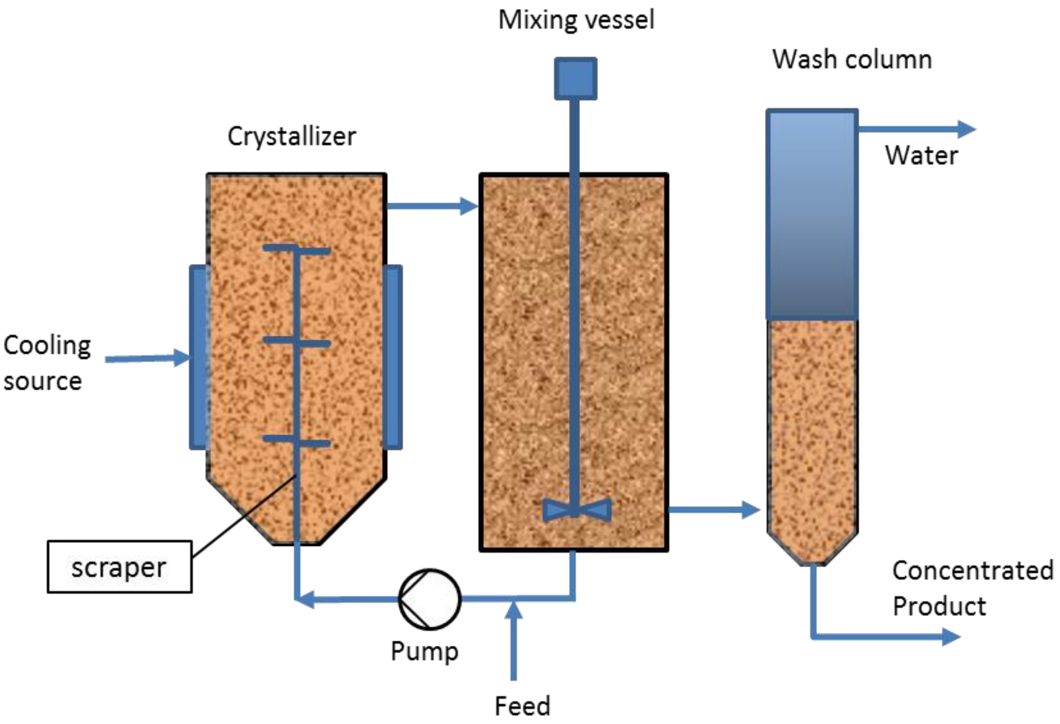


FIGURE 2-10 FREEZE CONCENTRATION – BASIC PROCESS DIAGRAM

(3) **Reverse Osmosis** is a process by which a mixture is passed through a semipermeable membrane letting water pass through and leaving a higher concentrated solution behind as illustrated in Figure 2-11. This is one of the most popular alternatives to thermal concentration in juice production (Miyawaki et al., 2005). As a non-thermal process many of the sensorial characteristics of the juice are conserved better than thermal processes.

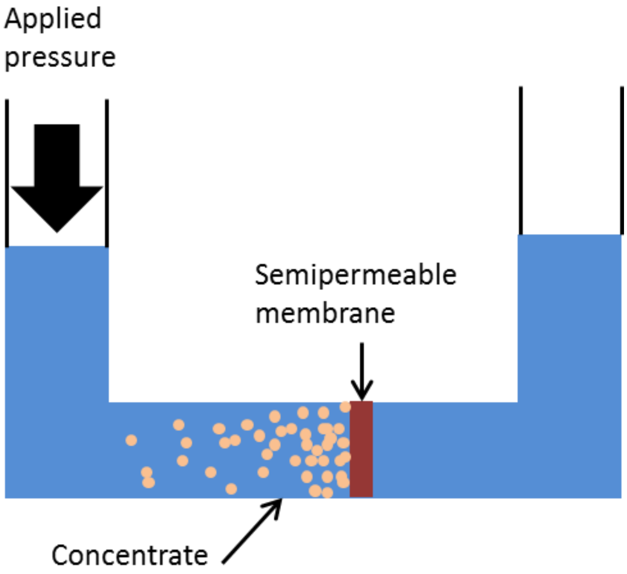


FIGURE 2-11 REVERSE OSMOSIS – BASIC PROCESS DIAGRAM

2.3.4 CONCLUSIONS ON PROCESS MODELLING IN SC NETWORK DESIGN

All of these technologies are evaluated as discrete possibilities of the SC network design, as well as the process capacity based on the production requirements that have to be met. It must be highlighted that the capacity of the equipment is limited in terms of the level of concentration that can be achieved for orange juice production. Evaporator technology can reach the highest concentration levels, two concentration levels that are standards for the orange juice industry are 66°Bx and 44°Bx, for the case study a 66°Bx is achieved through thermal concentration, while Freeze and R. Osmosis are assumed to reach 44°Bx roughly their highest capability. The emphasis of the model framework is to evaluate the technologies in terms of cost and environmental impact, both related to the type of energy required and the location of the process installations. For instance, the Evaporator technology requires mostly methane gas to produce heat, while Freeze and R. Osmosis require mostly electric energy. Each type of energy has a different cost and environmental impact (in the case of electricity) based on the region it is located.

2.3.4.1 BULK TRANSPORTATION

Bulk transportation refers to juice transportation from the supplying region to the market region. This reflects a real tendency in current world economics towards globalization, thus leading to a distributed supply chain. The case study considers the Mexican and Brazilian orange producing regions (which are some of the most important citrus exporting countries in the world). In addition the German and French markets are targeted given the value and size of the two countries. Furthermore, the two European countries are models of the global tendency of consumer preference and willingness to buy ecologically friendly products. The transportation stage reflects two main trajectories: (1) port of departure to port of arrival and (2) port of arrival to bottling plant. The first (1) is modeled as a sea freight (see Figure 2-12) trajectory from the port of departure of the supplying country (i.e. Mexico or Brazil) towards the market country's receiving port (i.e. Nantes and Amsterdam). The trajectory is measured in terms of kilogram kilometer (kgkm), this is to say the environmental and economic cost of transporting one kilogram transported one km. Although the market price of these trajectories fluctuates from moment to moment they are modeled as fixed values. The environmental impact is taken from the EcoInvent v2.2 database.

FIGURE 2-12 EUROPEAN JUICE SEA FREIGHT (EXTRATED 06/2015 FROM: HTTP://FR.SLIDESHARE.NET/KAI-LNV/EFFICIENT-MARITIME-BULK-LOGISTICS-ORANGE-JUICE-OPPORTUNITY-FOR-EGYPT-BY-TRILOBES)

The second (2) is the trajectory from the port of arrival towards the bottling plant. This trajectory is done through tanker freight trucks (see Figure 2-13); and is important given that it reflects a large portion of the economic and environmental contribution based on the bottling location.

FIGURE 2-13 EUROPEAN JUICE ROAD TRANSPORT (EXTRACTED 06/2015 FROM: HTTP://FR.SLIDESHARE.NET/KAI-LNV/EFFICIENT-MARITIME-BULK-LOGISTICS-ORANGE-JUICE-OPPORTUNITY-FOR-EGYPT-BY-TRILOBES)

2.3.4.2 BOTTLING

The model framework considers three alternatives in the product and process design of the bottling operation: PET bottle (plastic), Glass bottle and Aseptic carton illustrated in Figure 2-14.

FIGURE 2-14 EXAMPLES OF FRUIT JUICE CONTAINERS (EXTRACTED 06/2015 FROM SOURCE: HTTP://WWW.123RF.COM)

Furthermore it considers the equipment, materials, water and energy requirements in order to obtain the final product from the four juice streams. For the two streams of NFCOJ the bottling operation (illustrated in Figure 2-15) is the main process that is considered.

FIGURE 2-15 TYPICAL ORANGE JUICE BOTTLING OPERATION (HTTP://WWW.HSFILLING.NET)

For the two production streams to produce single strength juice from FCOJ a reconstitution processes has to be applied in order to dilute the concentrated orange juice to the levels of the natural juice, i.e. mixing with water (see Figure 2-16) to reach ~11°Bx from the concentrated juice at 44 or 66°Bx depending on the concentration technology used.

FIGURE 2-16 ORANGE JUICE RECONSTITUTION PROCESS (EXTRACTED 06/20015 FROM: HTTP://WWW.CITROSUCO.COM.BR)

Each alternative is associated with an environmental and economic cost related to the energy and materials required to obtain the container. In addition the model considers the water and energy requirements in order to reconstitute the concentrated orange juice steams.

2.3.4.3 FINAL PRODUCT DISTRIBUTION

The final transportation process models the distribution trajectories from the bottling plant location to the different markets that are served. This is important because depending on the bottling location with respect to the port of arrival and the markets, economic and environmental cost may vary. Furthermore, the transportation process is subject to special energy requirements based on the type of product being transported. Because NFCOJ can degrade in quality during transportation a *cold chain* has to be respected. This consists in maintaining the temperature of the final product below a certain temperature through refrigerated transport (see Figure 2-17). Refrigeration requires more energy during the transportation of NFCOJ products. This is modeled through an economic and environmental surcharge for NFCOJ products.

FIGURE 2-17 FREIGHT ROAD REFRIGERATED TRANSPORT (EXTRACTED 06/2015 FROM SOURCE: HTTP://WWW.EKOL.COM)

2.3.5 CONCLUSIONS ON ENVIRONMENTAL AND ECONOMIC COMPONENTS OF THE SC NETWORK DESIGN

In summary, the environmental assessment alongside the economic one is based on key indicators related to energy and resource consumption. Concerning the environmental issue, the LCA methodology is particularly sound since it is closely aligned as a complement to green supply chain management. The main relevant literature source is the work proposed in (Beccali et al., 2010) that illustrated the production of Italian orange juice. The model framework proposed in the following chapters extends and adapts the case study in order to evaluate the effects of location, scaling, allocation, technology selection, agricultural practices within the framework of green supply chain management paradigm. In contrast to the work presented in (Beccali et al., 2010), the proposed research gives special emphasis to supply chain issues related to processes, technologies and transportation. This is important because many of the food production systems are distributed around the world. Little research has been given to the exploration of evaluations and optimizations of food supply chain systems through an integrated SCND approach. This is achieved by formulating the problem as a Supply Chain Network Design itself framed as a multi-objective optimization mathematical model taking economic, operational and environmental criteria into consideration.

Section 1 of this Chapter has highlighted that agro food supply chains have two main echelons: agriculture and food processing. Since agricultural practice has so much importance on the quality value of the product, Chapter 3 is first dedicated to the supplier selection process. The supplier selection process that is proposed takes into account the different key environmental issues that have just been presented. The supplier selection problem is then embedded in a more holistic manner, thus leading to a higher level decision-making framework in the context of a Supply Chain Network Design problem approach in Chapters 4 and 5, in order to obtain *organic* eco-labelling.

2.4 Multi-objective optimization and MCDM methodology

The general research problem we are addressing focuses on optimizing a globally distributed supply chain network that has the special characteristics of producing agrofood products. This issue takes multiple supply chain network design decisions into account simultaneously, considering multiple objectives related to economic, operational and environmental performance, in order to obtain an attributed special value based on the raw materials sourcing (i.e. eco-label to food made with organically grown raw material).

The modelling and optimization approach must provide the scope and flexibility needed to consider integrated networks firstly of suppliers (Chapter 3) and secondly of the full supply chain (Chapters 4 and 5). The nature of the problem is characterized by the multiple nature of variables, the linear and nonlinear relations between them, and the multiple objectives being considered. Multi-objective optimization offers the conceptual framework in this study.

As explained in Chapter 1, the purpose is to search for feasible trade-off solutions through the population-based stochastic search genetic algorithm NSGA-II. The alternative trade-off solutions are then evaluated through a Multicriteria decisions analysis method in order to rank the *best* solutions through a multiple criteria decision making tool, i.e., M-TOPSIS method.

Multi-objective Optimization (MOO)

Engineering design and logistics problems can often be conveniently formulated as multi-objective optimization MOO problems.The MOO is formulated to capture the interrelation between the decisions variables, the model variables and the parameters that describe that system as a set of restrictions and objective functions. The following general model is the base of this formulation strategy.

$$\begin{aligned} &\min f_1\ x,y,z\ ,f_2\ x,y,z\ ,\dots,f_n\ x,y,z \\ &\qquad s.t.\ g\ x,y,z\ \leq 0 \\ &\qquad\quad h\ x,y,z\ = 0 \\ &\qquad y\ \in\ 0,1\ ^m, x \in \mathbb{Z}^n \end{aligned} \tag{2-1}$$

In which a set of objective functions from 1 to n to minimize, subject to a set of inequality constraints (*g*), a set of equality constraints (*h*), and where variables are defined as (*x*) for integer and (*y*) for binary.

Application of MOO to GrSCM

Multi-objective optimization is a popular approach to modelling green supply chains (Srivastava, 2007) since it allows for the antagonistic objectives of economic and environmental performance to be evaluated and optimized simultaneously. Trade-off solutions are found through this approach giving the decision makers a way to incorporate many objective and preferences in single decision framework. More specifically this research work proposes two main applications of the MOO approach to GrSCM: Supplier Selection problem formulation under the paradigm of *Partnership for Sustainability* (explained in detail in Chapter 3) and Green Supply Chain Network design problem (see Chapters 4 and 5).

Supplier Selection problem

The first focuses on the sourcing of raw materials for food production. Formulating through a multi-objective mathematical model that minimizes environmental and economic cost related to agricultural practices. Supplier and partner selection has been widely studied from an economic and operational point of view but limited work has been done in relation to green supplier selection optimization. Some recent publications have started to explore the benefits of such an approach (Azadnia et al., 2014; Bai and Sarkis, 2010; Sha and Che, 2005; Yeh and Chuang, 2011).

Green Supply Chain Network design problem

This same MOO strategy is further extended as part of the research work in order to incorporate the supplier selection problem into a wider reaching GSCND problem. This integration is of course more consistent with the supply chain management paradigm since the production life cycle is viewed as a network of interconnected and interdependent elements, so that global optimization can achieved; this is in contrast to locally optimizing each element of the SC that may well globally be inefficient. Some important work has been done in this field (Accorsi et al., n.d.; Altiparmak et al., 2006; Bouzembrak et al., 2011; Coskun et al., n.d.; Costa et al., 2010). The modelling approach presented in this work extends from (Guillén-Gosálbez and Grossmann, 2009; Hugo and Pistikopoulos, 2004) and incorporates eco-design principles from (Azzaro-Pantel et al., 2013; Dietz et al., 2007; Perez-Gallardo et al., 2014) and integrates SC modelling framework strategies from (Miranda-Ackerman et al., 2014).

Complex MOO problems like the GSCND formulation that is proposed can be solved through a limited number of techniques (see Figure 2.19). Scalarization Methods are applied to well-defined problems with explicit formulations of objectives and constraints (Azzaro-Pantel et al., 2013): weighted-sum method, utility method & lexicographic (De-León Almaraz et al., 2013) techniques are among the most cited MOO solving methods. A very interesting alternative is to use metaheuristic methods, in particular genetic algorithms (Cortez, 2014; Yang, 2008) that are categorized under Pareto methods in Figure 2-18. These techniques allow one to take a black box approach, where objectives and constraints are evaluated through computer code with limited restrictions to the model structure, while still finding feasible heuristic solutions, (Collette and Siarry, 2003; Cortez, 2014). For a single criterion viewpoint, the main disadvantage is that when using these techniques there is no guarantee of finding solutions that are near the global optimal; the quality of the solution is generally dependent on the implementation, analysis and intuition of the modeler to overcome local optima. This trade-off strategy has proven to be valuable when modelling complex SCND problems (Miranda-Ackerman et al., 2014).

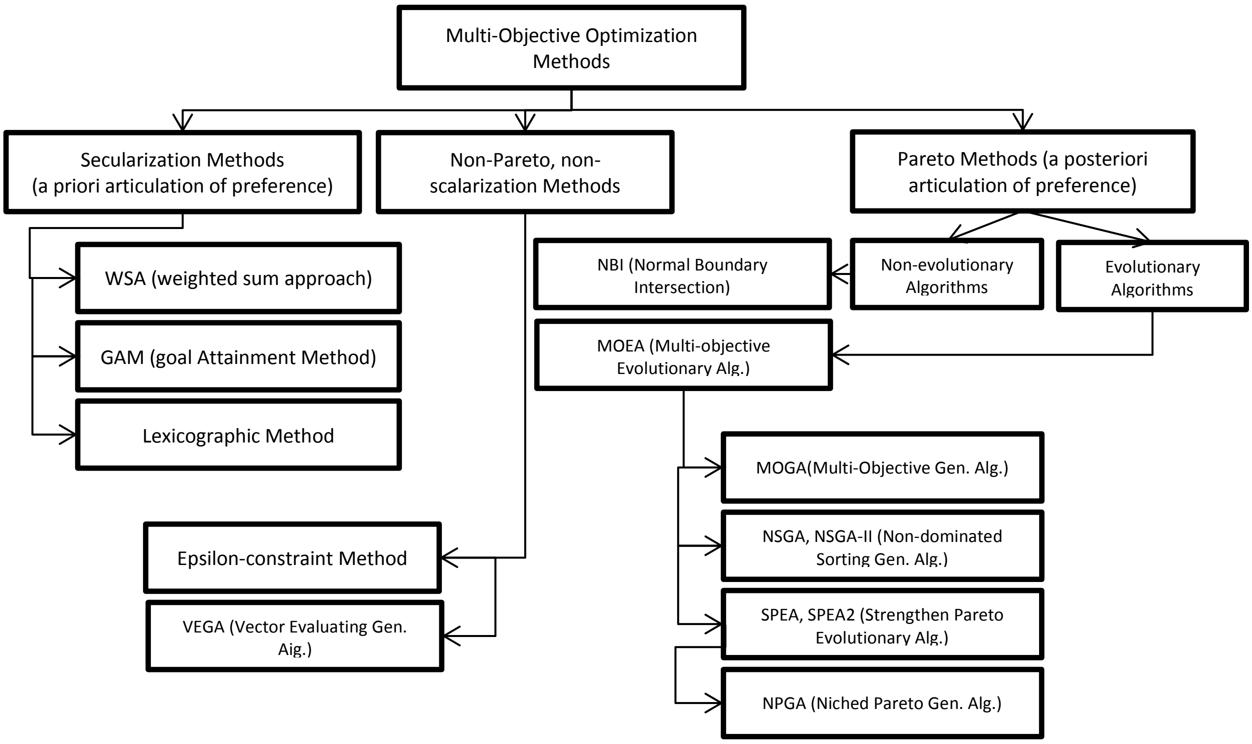


FIGURE 2-18 CLASSIFICATION OF MULTI-OBJECTIVE OPTIMIZATION METHODS BY (SAMARI AND HABIBA, 2013)

2.4.1 GENETIC ALGORITHMS

Recent publications in the context of green chain design show a recurrent use of GA (Ahumada and Villalobos, 2009; Arkeman and Jong, 2010; Yeh and Chuang, 2011). The solving method used in this research - is based on a multi-objective genetic algorithms solution approach through the Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al., 2002). It falls under the Pareto Methods in the (Samira and Habiba, 2013) classification.

NSGA-II is a population based stochastic search algorithm that produces Pareto non-dominated solutions. It has advantages and disadvantages compared to other similar algorithms (see Table 2-3). It holds the main advantage of being well tested for the problem type being considered in this work, detailed in later chapters. In contrast to other family of techniques such as weighted sum or lexicographic methods, that are *a priori* technique (i.e. a weight or order of the objectives as a matter of choice prior to the execution is needed), multi-objective GA denominated an *a posteriori* method produce a set of solutions (the so-called Pareto front) to choose from (Cortez, 2014), this is to say, without prior judgment or decision making. The NSGA-II is implemented through the so called MULTIGEN library developed by (Gomez et al., 2010a) that allowed to perform evaluations, data analysis and visualization for the case study presented in Chapter 5.

TABLE 2-3 LIST OF WELL-KNOWN MULTI-OBJECTIVE GA BASED ON (KONAK ET AL., 2006)

Algorithm	Fitness assignment	Elitism	Advantages	Disadvantages
MOGA (Fonseca and Fleming, 1993)	Pareto ranking	No	Simple extension of single objective GA	Usually slow convergence Problems related to niche size parameter
NSGA (Srinivas and Deb, 1994)	Ranking based on non-domination sorting	Yes	Fast convergence	Problems related to niche size parameter
NSGA-II (Deb et al., 2002a)	Ranking based on non-domination sorting	Yes	Single parameter (N) Well tested Efficient	Crowding distance works in objective space only
NPGA (Horn et al., 1994)	No fitness assignment, tournament selection	No	Very simple selection process with tournament selection	Problems related to niche size parameter Extra parameter for tournament selection
SPEA (Zitzler and Thiele, 1999)	Ranking based on the external archive of non-dominated solutions	Yes	Well tested No parameter for clustering	Complex clustering algorithm
VEGA (Schaffer, 1985)	Each subpopulation is evaluated with respect to a different objective	No	Straightforward implementation	Tend to converge at the extreme of each objective

The MULTIGEN environment previously developed in our research group (Gomez et al., 2010b) was selected as the genetic algorithm platform. A variant of NSGA-II developed for mixed problems and implemented in the MULTIGEN environment is selected. The stopping criterion proposed in MULTIGEN (in addition to the maximum number of generations) consists in comparing the Pareto fronts associated with non-dominated solutions for populations n and $n + p$, where the period $p \in$

[10, 20, 30, 40, 50] for example. If the union of the two fronts provides a single non dominated front, the procedure stops; else the iterations continue.

As it was initially developed within our research group in Visual Basic for Applications (VBA) in Excel, the same language is used for simulation purpose. The main advantages of VBA include the automation of repetitive tasks and calculations, the easy creation of macros in a friendly programming language.

NSGA-II was selected, as it is explained in (Gomez, 2008), because of the way to manage the diversity of populations. Algorithms based on the concept of niche as NPGA and MOGA do not ensure a proper convergence of the Pareto front. Algorithms such as SPEA or NSGA-II are based on the principle that single non-dominated individuals are better than individuals in dense areas. In SPEA, the probability of selection is based on the isolation of the individual, which implies a quantification of that probability, and therefore the implementation of more complex algorithms. NSGA-II opts for a simple elimination of individuals at dense areas after a sorting according to their density. In addition, NSGA-II needs low computational requirements.

The step-by-step procedure is illustrated in Figure 2-19 to Figure 2-21. Initially, a random parent population P_0 of size N is created. The population is sorted based on the non-domination principle.

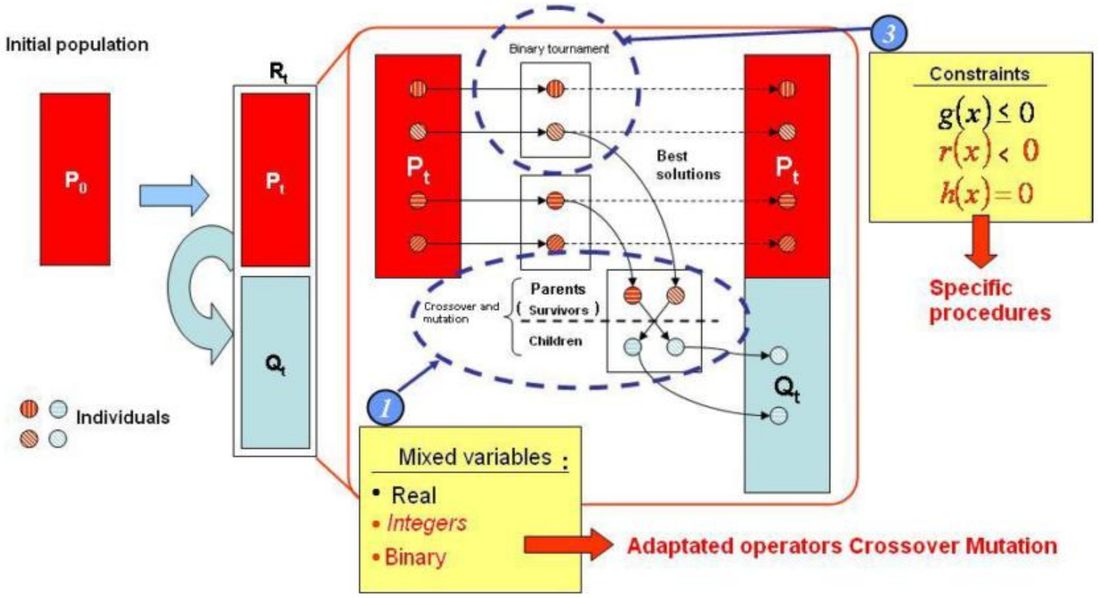


FIGURE 2-19 OPERATING PRINCIPLE OF NSGA-II (PART 1) (GOMEZ, 2008)

Each individual is assigned a fitness (or rank) equal to its non-domination level (1 is the best level, 2 is the next-best level, and so on). Thus, the maximization of fitness can be performed. At first, the usual binary tournament selection, recombination and mutation operators are used to create an off-spring population Q_t of size *N* (Figure 2-19). Since elitism is introduced by comparing the current population with the previously best found non-dominated solutions, the procedure is different after the initial generation.

First, a combined population $R_t = P_t \cup Q_t$ is formed (Figure 2-20). The population R_t is of size 2*N*. Then, the population is sorted according to non-domination. If the size of F_1 (set of individuals of rank 1) is lower then *N*, all the members of the set F_1 for the new population P_t *+1* are definitely chosen. The remaining members of the population P_t *+1* are chosen from subsequent non dominated fronts in the order of their ranking. Thus, solutions from the set F_2 are chosen next, followed by solutions from the set F_3, and so on. This procedure continues until no more set can be accommodated. Let us consider that the set F_1 is the last non-dominated set beyond which no other set can be accommodated. In general, the number of solutions in all sets from F_1 to F_l is higher than the population size.

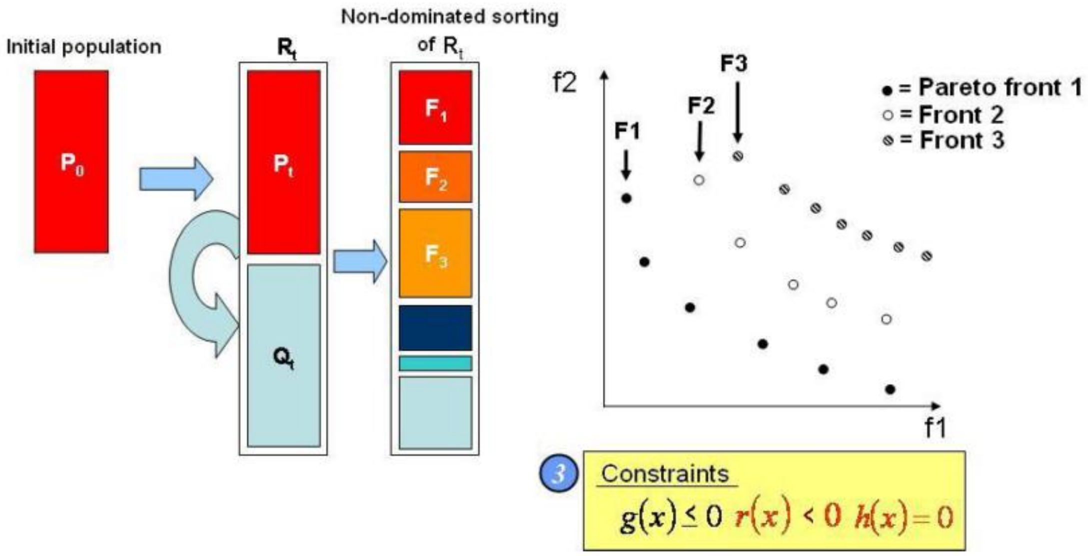


FIGURE 2-20 OPERATING PRINCIPLE OF NSGA-II (PART 2) (GOMEZ, 2008)

In order to choose exactly the population members, the solutions of the last front using the crowded-comparison operator are sorted in descending order and the best solutions needed to fill all population slots are selected. The new population Pt +1 of size N is now used for selection, crossover and mutation to create a new population Qt +1 of size N. It must be highlighted that a binary tournament selection operator is used but the selection criterion is now based on the crowded-comparison operator. Since this operator requires both the rank and crowded distance of each solution in the population, these quantities are calculated while forming the population Pt +1, as shown in Figure 2-21. The MULTIGEN library and NSGA-II are described in detail in (Gomez, 2008).

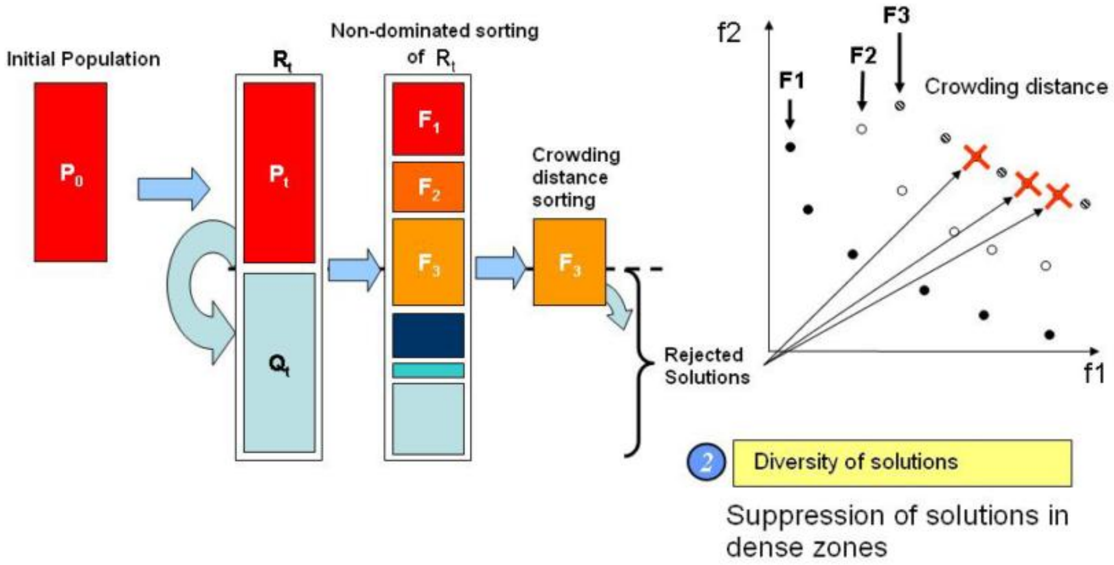


FIGURE 2-21 OPERATING PRINCIPLE OF NSGA-II (PART 3) (GOMEZ, 2008)

A set of issues arises in the GSCD problem formulation mainly, supplier selection, agro practice selection, supplier region selection, facility location, technology selection, capacity scaling at different stages in the supply chain. All variables are encoded as sets of binary and integer variables that represent active and inactive nodes in the network design.

Figure 2-22 illustrates how coding was implemented in the Genetic Algorithm to the model structure. The outcome of the optimization run is not a single solution, but rather a Pareto optimal set of solutions that are not dominated. This set of solutions is also known as the Pareto frontier or front.

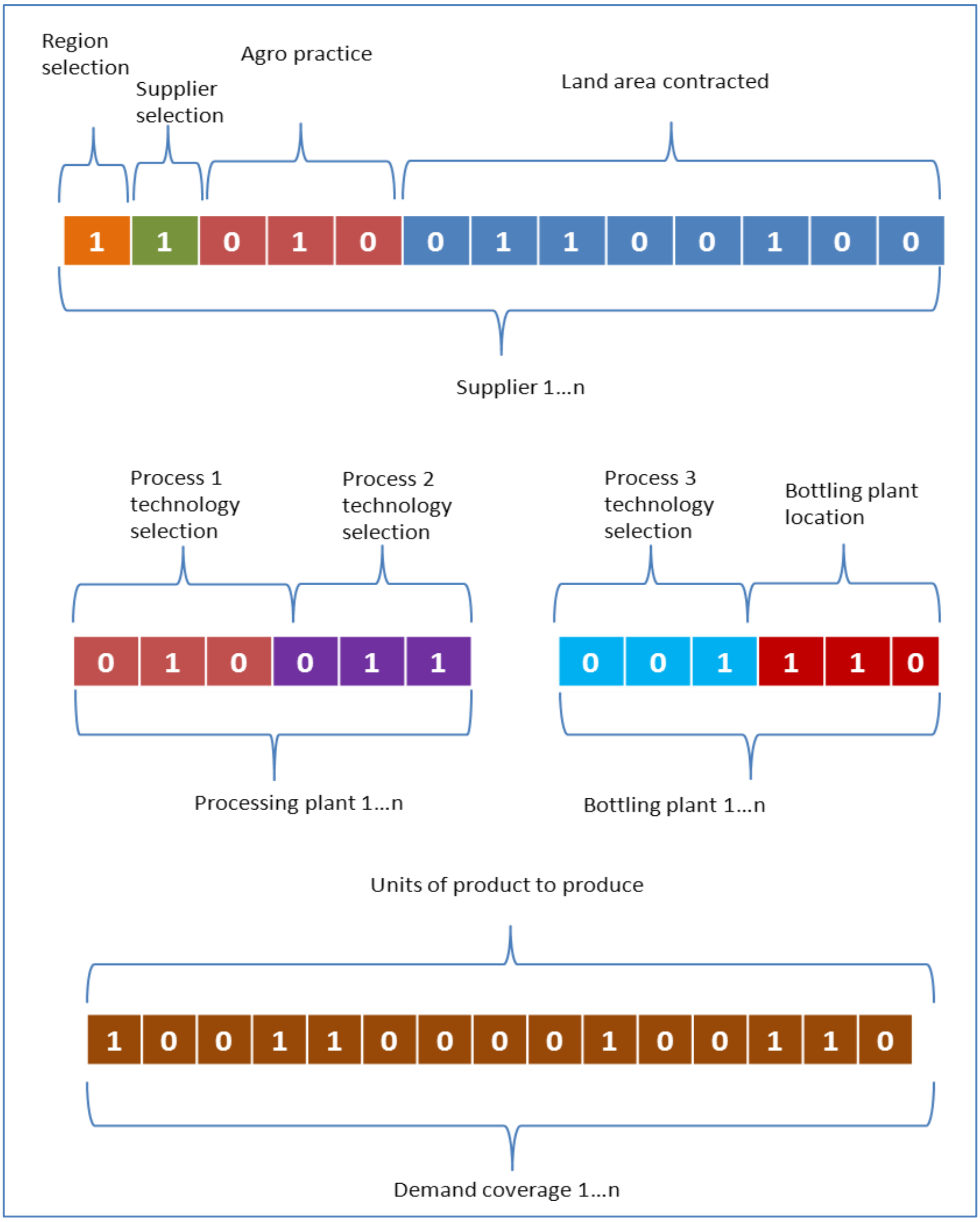


FIGURE 2-22 EXAMPLES OF CHROMOSOME CODING OF THE ORANGE JUICE CASE STUDY

This encoding is important because of the use of the two basic operators of GA, i.e., crossover and mutation that contribute to the performance of the optimization process, illustrated in Figure 2-23. Crossover operator defines the probability rate at which the parent chromosome information (A and B in the figure) passes to the offspring. If there is no crossover the offspring is an exact copy of a Parent. When crossover occurs, the offspring is made by a cross of both parent data. Mutation probability rate defines how often the parts of the chromosome will mutate (i.e. change arbitrarily). If no crossover is used the offspring is defined entirely from the parents. Mutation rate is used to add randomness in order to avoid local optima.

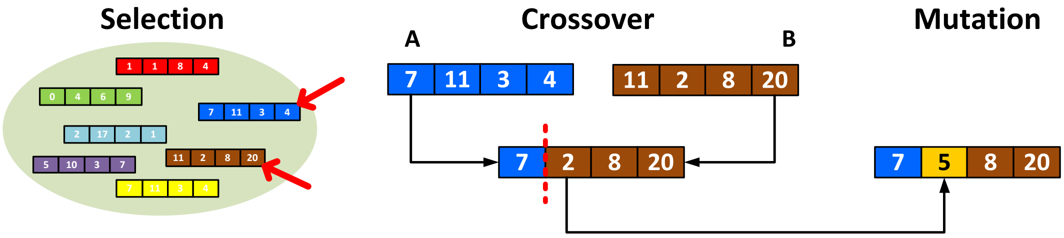


FIGURE 2-23 GENETIC ALGORITHM OPERATORS

2.4.2 MULTICRITERIA DECISION MAKING STRATEGY

The GA approach leads to a set of Pareto optimal (non-dominated) alternative solutions. These solutions represent SC network design configurations that produce equivalently good outcome in terms of the multiple objectives. The aim of MCDM is to aid the decision maker to select the best alternative. The objectives and preferences of the decision makers and stakeholders, play a role in choosing the model structure and characteristics, but a non-bias and systematic approach should be taken when choosing the final solution alternative. This is especially important in multi-objective formulations, also known as, multicriteria decisions, because it is difficult to make judgments on complex higher dimensional solution alternatives. To aid the decision maker, there is a wide range of MCDM tools one can access. Methods such as ELECTRE, PROMETHEE, AHP , TOPSIS , thoroughly evaluated by (Zanakis et al., 1998), provide a systematic and dimension independent ranking framework to compare and order solutions based on multiple criteria.

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), according to (Eraslana, 2015; Kim et al., 1997) has advantages over the other main methods, mainly: 1) it provides a scalar value that accounts for best and worst alternatives concurrently; 2) a logical approach that represents the human choice process; 3) the performance measurements for all alternatives can be visualized on a polyhedron, at least for any two dimensions; 4) simple to implement algorithm. In addition we use the M-TOPSIS a modified version of the TOPSIS method outlined by (Ren et al., 2010). This method helps to overcome some evaluation failures that occur in the original TOPSIS method such as top rank reversal (Eraslana, 2015; Zanakis et al., 1998).

2.4.2.1 M-TOPSIS METHOD

M-TOPSIS method (Ren et al., 2007) is an evaluation method that is often used to solve MCDM problems (Pinter and Pšunder, 2013). It is based on the concept of original TOPSIS (Hwang and Yoon, 1981). The basic idea behind the TOPSIS method is to choose a solution that is closest to the ideal solution (better on all criteria) and away from the worst (which degrades all criteria) (Markovic, 2010; Opricovic and Tzeng, 2004; L. Ren et al., 2007) The modification introduced by (Ren et al. ,

2007) in M-TOPSIS method helps to avoid rank reversals and solve the problem on evaluation failure when alternatives are symmetrical that often occurs in original TOPSIS.

A specific module with M-TOPSIS has been implemented as a tool for multicriteria decision, thus facilitating its use after obtaining Pareto fronts. Particular attention was paid to the simultaneous treatment of problems involving minimization and maximization criteria. The stages of the M-TOPSIS procedure are listed below. The normalization of the matrix is performed according to the original work of Hwang and Yoon (Hwang and Yoon, 1981).

Step 1: Build the decision matrix. Establish a matrix which shows m alternatives evaluated by n criteria (see Figure 2-24).

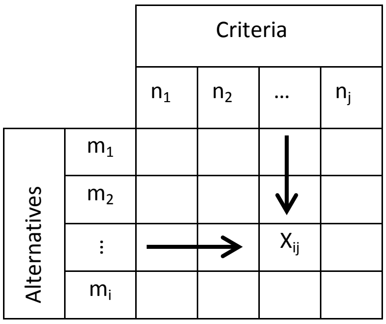


FIGURE 2-24 DECISION MATRIX

All the original criteria receive tendency treatment. Usually the cost criteria are transformed into benefit criteria by the reciprocal ratio method as it shown in equation (2-2). (García-cascales and Lamata, 2012; L. Ren et al., 2007)

$$\mathrm{X'}_{ij} = \frac{1}{\mathrm{X}_{ij}} \qquad \text{2-2}$$

Step 2: Calculate the normalized decision matrix *A*. Since different criteria have different dimensions, the values in the decision matrix *X* are first transformed into normalized, non-dimensional values in order to convert the original attribute values within the interval [0, 1] under the following Equation:

$$A = \left[a_{ij}\right]_{m\,x\,n}, a_{ij} = \frac{\mathrm{X'}_{ij}}{\sqrt{\sum_{i=1}^{n}\left(\mathrm{X'}_{ij}\right)^2}} \qquad \text{2-3}$$

where a_{ij} stands for the normalized value; $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$

Step 3: Coefficient vector of importance of the criteria. This step allows decision makers to assign weights of importance to a criterion relative to others. The weighted normalized matrix *V* is calculated by multiplying each value within the individual criterion in the normalized matrix *A* by the weight of this criterion:

$$v_{ij} = w_j \cdot a_{ij} \tag{2-4}$$

where w_j stands for the weight of the individual criterion *j*; *i* = 1, 2, …, *m*; *j* = 1, 2, …, *n*.

Step 4: Determine the positive ideal and negative ideal solution from the matrix A. The ideal solution (A^+) is the group of weighted normalized criteria values, which indicates the ideal criteria values (maximum value for benefit criteria and minimum value for cost criteria), and the non-ideal solution (A^-) is a group of weighted normalized criteria values, which indicates the negative ideal criteria values (minimum value for benefit criteria and maximum value for cost criteria):

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\}, v_j^+ = \{max_i(v_{ij}), j \in J^+; min_i(v_{ij}), j \in J^-\} \tag{2-5}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\}, v_j^- = \{min_i(v_{ij}), j \in J^+; max_i(v_{ij}), j \in J^-\} \tag{2-6}$$

Where J^+ = {*i* = 1, 2, …, *m*} when *i* is associated with benefit criteria ; J^- = {*i* = 1, 2, …, *m*} when *i* is associated with cost criteria. *j* = 1, 2, …, *n*.

Step 5: Calculate Euclidean distance. Calculate the separation measures, using the *n*-dimensional Euclidean distance. (García-cascales and Lamata, 2012; Pinter and Pšunder, 2013)

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_j^+ - v_{ij}\right)^2} \tag{2-7}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_j^- - v_{ij}\right)^2} \tag{2-8}$$

For *i* = 1, 2, …, *m.*

Step 6: Calculate the relative closeness to the ideal solution. In M-TOPSIS, unlike TOPSIS, the positive ideal solution (Di+) and negative ideal solution (Di −) in finite planes are found at first; and then, the D+ D−-plane is constructed and set the optimized ideal reference point. Finally, the relative distance from each evaluated alternative to the ideal reference point is calculated with (Lifeng Ren et al., 2007). Set the point A in Figure 2-25 [min (Di +), max (Di−)] as the optimized ideal reference point because the aim is to have the lowest distance

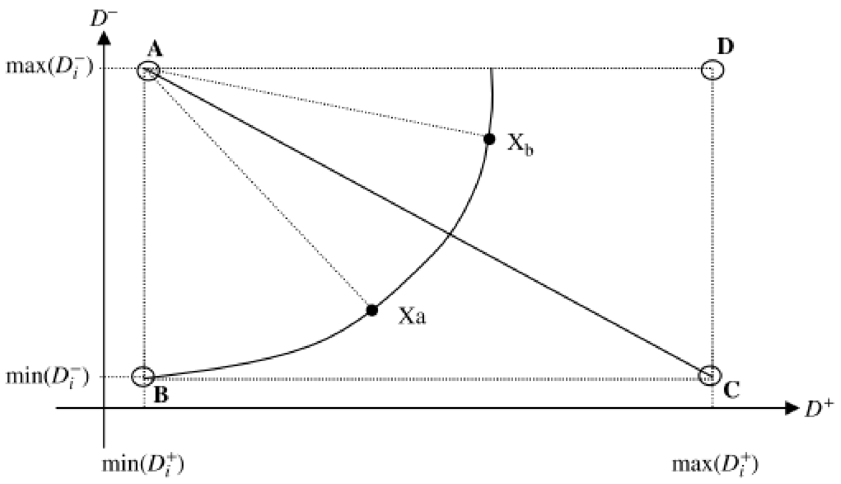


FIGURE 2-25 EXAMPLE D+ D– PLANE OF M-TOPSIS METHOD (LIFENG REN ET AL., 2007)

between the ideal criteria set values (A^+) and get away as much as possible of non-ideal criteria set values (A^-). The ratio value of R_i is calculated as follows:

$$R_i = \sqrt{\left(D_i^+ - min\left(D_i^+\right)\right)^2 + \left(D_i^- - max\ \left(D_i^-\right)\right)^2} \qquad 2\text{-}9$$

Step 7: Rank order. Rank alternatives in increasing order according to the ratio value of R_i. The best alternative is the one that having the M-TOPSIS coefficient R_i nearest to 0.

By means of this technique, objective function results that are generated by the GA execution are evaluated. The ranking that is found through M-TOPSIS allows the decision maker or analyst to numerically evaluate the trade-off between the different criteria being evaluated no matter the number of objectives being evaluated. Further, it provides a logical base solution in order to make comparisons between different optimization scenarios that find solutions in different search spaces. In Chapter 5 the model framework from Chapter 4 is extended and developed through a case study evaluating different solution strategies. In order to make comparisons between different policies and strategies scenarios, M-TOPSIS top ranked solutions are used. By using MDCM one can bypass the use of empirical analysis and managerial judgment (that may have biases) by an objective and logical solution selection method.

2.5 CONCLUSION

In this chapter a detailed description of the production system that is used as an illustrative case study is presented. This chapter highlights LCA alignment to green supply chain management issues: identifying the source and impact information of materials and processes for an LCA requires knowledge of the supply chain's materials, products and processes and vice versa.

The echelons of the agro food supply chain for orange juice derive from the work proposed in (Beccali et al., 2010). The model framework proposed in the following chapters extends and adapts the case study in order to evaluate the effects of location, scaling, allocation, technology selection, agricultural practices within the framework of green supply chain management paradigm. In contrast to the work presented in (Beccali et al., 2010), the proposed research gives special emphasis to supply chain issues related to processes, technologies and transportation. Similar to environmental assessment, life cycle cost will also be carried out at each echelon of the SC network as it will be presented in the following chapters.

Multi-objective optimization, mainly Genetic Algorithms are population based search algorithms that help find Pareto optimal solutions. By using this heuristic approach to optimization, a set of trade-off solutions that optimize multiple objectives is obtained guaranteeing that compromise solutions are found.

MCDM such as M-TOPSIS are techniques that allow the evaluation and ranking of alternatives. These techniques provide a means to objectively rank solutions taking all criteria into account based on the decision makers’ preferences.

Section 1 of this Chapter has highlighted that agro food supply chains have two main echelons: agriculture and food processing. Since agricultural practice has so much importance on the quality value of the product, chapter 3 is first dedicated to the supplier selection process, taking into account the different key environmental issues that have just been presented. The supplier selection problem is then embedded in a more holistic manner, thus leading to a higher level decision making framework in the context of a Supply Chain Network Design problem approach that is presented in Chapters 4 and 5, in order to obtain *organic* eco-labelling.

Chapter 3 Partnership for Sustainability: Supplier-Producer Interface

Résumé

Une contribution importante à l'impact environnemental des chaînes d'approvisionnement agro-alimentaires est liée aux pratiques agricoles pour la production des matières premières. Ce problème peut être formulé du point de vue de l'entreprise focale dans le cadre de la chaîne logistique verte, comme un problème de sélection de fournisseurs (en matières premières) « verts» . Ce chapitre propose un cadre méthodologique baptisé « Partenariat pour le développement durable » pour résoudre ce problème qui intègre l'évaluation du cycle de vie, les collaborations environnementales, et l'agriculture sous contrat afin de tirer des avantages sociaux et environnementaux liés à ces paradigmes et de tendre vers une chaîne d'approvisionnement durable. Ce système de collaboration est appliqué à des chaînes agro-alimentaires. Dans cette approche, les risques et les gains sont partagés par les deux parties, de même que des informations liées aux pratiques agricoles de telle sorte que l'entreprise « focale » peut optimiser la performance globale en décidant du choix des fournisseurs sous contrat, de la capacité à installer, des technologies à mettre en œuvre au niveau du champ afin de maximiser la performance économique tout en minimisant l'impact environnemental. La société focale fournit les connaissances et informe les fournisseurs des pratiques agricoles à adopter afin d'atteindre ces objectifs par ce système d'agriculture contractuelle. Une étude de cas est proposée afin d'illustrer la méthodologie qui est décrite pas à pas. La résolution du problème implique d'une part une stratégie d'optimisation multi-objectif basée sur des algorithmes génétiques et d'autre part une méthode multicritère d'aide à la décision (TOPSIS). Des scenarii sont étudiés et soulignent que des gains substantiels peuvent être obtenus.

Abstract

An important contribution to environmental impact of agro-food supply chains is related to the agricultural practices during raw materials production. This problem can be stated from the point of view of the Focal Company (FC) within the scope of GrSCM, as Green Supplier Selection Problem (GSSP) for raw materials. This paper proposes a methodological framework for GSSP referred to as Partnership for Sustainability that integrates life cycle assessment, environmental collaborations, and contract farming in order to gain the social and environmental benefits related to these paradigms in order to get closer to a sustainable supply chain. The collaborative scheme is applied to agro-food chains. In this approach, risk and gains are shared by both parties, as well as information related to agricultural practices through which the FC can optimize global performance by deciding which suppliers to contract, how much capacity to demand and which practices to use at each supplying field in order to maximize economic performance while minimizing environmental impact. The FC provides the knowledge and technology needed by the supplier in order to reach these objectives per contract farming scheme. A case study is developed in order to illustrate and a step-by-step methodology is given involving on the one hand a multi-objective optimization strategy based on

Genetic Algorithms and a MCDM approach (TOPSIS) on the other hand. Scenarios are studied to emphasize the potential improvement gains in performance.

Acronyms

ASC	AGROFOOD SUPPLY CHAIN
CF	CONTRACT FARMING
EI	ENVIRONMENTAL IMPACT
FC	FOCAL COMPANY
GrSCM	GREEN SUPPLY CHAIN MANAGEMENT
LCA	LIFE CYCLE ASSESSMENT
LCI	LIFE CYCLE INVENTORY
MCDM	MULTIPLE CRITERIA DECISION MAKING
MOO	MULTI-OBJECTIVE OPTIMIZATION
MS	MULTIPLE STRENGTH
M-TOPSIS	MODIFIED TECHNIQUE FOR ORDER OF PREFERENCE BY SIMILARITY TO IDEAL SOLUTION
NSGA	NON-DOMINATED SORTING GENETIC ALGORITHMS
PfS	PARTNERSHIP FOR SUSTAINABILITY
SC	SUPPLY CHAIN
SCM	SUPPLY CHAIN MANAGEMENT
SCND	SUPPLY CHAIN NETWORK DESIGN
SN	SUPPLIER NETWORK
SS	SINGLE STRENGTH
SSP	SUPPLIER SELECTION PROBLEM
TOPSIS	TECHNIQUE FOR ORDER OF PREFERENCE BY SIMILARITY TO IDEAL SOLUTION

Index & Sets

i	supplier index of a set I
g	technology package of a set G

Variables

b_i	Binary variable used to select a supplier (i)
s_i	Production capacity to be contracted per supplier (i) as a continuous measurement of land area
$Y_{i,g}$	Production yield estimated per technology package (g) used at each supplier (i)
$CT_{i,g}$	Production cost estimated per technology package (g) used at each supplier (i)
EI	Environmental impact measurement of the full set of suppliers (i)
EIs_i	Environmental impact estimation for each supplier (i)
CO_i	Cost incurred for operations for each supplier (i)
CE_g	Environmental cost estimated per unit of production based on technology (g)
Cost	Cost incurred of the full set of suppliers
LLC_i	Lowest value of land capacity to be contracted of each supplier (i)
P	Total raw material produced
PCap	Processing plant raw material requirement

3.1 INTRODUCTION

Environmental awareness has shifted consumer behaviour towards more efficient and environmentally friendly products, including processed foods. This has led food manufacturers to find opportunities by developing strategies targeting eco-friendly consumers and markets, through the use of eco-labelling (Bougherara and Combris, 2009; Roheim et al., 2011). In order to satisfy these niche markets and continue developing this branding strategy, a shift from conventional to more sustainable food production has been progressively pursued. Consumer awareness about the *greenness* of products is incentivising a change towards alternative practices and technologies that may affect the entire agro-food supply chain (ASC).

One of the most important links in the ASC is in the interface between farms and manufacturers as highlighted in Chapter 2, due to raw material sourcing needed to produce the current selection of food products at retail stores and markets. Environmental impact of agriculture depends to a large extent on farmer production practices (Marsden et al., 1999; Van der Werf and Petit, 2002). This is why there is an interest both in sustainable agricultural practices and in the downstream green process design in order to look at the sustainability of ASC, in order to identify the potential improvements.

The study of this interface is sometimes referred to as the supplier selection problem (SSP). This subfield of supply chain management (SCM) has largely been tackled in the dedicated literature, where it is mostly described by taking into consideration a set of criteria, traditionally based on cost, delivery time and quality among others, to classify and rank suppliers (Abdallah et al., 2011; de Boer et al., 2001). This chapter looks at the SSP of an orange juice producing company that uses suppliers in a collaborative scheme, that additionally includes in their supplier roster small and medium farmers under contract farming model. Furthermore, it proposes the use of the green supplier selection paradigm that incorporates environmental performance of suppliers in the selection process. The objective of this chapter is then to show how through synergy made through collaboration, contract farming and a green supplier selection perspective, improvements in the performance of the food supply chain can be achieved in economic, social and environmental terms. This approach will be referred in this chapter as Partnership for Sustainability (PfS) (see Figure 3-1).

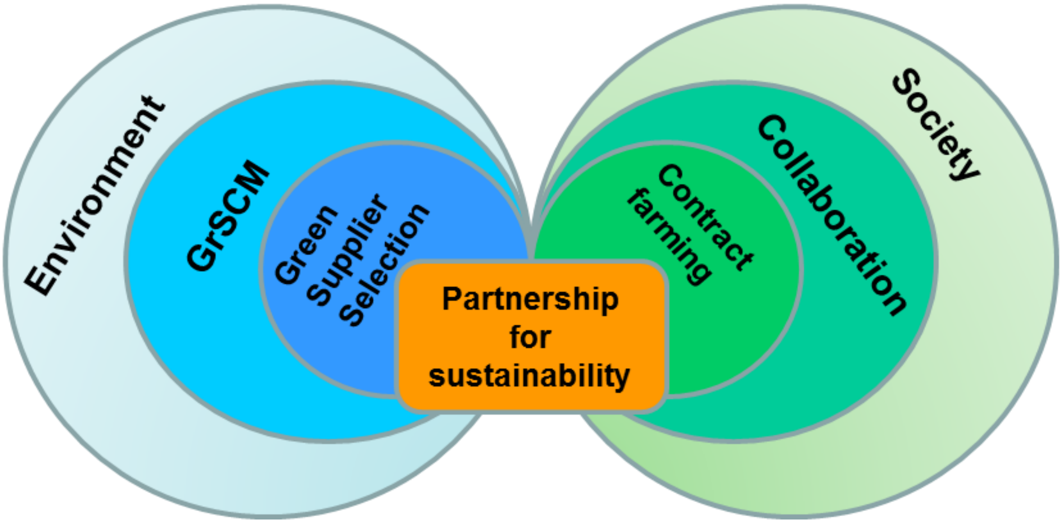


FIGURE 3-1 DIAGRAM ILLUSTRATING PARTNERSHIP FOR SUSTAINABILITY METHOD INTEGRATION

In order to illustrate the approach and proposed solution methodology, a case study is developed focusing on the production and supplying of oranges from Mexico used for juice production. This case study is based on the locally available technological alternatives which are used at each supplying orchard, taking into account a local agricultural practice and its corresponding production yields and related environmental impacts for the specific citrus fruit producing region. The use of a multi-objective optimization strategy through genetic algorithms is applied for this purpose, as well as a multicriteria decision making method in order to select a solution. This chapter is divided into 5 sections following this introduction section. Section 2 introduces the green supplier selection problem as a key item of the green supply chain management problem. The Partnership for Sustainability is then defined in Section 3 and the proposed methodology for this type of partnership following a step-by-step methodology is then implemented in Section 4. The results of the case study for a subsequent application of orange juice production are then discussed. The conclusions and perspectives of this chapter are finally proposed in Section 6.

3.2 BACKGROUND

3.2.1 GREEN SUPPLY CHAIN MANAGEMENT

The backdrop of the proposed approach lays in a promising and somewhat recent paradigm to evaluate and improve the environmental and overall performance of production systems called Green Supply Chain Management (GrSCM). This approach integrates two conceptual scopes: Supply Chain Management (SCM) and Life Cycle Assessment (LCA). The former provides a framework to visualize and improve the economic and operational performance of productive systems by modelling the flow of materials, information and money, throughout the links in the production chain, with the end objective of economic profit (Hugo and Pistikopoulos, 2005). The latter, is a technique to aid in the decision making process by providing a system-oriented approach to evaluate the environmental impacts at some or all the stages in the life cycle of a product (Jolliet et al., 2010a). By integrating these two holistic approaches, the economic and operational objectives can be set side by side with sustainability objectives in order to make decisions on design or improvements of the overall performance of a production system.

Although much progress has been made in this field, there are still opportunities in exploring the application of GrSCM in different application fields such as agro-food supply chain systems (Seuring and Muller, 2008; Srivastava, 2007). This work proposes the extension of the current GrSCM model to include special issues dedicated to agro-food supply chain systems and focuses on the decision making process of supplier selection in this context, i.e. when suppliers are farms.

3.2.2 GRSCM MODELLING AND OPTIMIZATION APPROACH

The modelling approach assumes that there is a set of products that can be differentiated by "green" quality based on the technological methods used to produce them. When a product is made with specific quality characteristics, for example "big" oranges, that have a higher demand and/or market price against, "small" oranges, this leads the orange farmer to change, within physical and cost-benefit limitation, the production processes configuration and capacity, in order to increase the output of the most profitable product i.e. "big" oranges.

Let us consider that a new product quality attribute is now being associated with environmentally produced/processed products. These products are marketed through eco-labels such as: organic, bio, green, eco-friendly, etc. Let us also consider that these new attributes have changed the market value and pricing of green products. Although this type of labelling have been widely used since the 1990's in the US and 1980's in France (Dobbs et al., 2003), it is interesting to explore the possible effect this could have when modelling and optimizing an ASC. Thus, the approach proposed here takes this green preference into account and integrates it within a GrSCM modelling and optimization framework.

In the literature, different methods have been proposed in order to solve this type of problems, some authors use MILP techniques (Mixed Integer Linear Programming) (Amin and Zhang, 2012; Ramudhin et al., 2008) as a preferable technique for network configuration; others take into account the non-linear behaviour (embedded through capital cost limitation for instance) that requires MINLP (Mixed Integer Non Linear Programming) capability (Corsano et al., 2011), or a stochastic programming approach to handle uncertainties (Guillén-Gosálbez and Grossmann, 2009). A relevant approach that has been widely used to handle the multi-objective nature of GrSC models (sometimes in tandem with other modelling approaches such as MILP) is the so-called MOO (Multi-Objective optimization) technique (Amin and Zhang, 2012; Bouzembrak et al., 2011); as well as other Multicriteria Decision Methods (MCDM) such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and AHP (Analytic Hierarchy Process) (Cao and Zhang, 2011; Lin and Juang, 2008; Lu et al., 2007). Both approaches, MOO and MCDM, were selected here to manage the complex decision-making that takes place when working with a SC scope.

The proposed work assumes that the production practices at all stages of the supply chain can be changed to improve environmental performance, which means the changes in consumer preference for “green” products have to be met by a market demand (as this attribute adds intangible value to the product). In supply chain modelling terms, using the orange juice production as an example, the following set of questions have been formulated:

1) Production design problem: which agricultural practices should be used to add “green” value to the product at the raw material production stage e.g. use of pesticides, fertilizers, gasoline powered machine, etc.?
2) Product mix problem: what quantity of each quality-type orange should be produced to obtain the desired orange juice quality mix (e.g. “organic”, “environmentally friendly” or “30% less environmental impact”)?
3) Location-allocation problem: which and how many orchards should produce environmentally friendly oranges; which and how many should use intensive agricultural in order to satisfy demand?
4) Supplier selection problem: which supplier to buy from? How much to buy? Which criteria to use to evaluate supplier performance?

In order to answer these questions, the Partnership for Sustainability approach takes the green supplier selection problem integrating the benefits from contract farming and an environmental collaborative approach described in the following sections.

3.2.3 GREEN SUPPLIER SELECTION PROBLEM

In the field of supplier selection, there is a wide body of publications looking at many different aspects such as formulation, method and application (Amid et al., 2006), These include recent works on green or sustainable supplier selection. Although Green Supplier Selection (GSS) has been named in different ways such as Green Vender, Green Purchasing, Environmental Purchasing, most definitions in general coincide in its reach. The definition proposed in (Zsidisin and Siferd, 2001), assimilates Green supplier selection to *"…the set of purchasing policies held, actions taken and relationships formed in response to concerns associated with the natural environment."* It goes on to clarify that "*These concerns relate to the acquisition of raw materials, including supplier selection, evaluation and development…*". This integration is promoted because of the benefits that interaction of the different members of the supply chain produces not only on sustainability issues but also on economic and operation performance (Walton et al., 1998). A recent review on green supplier selection has highlighted some interesting research challenges (Tate et al., 2012). According to these authors, the integration of Life Cycle Assessment in the definition and measurement of environmental criteria offers an interesting methodological framework, since it involves a system wide approach for environmental impact evaluation. Some other examples of GSS have been published for industries such as electronic and consumer goods, (Humphreys et al., 2003; Lee et al., 2009). A study on the effectiveness of a large scale Sustainable Supplier program in Mexico was recently published, highlighting a need to focus on micro and small business as an important objective in further research (van Hoof and Lyon, 2012).

This chapter is in phase with this mode of thinking that supports the use of LCA as an aid tool for the supplier selection process. The case study of an agro-food chain illustrated the methodology in order to contribute to the current body of research in the field. It also contributes to the potential improvement of the supply chain initiated at contract farming level and to its derived environmental collaboration that is further discussed in the following section.

3.2.4 CONTRACT FARMING

In the SCM paradigm as in the GrSCM, a central or focal company (FC) as proposed in (Seuring and Muller, 2008) is characterised by being the designer or owner of the product or service offered, governing the supply chain, and having contact with all SC stakeholders including the customers. The FC can also sometimes be the processing or manufacturing company, as in the case study.

The FC is considered to be the *integrator firm* within the context of contract farming as described by (Rehber, 2000), under a Management and Income Guaranteeing contract, (Richard and Kohls, 1998) also known as Production management contract (PMC) (Minot, 1986). They describe PMC type of contract model as one that specifies product quality measures that are acceptable to the integrator: the integrator provides production resources, taking on substantial managerial responsibilities, and supervises the SC. This form matches well with the green supplier development aspect of the GrSCM approach, given that green supplier development draws its importance from the fact that suppliers are often small and do not have the knowhow or resource necessary to face the environmental issues related to their business process (Bai and Sarkis, 2010; Seuring and Muller, 2008). This is why some research has been focused on collaboration, certification and education of suppliers (Leppelt et al., 2013; Rao and Holt, 2005; Zhu and Sarkis, 2004). The overlapping from GrSCM and contract farming models are illustrated in Figure 3-2. For each basic component in one framework there is its counterpart in the other, e.g. Green Suppliers in GrSCM are the Farmers in the Contract Farming scheme.

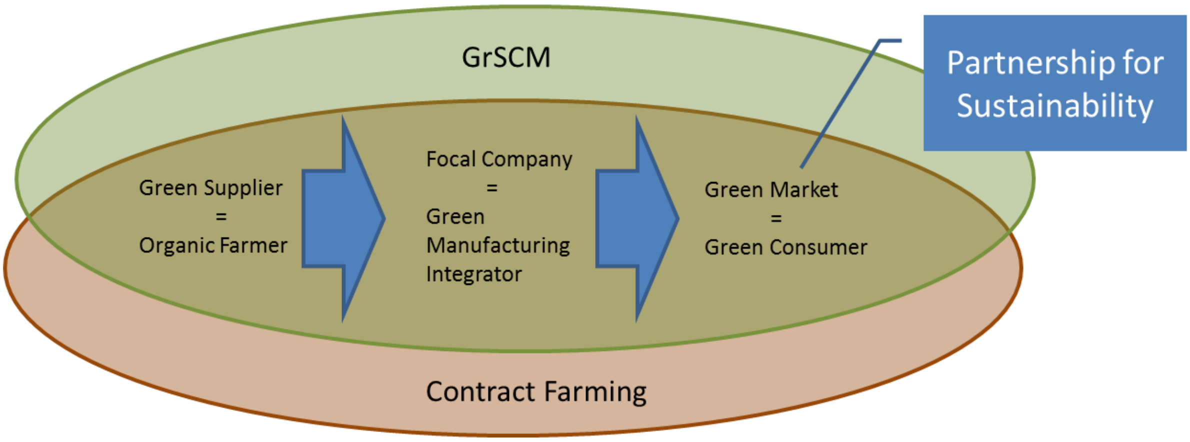


FIGURE 3-2 ANALOGY BETWEEN GRSCM AND CONTRACT FARMING ELEMENTS

The manufacturer used in the case study is both the Focal Company and Integrator: the proposed model is adapted to this type of supply chain configuration. In other words, this work is limited to this situation, i.e. where the focal company is the processing company, and is the principal negotiator with suppliers and distributers or consuming markets.

It is important to highlight that the details related to the negotiation and contracting stages are out of the scope of this research; however, the contract form that allows for the collaboration and technology transfer, that includes which agricultural practice to use at the suppliers' fields, is part of the general approach.

Contract farming as described in a special report issued by the Food and Agriculture Organization of the United Nations (FAO) (Eaton and Shepherd, 2001), as the use of contracts to build a foundation of collaborations between the FC and the supplier, where the whole or a fraction of production output from suppliers is bought guaranteeing (not without risk) a reliable source of product, while the supplier has an assured buyer. According to the FAO report, this model is an effective way of taking advantage of the investment power and knowledge base of the FC by transferring technical skills in order to use the synergy reached to improve supplier performance. This in turn helps to guarantee both parties a partnership for growth and helps mitigate and spread risk. Most importantly, within the context of this work, it allows the FC to require and share technological and agricultural practices to be used at the supplier field in order to obtain conforming and consistent raw materials. It also gives enough flexibility to find the optimal supplier technology package selection.

3.2.5 PARTNERSHIP FOR SUSTAINABILITY

Partnership for sustainability is derived from the premise documented by (Vachon and Klassen, 2006) that the improvement in operational performance is based on partnerships in the supply chain. They use the term "green project partnership", to describe *"…the extent of interaction between a plant and its primary suppliers and major customers in developing and implanting pollution prevention technologies*". This paradigm is considered here and implemented in what follows it into the food supply chain within the GrSCM scope. As pointed out by (Vachon and Klassen, 2006) and corroborated by (Albino et al., 2012), the integration of suppliers through partnerships has a positive effect of operations performance, and furthermore may stimulate gains in integrated knowledge and knowhow from the supply network (Bowen et al., 2001), which in turn can have a positive effect on the development of agricultural practices and supply chain negotiations and distribution issues.

3.3 METHODOLOGY FOR PARTNERSHIP FOR SUSTAINABILITY IMPLEMENTATION FOR SSP

3.3.1 INTRODUCTION

The general approach to solve the SSP is a multi-step process (seeTable 3-1). It first involves the scouting of a list of potential suppliers through basic common sense judgements; this is followed by a measurement and characterization step based on requirements and desirable attributes. Then, a classification or ranking is done in order to target negotiations and contracting.

Although this can be a dynamic process, meaning that there are new suppliers being added and old suppliers eliminated from the approved supplier catalogue, it can also be part of strategic and tactical planning stages for long-term improvements that can be reviewed periodically. This research is scoped in the latter approach.

TABLE 3-1 PARTNERSHIP FOR SUSTAINABILITY SUPPLIER SELECTION PROCESSES

PfS supplier selection process	
No.	Description
1	Pre-selection or scouting of suppliers
2	Short listing based on common sense judgment
3	Supplier characterization
4	Supplier network model
5	Supplier network optimization
6	Supplier network selection
7	Supplier negotiation & contracting

Table 3-1 displays the set of extended steps in the Partnership for Sustainability supplier selection process. This includes the first steps of the conventional supplier selection process in addition to a set of extended steps beyond step 2. These additional steps form part of a holistic approach to characterize the potential partners in addition to modelling, optimization and selection step, to end with the execution of a contractual negotiation and agreement: this last step is yet not described in detail since it falls outside of the scope of this chapter; steps 3 to 6 are described in detail in this section.

Supplier characterization

The current SSP is framed by looking at a set of characteristics required by the production plant being supplied. The most common characteristics evaluated include quality, cost and delivery performance; although some efforts have been made to include environmental criteria in the supplier selection process, this kind of approach is not yet the norm.

It must be also highlighted that the evaluation methods found in the domain literature describe the supplier selection process as a search for the most competitive vender without looking necessarily at the potential benefit of a long-term partnership, although there are some instances. In this approach the characterization process itself consists of looking at the requirements or criteria most valued by the FC and implementing scoring or measurement systems in order to allocate a value to each supplier based on observed or estimated performance. For this purpose, the Partnership for Sustainability takes into account the potential capability of the supplier given the field or region characteristics, and the agricultural practice that can be used. This means that the question is not only which supplier to choose but also what technology should be matched to obtain the best criteria measurements.

The justification of this approach is also made given that many of the sustainability leaders, at least in the chemical industry, that manage ecology and social sustainability beyond their company boundary, view managing supplier relations as part of their fundamental strategy (Leppelt et al., 2013)

Yield and Cost characterization

The output from each region, even from each orchard and even with the same technology, can differ. This is why an initial estimation of the output and cost from each orchard or the regional location of the supplying orchards must be made. This information is then analysed and processed in order to have useful operational information. This may be difficult for some agro-food products but is already used in some cases such as orange production in many regions of Mexico. These types of characterisations can be made by collaboration through confederation of growers, trade group, sponsorship of the FC or by government and independent research bodies.

The characterization of the performance of the fields can be either an internal exercise of the different production fields or it can be an experimental one carried out by expert bodies. In the second alternative, a third body has to collect and integrate data into information that can be used by all stakeholders. This can be carried out by the use of experimental fields in order to characterize the surrounding environment and local soil production.

The information that is necessary to apply this methodology is field production yield, e.g. tons per hectare per year and operations cost (energy cost, agrochemicals input cost, etc). Other important indicators may also be considered such as land and irrigation cost, but are not included in the scope of the case study of this investigation.

Environmental Impact characterization

The most widely used technique to measure the environmental impact in the current literature on GrSCM is using LCA (see Chapters 1 and 2), which matches well with the holistic systems approach of SCM. LCA can provide information on the effect of each step depending on the depth of the analysis, from process and product design to industrial systems design and even at more strategic scales, such as GrSCM. For the SSP, a collaborative scenario is investigated in which information and knowhow are shared between the Focal Company and the suppliers, this is also known as Supplier Development (Bai and Sarkis, 2010); the objective is to use the synergy created through the flow of information that helps the Focal Company make better decisions. This explains why FC has the insight to perform a system-wide analysis such as LCA. To collect and analyse the potential, suppliers must be willing to share information on field, plants and management practices; in turn, the centralized manager must be transparent in its measurement and evaluation techniques. This process can be divided into three steps as explained in the two following sections.

Technology package characterization

In this step, a characterization of regionally used agricultural practices has to be evaluated, this can be based or made at the same time as the Yield and Cost characterization process; these packages may consist of agrochemicals used, soil treatment, physical manipulation (e.g. hedging, pruning, shaping, etc), machinery used, among other things. During this phase, experts are needed not only to characterize the production systems at field, but also to help classify them by level of sophistication. The result should be a manageable set of categories in which an average is used as a typical example per category that describes how production systems work (e.g. “organic” production, average production and intensive production system). Although it is important to have a well-developed approach in order to classify, this falls out of the scope of this research. It is assumed that this step is performed through expert opinion; for the case study, information from a regional government funded agricultural research centre is used.

Technology package indicators

Once the categories are developed, a systematic evaluation is achieved to basic indicators that will be used in the modelling and optimization process. These indicators may consist of operational functions such as the average yield obtained per area, plant or tree. It can also include economic functions such as average cost per unit of product given a agricultural practice used which are developed during the Yield and Cost characterization; in addition, environmental impact indicators such as CO_2 emissions or eutrophication are calculated per area, plant or tree in a given timeframe e.g. per year. The environmental impacts have been evaluated by LCA. This analysis requires different levels of information provided by field and literature research, expert collaborators and dedicated LCA software tools that are commercially available.

The environmental impact assessment is then integrated in the model as well as the other indicators. The model is useful to predict the impact that a decision alternative has not only towards operational and economic performance, but also towards environmental aspect given a set of decision variables.

3.4 PARTNER FOR SUSTAINABILITY SUPPLIER SELECTION PROCESS

3.4.1 SUPPLIER NETWORK MODEL

In order to improve directly the overall performance of the SN not only by selecting the suppliers but also by incorporating a long-term partnership in which an interchange of technological knowledge and risk sharing is made by contract, a multi-objective optimization formulation is proposed. This approach allows the consideration of multiple and possibly antagonistic objectives to be optimized concurrently (Azzaro-Pantel et al., 2007; Dietz et al., 2006).

The general model is described below:

Objective functions

$Z_1 = \min(\text{Costs})$

$Z_2 = \min(\text{Environmental Impacts})$

The Cost variable represents the cumulative cost of all orchards; this is to say the sum of the cost of each supplier given the technology package used and the capacity contracted represented by CO_i (see equation 1):

$$Cost = \sum_{i=1}^{n} CO_i \qquad \text{3-1}$$

The CO_i expression in equation (3-2) is calculated considering the selection of a supplier, the capacity that is contracted multiplied by the cost per hectare given a given agricultural practice here represented by the (g) index, all of this calculated per supplier (i):

$$CO_i = b_i s_i \times CT_{i,g} \qquad from\ i=1,2,\ \ldots,n \qquad \text{3-2}$$

The global environmental impact generated by all suppliers can be evaluated by equation (3-3):

$$EI = \sum_{i=1}^{n} EIs_i \qquad \text{3-3}$$

In expression (4), the environmental impact based on selection variable (b), capacity to be contracted (t) and technology package selected (g) is expressed by:

$$EIs_i = b_i t_i Y_{i,g} CE_g \qquad for\ all\ i=1,2,\ldots,n \tag{3-4}$$

<u>Subject to</u>

Raw material requirement of the processing plant (FC) expressed in equation (3-5)

$$P \leq PCap \tag{3-5}$$

A restriction on the contract specification of minimum land to be guaranteed in contract phase is represented by equation (3-6)

$$s_i \leq LLCi \;\; for\ all\ i=1,2,\ldots,n \tag{3-6}$$

Assumptions:

1. Each supplier has a given physical or contractual capacity constraint.
2. Each supplier is willing to accept the agricultural practice selected for the optimal SN in the negotiation & contracting step.
3. The total quantity requirement of raw material is fixed given the capacity at the processing plant.

It is important to mention that although this approach seeks to improve the overall supply chain, the scope of this study is yet limited since some important environmental impacts and cost producing elements related to transport distance, mode (e.g. sea freight, land freight, train, etc.) and size (e.g. 18 ton fright container, etc.), are not considered.

3.4.2 SUPPLIER NETWORK OPTIMIZATION

The optimization approach proposed in this work is performed by a genetic algorithm method as justified in Chapter 2. This choice was made according to the flexibility of this approach to tackle problems with multiple objectives, its potential to solve problems without restriction on the type of variables, either integer or continuous, in addition to its capacity to solve linear and non-linear problems (Dietz et al., 2006). Generally, the engineering design problem tends to be of multi-objective nature with different variables and characteristics. Other methods may be considered that can also handle multiple objectives at once with variable complexity (see Chapter 2).

3.4.2.1 SUPPLIER NETWORK SELECTION

The final selection process is made using a multicriteria decision-making process that takes into account the optimal alternatives found in the Pareto front. These alternatives are found to be non-dominated solutions near optimal value, and although the decision maker may use judgment to make the final selection from the alternatives, a formal method based on TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is proposed here (Lai et al., 1994). This method is based on the idea of choosing the best alternative solution from a set by analysing the shortest geometric distance from the positive ideal solution and the longest distance from the negative ideal solution. It also requires weights to be assigned per criterion and normalizes the information, so that the various alternatives are ranked. In the case study this all criteria are given equal weights. Although other ranking and classification methods exist, TOPSIS has proven its efficiency in the final alternative selection process obtained through GA (Gen et al., 2005, 1999).

3.4.2.2 SUPPLIER NEGOTIATION & CONTRACTING

Supplier contracting is proposed within a Contract Farming (CF) framework, where a partnership is made by a contractual agreement in order to share knowledge and risk. Through this type of contracting, the possibility of incorporating centralized decision making regarding technology used during production process at farm is allowed because of the shared risk and growth that contract farming promotes (Eaton and Shepherd, 2001). Although the use of CF may be difficult in some circumstances and regions, in the case of many developing countries, where a large part of the production systems have not yet become intensified, this type of collaborative framework can be seen as an opportunity for both parties.

3.5 CASE STUDY: ORANGE JUICE PRODUCTION

The supply chain network for the orange juice production industry serves as an illustration of the proposed methodology and raises a lot of issues of GrSCM. The case study is located in the Mexican golf cost region of Martinez de la Torre, Veracruz, which is the most important citrus fruit producing region in Mexico. The SSP implies orange fresh fruit supplying orchards that are to be selected as suppliers for an orange juice producing company. The case study follows the steps proposed in the previous methodology section. They are presented in what follows.

3.5.1 SUPPLIER CHARACTERIZATION

3.5.1.1 TECHNOLOGY PACKAGE CHARACTERIZATION

The regional characteristics of production systems involve 4 basic agricultural practices. These packages range from organic (1), basic (2), standard (3) to intensive (4) systems, as shown in Table 3-2.

TABLE 3-2 CHARACTERISTICS OF EACH TYPE OF TECHNOLOGY PACKAGE

	Technology package			
Agricultural practices	**1 (organic)**	**2 (basic)**	**3 (standard)**	**4 (intensive)**
Soil loosening	0	1	2	2
Weeding	2	2	2	0
Plantation	1	2	2	1
Chemical weeding	0	1	2	5
Pruning	0	0	1	1
Trunk protection	1	1	1	2
Chemical insecticide	0	0	4	6
Chemical fungicide	0	0	4	6
Urea (N)	0	0	2	4
K_2O_5	0	0	2	4
P_2O_5	0	0	2	4
Fuel*	0	0	90.3	105.35
Communication	1	1	1	1
Harvesting	1	1	1	1

Note: Unit is in number of applications during one year   * in liters of standard gasoline

Each agricultural practice was studied in order to determine the mean production yield and production cost as input parameters of the modelling stage; the values are presented in Table 3-3.

TABLE 3-3 YIELD AND COST MATRIX PER AGRICULTURAL PRACTICE

Indicator	Unit	1 (organic)	2 (basic)	3 (standard)	4 (intensive)
Production yield	ton/ha	5	8	15	25
Production cost (contract)	$(mxn)/ha	635	1275	3064	4205
Production cost (product)	$(mxn)/ton	127	159.38	204.27	168.2

An investigation related to this case study was performed by the Research Centre on Economic, Social and Technological Aspects of International Agriculture Policies (CIESTAAM), a research institution which is part of the Autonomous University of Chapingo (UACh). The study involved specialists on agricultural issues of the region (Gómez Cruz et al., 1997). The average yield of production as well as the operational cost related to these types of agricultural practices and practices were determined and presented. An orange production manual for the geographical region made by the National Institute for Forestry, Agricultural, and Animal Husbandry Research (INIFAP) (Curti-Díaz et al., 1998) provided the information needed to perform the LCA.

3.5.1.2 TECHNOLOGY PACKAGE INDICATORS

Using the information gathered during the previous steps, a LCA was carried out through the use of the specialized software tool Simapro ® (Goedkoop et al., 2008).

Figure 2 presents the main environmental impact midpoint categories. From this set of 15 categories, not surprisingly, large discrepancies exist between technologies 1 and 2 (involving respectively no use and little use of agrochemicals and fuels and leading to null and very low environmental impact) on the one hand and technologies 3 and 4 that are the most harmful on the other hand. According to the category considered, technologies 3 and 4 exhibit reversed trends.

Table 3-4 shows the selected environmental impact indicators from the IMPACT 2002+ method that is adopted in the optimization phase. Many environmental indicators follow the general tendency of the Global Warming Potential (GWP). This is why it was selected to be evaluated and included in the simulation model; other indicators related to agricultural practices such as Acidification, Terrestrial Eutrophication, among others (Brentrup et al., 2004) can also be used when modelling environmental performance within the proposed methodology based on requirements and goals of the study. It must be emphasized that aquatic eutrophication was selected given the effect of chemical fertilizers have, regarding water nutrient contamination (Brentrup, 2003; Huijbregts and Seppälä, 2001).

Table 3-4 Environmental indicators output table per technology package

Impact category	Unit (per kg of orange)	Technology package			
		1 (organic)	2 (basic)	3 (standard)	4 (intensive)
Aquatic eutrophication	kg PO_4 P-lim	0	$5{,}060\ 10^{-6}$	$1{,}230\ 10^{-5}$	$1{,}620\ 10^{-5}$
Global warming	kg CO_2 eq	0	$1{,}355\ 10^{-3}$	$1{,}149\ 10^{-2}$	$1{,}291\ 10^{-2}$

3.5.2 SUPPLIER NETWORK MODEL

The supplier network model was then developed using the abovementioned information developed and integrating it to the set of systems parameters gathered by the procurement analyst or model developer.

In the case of suppliers, a set of 20 suppliers is evaluated which are related to index (i) of set (I) (see Index & Sets). Four agricultural practices are considered and integrated as the (g) index of the set (G).

The minimum requirement for the processing plant (see equation (5)) is set at a value of 60,000 tons of oranges, which is the capacity of a medium to large orange juice processing plant in Mexico.

Three objective functions are considered, one related to cost and two to environmental impacts:

Z1= minimization of operational cost = min (Cost)

Z2= minimization of CO_2 *emissions equivalent = min (GWP)*

Z3= minimization of aquatic eutrophication equivalent = min (Eutro)

This cost criterion was selected since it can be viewed as useful to convince the participating potential supplier that this strategy is mutually beneficial in contrast to supplier sale price or other forms of economic criteria.

The input for the restriction related to minimum and maximum land area to be contracted (see equation 6), is presented in Table 3-5. A minimum value within the contract scheme stipulates that at least half of the capacity is contracted in the case of a selected supplier. This is done to promote the supplier participation in the type of proposed collaboration, as well as to reduce the number of suppliers that the optimization process can select.

TABLE 3-5 RELATION BETWEEN SUPPLIERS AND RESPECTIVE FIELD SIZE THAT CAN BE CONTRACTED FOR USE

Supplier	Contractible hectares (t_i)	Supplier	Contractible hectares (t_i)
1	226.48	11	50
2	101.38	12	298.82
3	190.73	13	107.57
4	650.81	14	115.81
5	43.12	15	69.11
6	512.61	16	258.94
7	43.05	17	273.76
8	560.81	18	250.52
9	26.29	19	221.52
10	22.97	20	17.75

3.5.3 SUPPLIER NETWORK DESIGN OPTIMIZATION

Optimization is then carried out using the MULTIGEN® genetic algorithm extension library (Gomez et al., 2010a). The optimization simulations parameters used are shown in Table 3-6. The population size and number of generations were empirically evaluated by a preliminary analysis showing that a ratio roughly set at 20 individuals per variable, and a double of population size is effective within the MULTIGEN environment The crossover and mutation rates were set at default values as suggested in (Gomez et al., 2010a). The use of the variant of the NSGA II optimization algorithm is selected given its capacity to find a non-dominated set of alternatives to develop the Pareto Fronts needed (Deb et al., 2002b).

TABLE 3-6 OPTIMIZATION RUN PARAMETERS

Parameters	Values
Population size	400
Number of generations	800
Algorithm	NSGA II
Crossover rate	0.9
Mutation rate	0.5

The optimization was run 5 times in order to validate and search a wider area of the feasible space, this generated a set of 192 alternatives to be analysed. Figure 3-3 shows a three-dimensional scatter plot where the vertical axis is Cost (in dollars; \$), the right axis is GWP (in kilograms of carbon dioxide equivalent; kg CO_2 eq) and the depth axis is Eutrophication (in kilograms of phosphate equivalent in a phosphate limited system; kg PO_4 P-lim).

Figure 3-3 exhibits the set of the different series of Pareto front runs. Because this is a set of many Pareto fronts that were not evaluated concurrently, there are dominated points within the data set, which must be eliminated prior to apply the final selection.

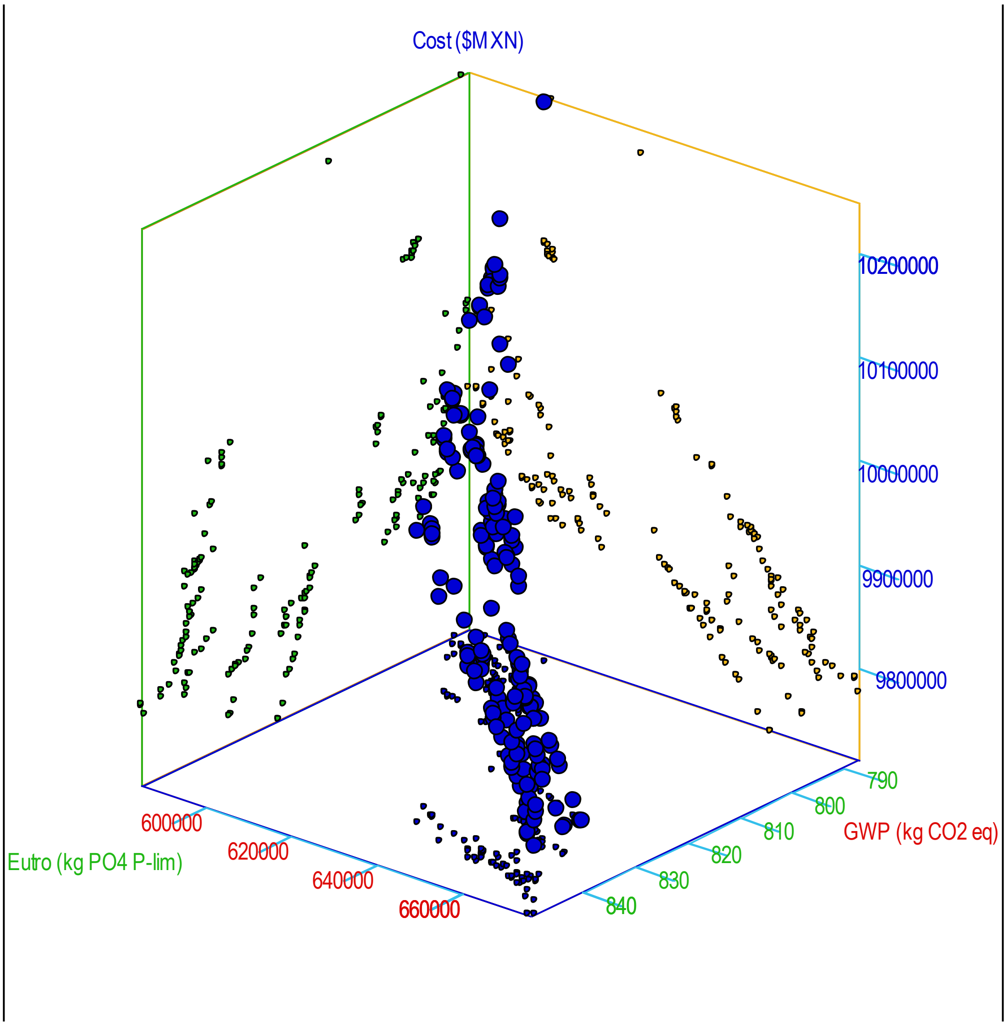


FIGURE 3-3 THREE-DIMENSIONAL SCATTER PLOT OF ALL 5 PARETO FRONTS

3.5.4 SUPPLIER NETWORK DESIGN SELECTION

Given that the resulting set of 5 Pareto fronts does not show a clear optimal decision alternative or region, the use of a decision-making tool becomes ever more necessary. This final selection process is carried out through the use of TOPSIS method that consists of ranking the alternatives through a comparison with the values of the "ideal" curve. Before applying the TOPSIS method with equal weighting to all criteria, a selection is made in order to keep only non-dominated alternatives from the 5 Pareto Fronts. This series of steps is described below:

U{Pareto Front runs i=1,…,5}
Pareto {U} 3-7
TOPSIS {Pareto}

By applying steps 1 and 2 of the abovementioned procedure, leading to the Pareto of the Pareto fronts (i.e. Pareto {U}), a lower number of 46 non-dominated alternative solutions is obtained, from them the TOPSIS method (Ren et al., 2010) is applied in order to find the best ranked values. Figure 3-4 shows the resulting values with the location of special TOPSIS values called 1, 13 and 45, which correspond to the overall top-ranked one, the best TOPSIS value in relation to GWP and the best TOPSIS value in relation to Eutrophication respectively.

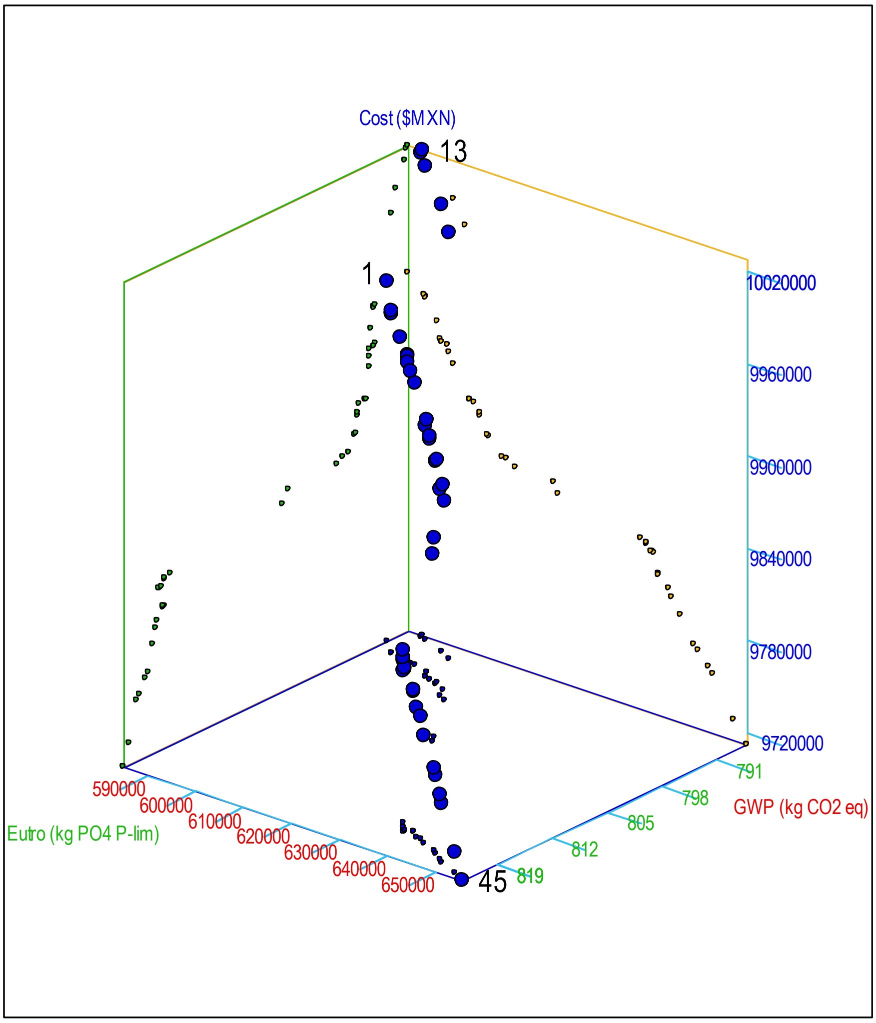


FIGURE 3-4 THREE-DIMENSIONAL SCATTER PLOT OF THE FINAL SET WITH TOPSIS RANKED POINTS

Figure 3-4 shows that the TOPSIS 1 value is in the higher Cost range. This solution is yet selected due to the trade-off against the environmental criteria. The improvement of Cost is low relative to the gains in environmental performance.

In Figure 3-5 to Figure 3-7, the TOPSIS alternatives are presented in two-dimensional scatter plots in order to see the scales and location of some TOPSIS ranked values.

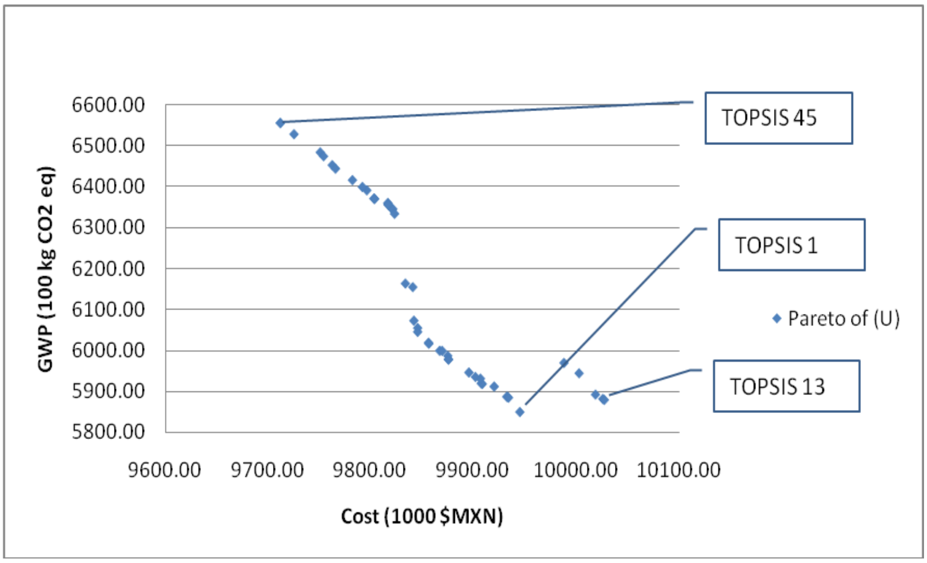


FIGURE 3-5 GWP VS COST FROM PARETO {U}

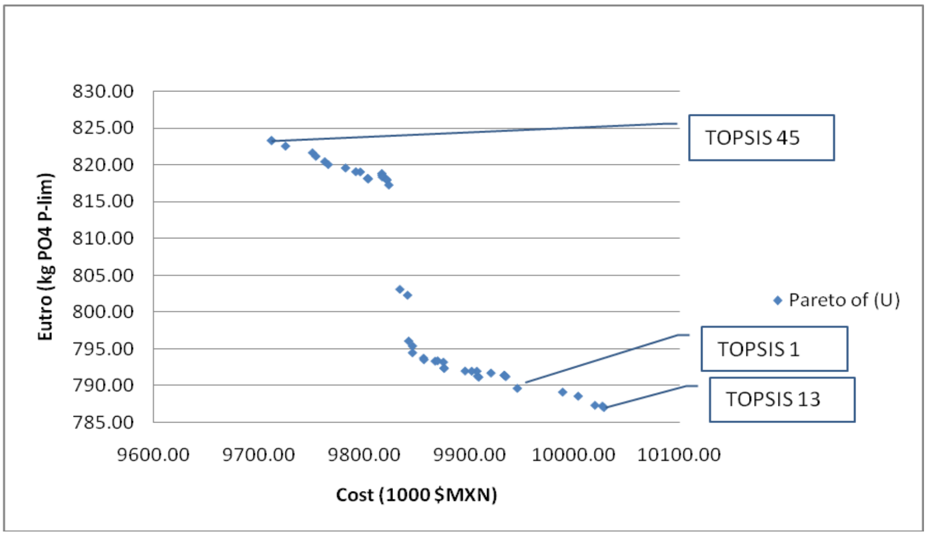


FIGURE 3-6 EUTROPHICATION VS COST FROM PARETO {U}

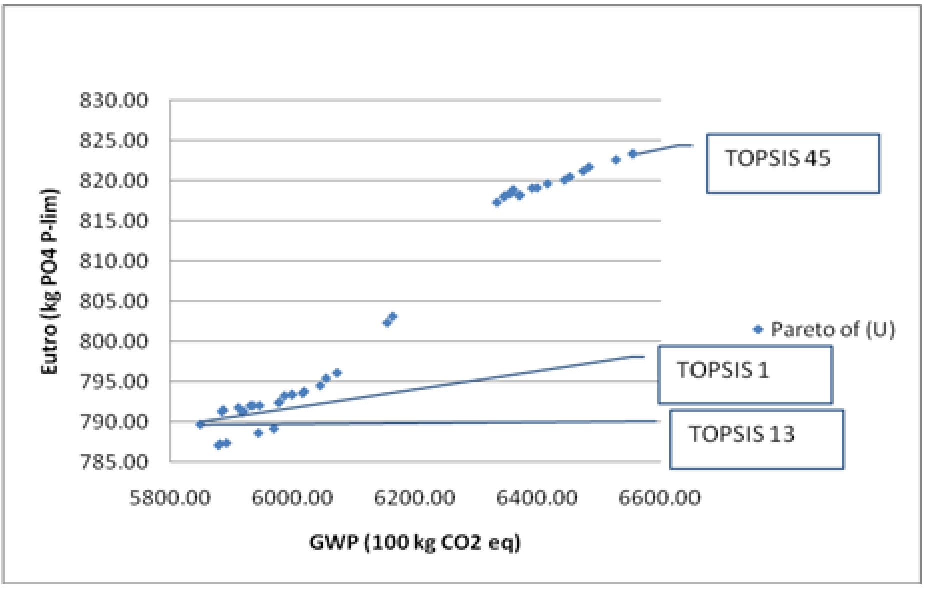


FIGURE 3-7 EUTROPHICATION VS COST FROM PARETO {U}

Table 3-7 presents the values for each criterion for some representative TOPSIS ranked alternatives: number 1 (TOPSIS 1), the 13th (TOPSIS 13) and 45th (TOPSIS 45) values. TOPSIS 1 has the best compromise since it provides the best value for GWP and only differs from the best value for Eutrophication criteria by 0.33% (TOPSIS 13). Its cost is slightly higher of 2.35% of the best cost criterion performing alternative (TOPSIS 45). The three points can also be visualized in Figure 3 where TOPSIS 13 and 45 are at the extremes, whereas TOPSIS 1 is located at the upper part of the scatter plot (see Figure 3-5 to Figure 3-7).

TABLE 3-7 TOPSIS EVALUATION PER CRITERION

Criterion	TOPSIS 1	TOPSIS 13	TOPSIS 45	Discrepancy 1 vs 13	Discrepancy 1vs 45
Cost ($)	994 546	1 002 769	**971 200**	0.83%	2.35%
GWP (kg CO_2 eq)	**585 024**	587 981	655 538	0.51%	12.05%
Eutro (kg PO_4P-lim)	789	**787**	823	0.33%	4.26%

Table 3-8 presents a comparison between the TOPSIS 1 solution and the TOPSIS 1 of a sample taken from the first Pareto Front run at the 10th generation. The 10th generation was selected because it was the first generation in which all the individuals (solutions) are in the feasible space.

TABLE 3-8 COMPARISON BETWEEN TOPSIS 1 AND SAMPLES FROM 10TH GENERATION OPTIMIZATION VALUE OF THE FIRST PARETO FRONT

		TOPSIS 1 of Sample PF		Average of Sample PF	
Criterion	TOPSIS 1	Value	Discrepancy	Value	Discrepancy
Cost ($)	994 546	1 034 808	4%	1 135 873	**14%**
GWP (kg CO_2 eq)	585 024	669 783	14.5%	790 669	**35%**
Eutro (kg PO_4P-lim)	789	849	7.6%	974	**23%**

The differences that can be observed are significant for all criteria, which justify fully the application of the optimization procedure. A comparison between the average values of the sample is used in order to visualize the improvement that can be achieved through Partnership for Sustainability method, exhibiting a significant performance between 14% to 35% for the different criterion.

3.5.5 SUPPLIER CONTRACTING AS A PARTNER FOR SUSTAINABILITY

Supplier contracting is then the final stage in the selection process: for the case study, the optimization results then allow to select the suppliers, the type of agricultural practice to use, and the area of land to be guaranteed in the final contract. Table 3-9 displays the final set of values for the decision variables for TOPSIS 1 alternative. It can be first observed that it implies all suppliers, since the optimization search leads to select different types of technologies of low yield but with a better overall performance. The second interesting point is that the mix of technologies used does not include technology package 3, which is the most commonly used agricultural practice in the region. It must be also highlighted that there was only one field of small area with a technology package type 1. This is most probably due to the fact that technology package 2 yields more products for a similar environmental impact performance.

TABLE 3-9 DECISION VARIABLE RESULTS FOR TOPSIS 1

Supplier	Technology	Selection*	Land area
1	2	1	218
2	2	1	100
3	4	1	189
4	2	1	650
5	4	1	42
6	2	1	507
7	4	1	43
8	4	1	490
9	4	1	26
10	4	1	21
11	4	1	48
12	2	1	297
13	4	1	107
14	4	1	113
15	4	1	68
16	4	1	245
17	2	1	271
18	4	1	235
19	4	1	204
20	1	1	14

*1=supplier selected; 0=not selected

The application of the methodology results in a set of alternatives given by rank. Although other external factors such as agricultural, economic and environmental policies have to be considered in the final judgment, the decision aid provides the insight needed for an objective and efficient supplier selection tool.

3.6 CONCLUSIONS AND PERSPECTIVES

Partnership for Sustainability can be a useful tool in tackling the supplier selection problem by providing a paradigm shift regarding collaboration as a means to improve overall sustainable food supply chains performance. The steps laid out in this chapter provide a roadmap to improve and incorporate different ways on how GrSCM may be used and structured to overcome weaknesses in conventional management practices when confronting strategic long-term decisions such as the Supplier Selection Problem. The chapter developed a complete and comprehensive case study in order to illustrate the capabilities and limitation of the proposed approach, and provided insight on what type of information is required and how it could be used in order to develop feasible and non-dominated optimal solutions.

The case study also illustrates some of the patterns one could confront when developing other specific green supplier selection models based on the methodology. Although it may have some areas to improve, it provides the basis work to analyse and integrate important factors in the decision making process in the context of collaboration with suppliers that may become partners.

The approach presented involves many levels and links within the agrosystems framework and integrates many different approaches. Some opportunities for improvements can yet be highlighted:

- Negotiation and contract development: this is one of the fundamental stages in the methodology described here, and is not developed. Future work should look at the existing negotiation and contract scheme, and the possible limitations related to objectives and preferences of the negotiating parties.
- Supplier management systems: related to negotiation and contract development is the development of suppliers and sharing of knowledge and resources. As well as the management of acceptance-resistance to change and learning curve that can be challenging factor in implementation of new approaches (Ryder and Fearne, 2003)
- Information sharing: this is a field in itself and possible integration through IT (Information Technology) systems and new mobile hand held devises could help in the data development stage.
- Development of not-selected supplier for future rosters: it is a key element in order to eliminate the possible conflict of interest in the negotiation and collaboration process.
- Nature of agricultural production, seasonality and uncertainty were not taken into consideration, possibilities to enhance the forecasting ability of the approach could be explored through techniques that could help model and mitigate uncertainties.

- Transport and logistics issues were not considered here, but are in a wider GrSCM perspective.

- Issues in logistics could also extend to the differentiation and traceability of product types.

Some of the main perspectives to this chapter are clearly the further development and integration of contract policies into the supplier selection process methodology. This is a difficult task since information flow and synchronization among parties are not so “open”, but it is worth exploring the potential of Contract Farming and collaborative farming in the context of the SSP. A second opportunity is to target the information collection, in the sense of better establishing which type of information a buyer requires from its potential and current suppliers, in order to make the best decision and to continuously maintain an effective supplier network.

Finally, the next step is to integrate the results of this model into a global green supply chain design model that may use a similar approach for visualizing, optimization and solving the other large-scale strategic challenges of GrSCM. This is the core of the following chapters.

Chapter 4 Modelling and Optimization Framework for Green Supply Chain Network Design: application to an orange juice cluster

Résumé

Ce chapitre présente le cadre de modélisation et d'optimisation pour la conception du réseau d'une chaîne logistique verte (acronyme anglo-saxon GrSCND). La partie introductive met l'accent sur les concepts clés de la chaîne logistique verte, les indicateurs de performance économiques et environnementaux. Il fournit également une introduction au domaine de la recherche dans le domaine GrSCND. Sont ensuite abordées les problématiques traitées par l'approche intégrée impliquant principalement la sélection des fournisseurs, le choix des technologies et de l'expansion de capacité, ainsi que les décisions d'implantation et d'affectation. Le cadre de modélisation et d'optimisation mathématique qui sera développé pour l'étude de cas consacrée à la filière du jus d'orange est développé de façon détaillée. Une instance du problème est définie et chaque élément de la chaîne d'approvisionnement principale est présenté. Enfin, la formulation mathématique est développée et les composantes des fonctions objectifs en lien avec les échelons de la chaîne logistique sont explicitées.

Abstract

This chapter presents the modelling and optimization framework for Green Supply Chain Design (GrSCD). The introduction section focuses on the key concepts of GrSC and on environmental and economic performance indicators. It also provides an introduction to the research field on Green Supply Chain Network Design (GSCND). The issues that are tackled by the proposed integrated approach, involving mainly supplier selection, technology choice and capacity expansion, as well as location-allocation decisions are then highlighted. The mathematical modelling and optimization framework that will be developed for the case study dedicated to an orange juice supply chain is developed in detail. A problem instance is defined and each item of the main supply chain is presented. Finally, the mathematical formulation is developed and the components of each objective function related to each supply chain echelon is presented.

Acronyms

AVUC	AVERAGE VARIABLE UNIT COST
DC	DISTRIBUTION CENTRE
FCOJ	FROM CONCENTRATE ORANGE JUICE
GrSCM	GREEN SUPPLY CHAIN MANAGEMENT
GSCND	GREEN SUPPLY CHAIN NETWORK DESIGN
GWP	GLOBAL WARMING POTENTIAL
HHP	HIGH HYDROSTATIC PRESSURE
KEPI	KEY ENVIRONMENTAL PERFORMANCE INDICATORS
KPI	KEY PERFORMANCE INDICATORS
LCA	LIFE CYCLE ASSESSMENT
MINLP	MIXED INTEGER NONLINEAR PROGRAMMING
MS	MULTIPLE STRENGTH
NFCOJ	NOT FROM CONCENTRATE ORANGE JUICE
NLP	NONLINEAR PROGRAMMING
NPV	NET PRESENT VALUE
PEF	PULSE ELECTRIC FIELD
PfS	PARTNERSHIP FOR SUSTAINABILITY
SC	SUPPLY CHAIN
SCM	SUPPLY CHAIN MANAGEMENT
SCND	SUPPLY CHAIN NETWORK DESIGN
SP	SALES PRICE
SS	SINGLE STRENGTH
VUC	VARIABLE UNIT COST

Index & Set

f	fabrication steps or stages performed to product F
i	label denomination I
p	fabrication technology P
r	supplying regions in R
r’	market region R’
s	suppliers in S
t	agricultural practice type used to produce fruit in T

Parameters

$\beta_{r,t}$	Average yield per unit of land using agro practice *t* in region *r* (kg/ha)
$\omega_{r,s}$	Land surface available for each supplier *s* in region *r* (ha)
$\delta_{r,t}$	Average cost per unit of agricultural output in region *r* using agricultural practice t ($/kg)
$\varphi_{r,t}$	Average environmental impact per unit of agricultural output in region *r* using agricultural practice t (kg CO_2 eq /kg)
$\varepsilon_{r,e}$	Average cost of resource type *e (electricity, gas, water)* per region *r* and *r’*
γ_p	Concentration ratio in °Brix for raw materials type given technology *p*
$\phi_{r,e}$	Average environmental impact emissions due to consumption of resource *e* in region *r*
ρ	Average output of raw juice per unit of fruit (i.e. 2.29 kg orange ≈ 1 L of juice)
$\lambda_{f,e,p}$	Average quantity of resource *e* needed to operate fabrication stage *f* using technology *p*
$\varepsilon_{r',e}$	Cost of resource type *e (electricity, gas, water, materials)* in region *r’*
$StdCap_p$	Standard capacity of equipment of technology *p*

$StdCC_{f,p}$	Standard capital cost of equipment of technology *p*

Decision variables

BR_r	Binary variable to select the sourcing region *r* (Mexico, Brazil)
$BS_{r,s}$	Binary variable to select suppliers *s* {0,1} in region r (Mexico, Brazil)
$D_{i,f,m,r'}$	Integer variable to define the quantity of demand that will be targeted of product label type *i* processing type *f* for market *m* in region *r'*
$IL_{r'}$	Integer variable to select the location for bottling plant in region *r'* {1,6}
IP_f	Technology for fabrication step *f* {0,1} {1,3}
IT_s	Integer variable to select the agro practice at orchard/supplier *s* {1,4}
IS_s	Integer variable to define the percentage of land surface contracted {50-100}

Problem variables

A_j	Amortization per period j
$AOC_{f,p}$	Annual operations cost for manufacturing step *f* using technology *p*
ASC_t	Annual supplier (operation) cost per type of agro practice *t*
$ASEI_t$	Annual supplier environmental impact emissions per type of agro practice *t*
BMC_p	Bottling operations cost per type of bottling technology *p*
$BMEI_p$	Bottling operations environmental impact emissions per type of bottling technology *p*
Cap_f^{IN}	Intake capacity of fabrication step *f*
Cap_f^{OUT}	Output capacity of fabrication step *f*
C_j	Total variable cost in period *j*
$D_{i,f,m,r'}$	Demand targeted of product label type *i* processing type *f* for market *m* in region *r*
f_L	Lang factor
$InvCost_f$	Capital cost installed capacity for fabrication step *f*
$LandArea_{r,s}$	Land area contracted of supplier s in region r
$LLD_{i,f,m,r'}$	Demand lower limit for product label type *i* processing type *f* for market *m* in region *r'*

$OpCost_{r,s,t}$	Annual operations cost of each supplier *s* in region *r* using agro practice *t*
$OpEI_{r,s,t}$	Annual operations environmental impact measurement for each supplier *s* in region *r* using agro practice *t*
$Q^{A\rightarrow B}_{i,f,m,r'}$	Quantity of intermediate product label type *i* processing type *f* for market *m* in region *r′* to be sent from location A to location B
RM_i^{batt}	Quantity of bottled final product required of label type *i*
RM_i^{conct}	Quantity of concentrated juice intermediate product required of label type *i*
RM_i^{juice}	Quantity of raw juice intermediate product required of label type *i*
RM_i^{orange}	Quantity of orange raw material required of label type *i*
RM_i^{past}	Quantity of pasteurized juice intermediate product required of label type *i*
$RMUC_i^{batt}$	Bottled final product variable unit cost of label type *i*
$RMUC_i^{conct}$	Concentrated juice intermediate product variable unit cost of label type *i*
$RMUC_i^{orange}$	Orange raw material variable unit cost of label type *i*
$RMUC_i^{past}$	Pasteurized juice intermediate product variable unit cost of label type *i*
$SP_{i,f,m,r'}$	Sales price per unit of product label type *i* processing type *f* for market *m* in region *r′*
$TotalCapacity_t$	Total orange raw material production capacity per type of agro practice *t*
$TUC^{A\rightarrow B}_{i,f,m,r'}$	Variable unit cost of transporting for intermediate product from location A to location B
$TUEI^{A\rightarrow B}_{i,f,m,r'}$	Variable unit environmental impact emissions of transporting for intermediate product from location A to location B
$ULD_{i,f,r',m}$	Demand upper limit for product label type *i* processing type *f* for market *m* in region *r*
V_j	Total sales income in period *j*
$VUC_{i,f,m,r'}$	Variable unit cost for final product label type *i* processing type *f* for market *m* in region *r′*

4.1 INTRODUCTION AND RESEARCH MOTIVATIONS

The general research problem addressed in this work deals with the optimization of a globally distributed supply chain network of agro-food products, with multiple objectives related to economic, operational and environmental performance. A big challenge is to manufacture products to which a special value based on the raw materials sourcing (e.g. organically grown) is allocated. The problem formulation is based on the Green Supply Chain Management (GrSCM) paradigm.

GrSCM deriving from Supply Chain Management (SCM) adds a « green » component to address the influence and relationships between supply-chain management and the natural environment. Traditionally, Key Performance Indicators (KPI) measure operational and economic aspects of interest to the stakeholders of a classical supply chain. KPIs that provide a way to measure global performance by taking a wide-angle view of the interconnected processing steps to produce goods and services, from raw materials extraction to end-user product delivery and disposal, this is to say the product life cycle. Among the wide range of KPIs (Gunasekaran et al., 2004; Gunasekaran and Kobu, 2007), a consensus is generally reached to consider Net Present Value (NPV) to long term planning decisions. The incorporation of breakeven point and variable unit cost (VUC) as economic criteria is also proposed as a way to consider the consumer preference and thus market competitiveness.

In the case of GrSCM paradigm, Key Environmental Performance Indicators or KEPIs (Singhal et al., 2004) are particularly sound at early design stage of a - product or system - in order to improve the environmental performance in a systemic way. These KEPIs are measured and used through different techniques, generally following the standardized LCA approach. LCA provides a systems-oriented approach for the evaluation of the environmental impacts associated with the considered processes and systems. Based on the works presented in (Doublet et al., 2014; Landquist et al., 2013) considering agro-food chains, Global Warming Potential (GWP), (measured in kg CO_2 eq.) is one of the most used indicator of environmental impacts (e.g. in the Kyoto Protocol). Other important KEPIs that are evaluated in their works include human toxicity, acidification, land eutrophication, marine eutrophication, eco-toxicity land use, abiotic resource depletion and water depletion. Although the developed framework is generic enough to embed a multi-objective formulation, the approach is not extended here to the other environmental impacts due to a lack of information considering the quantification of these impacts at the different steps of the supply chain.

The Supply Chain Network Design (SCND) problem has been well studied under the branch of facility location analysis (Melo et al., 2009; ReVelle and Eiselt, 2005). It is classified by (Srivastava, 2007) as a *"Location & Distribution Network Design"* problem. Following the GrSCM paradigm, the corresponding SCND problem is referred as Green Supply Chain Network Design (GSCND). The network design approach provides the modeller and decision maker a framework to integrate many different levels and layers of decision within a single structure.

The approach proposed in this work derives from the study presented in (Guillén‑Gosálbez and Grossmann, 2009), that focused on the application of GSCND for sustainable supply chains in the chemical industry with uncertainty considerations. The ideas developed by these researchers stemmed from the general mathematical formulation proposed in (Hugo and Pistikopoulos, 2004).

The design approach they propose is mathematically formulated as a bi-criterion stochastic mixed-integer nonlinear program (MINLP) that simultaneously accounts for the maximization of the net present value and the minimization of an environmental impact for a given probability level.

They propose a decomposition technique applied for solving the design strategy based on decomposing into two levels. In the upper level, a master convex MINLP, in which the ε–parameter is treated as a free variable, is solved to provide a vector of integer variables. This vector is then passed to the lower level, in which a parametric NLP (Non Linear Programming) resulting from fixing the binary variables calculated by the upper level is solved to obtain a lower bound to problem. This procedure is repeated iteratively. In each iteration, the master problem is forced to improve the current lower bound (i.e., the current approximation of the Pareto set) in at least one point, whereas the parametric profile is updated with the results of the new parametric NLP being solved. The NPV is regarded as a main objective and the environmental impact is transferred to the auxiliary epsilon constraint. The design supply chain is a three-echelon network involving plants, warehouses and markets and is less complex than the agrofood one proposed in this work.

The GSCND approach we use is the formulation of supply chain design as a network of interconnected possible configurations of items for each echelon in the context of an agro-food supply chain. It is formulated as a pure integer non-linear problem with multiple objective functions in order to find the optimal trade-off configuration considering not only operational or economic criteria, but also environmental ones.

The proposed framework is designed as a base to integrate the plant location analysis, technology selection, equipment capacity scaling and product mix decisions in a single problem formulation. The most important contribution of this work is its adaptation to the agro-food production industry systems. The case study of an orange juice supply chain system supports the methodology. In this context the sourcing of the raw material is a key component in the achievement of the added-value resulting from *organic* eco-label quality classification of the final products.

The main motivation to develop the proposed framework is threefold.

(1) First, the purpose is to model and optimize an agrofood supply chain through a GSCND approach, so that the decision maker can find better alternatives and solutions on strategic long-term planning decisions than those that could be obtained through empirical means.

(2) Second, given the complexities that real world systems exhibit (multi-objective, multi-product, multi-stakeholder, multi-period, multi-echelon, etc), an integrated approach can reach better outcomes than an optimization procedure iterating by isolated parts, thus leading to a suboptimal solution.

(3) Finally, the proposed methodology can model, optimize, tune and analyze supply chain design solutions that constitute feasible “best” trade-off solutions based on a holistic decision-making process.

In the following sections, the GSCND problem is presented in detail and the modelling approach is then formulated. The *Integration Scope* outlines the framework by briefly describing the problems and issues that are tackled by the proposed integrated approach, involving mainly supplier selection, technology selection and capacity scaling, as well as location-allocation decisions. The mathematical *Modelling and Optimization Approach* used for the Case Study that will be presented in detail in Chapter 5 is defined. After providing this backdrop, a problem instance is defined in *Problem Statement* and each item of the main supply chain is detailed. Finally, the *Mathematical Formulation* is developed through the decomposition of the objective function components in terms of supply chain links.

4.2 GSCND PROBLEM FORMULATION

The GSCND for agro-food industry problem searches for the optimal configuration of a four-echelon supply chain, made up by the supplier, processing plant, bottling (packaging) plant and market; in addition, it has nested decisions at each echelon related to agricultural practice selection, technology selection, product mix and market demand to be satisfied. As abovementioned, the aim is to maximize the economic benefit as measured by (NPV), while minimizing the environmental impact through (GWP). In addition, capital cost Investment (I) and the Average Variable Unit Cost (AVUC) are also evaluated to reflect other interests from the principal stakeholders i.e. Focal Company and Consumer. They can also be considered as objective functions in scenarios reflecting the particular interests of some stakeholders of the supply chain. The decision network of the supply chain is displayed in Figure 4-1 and is presented in detail in what follows.

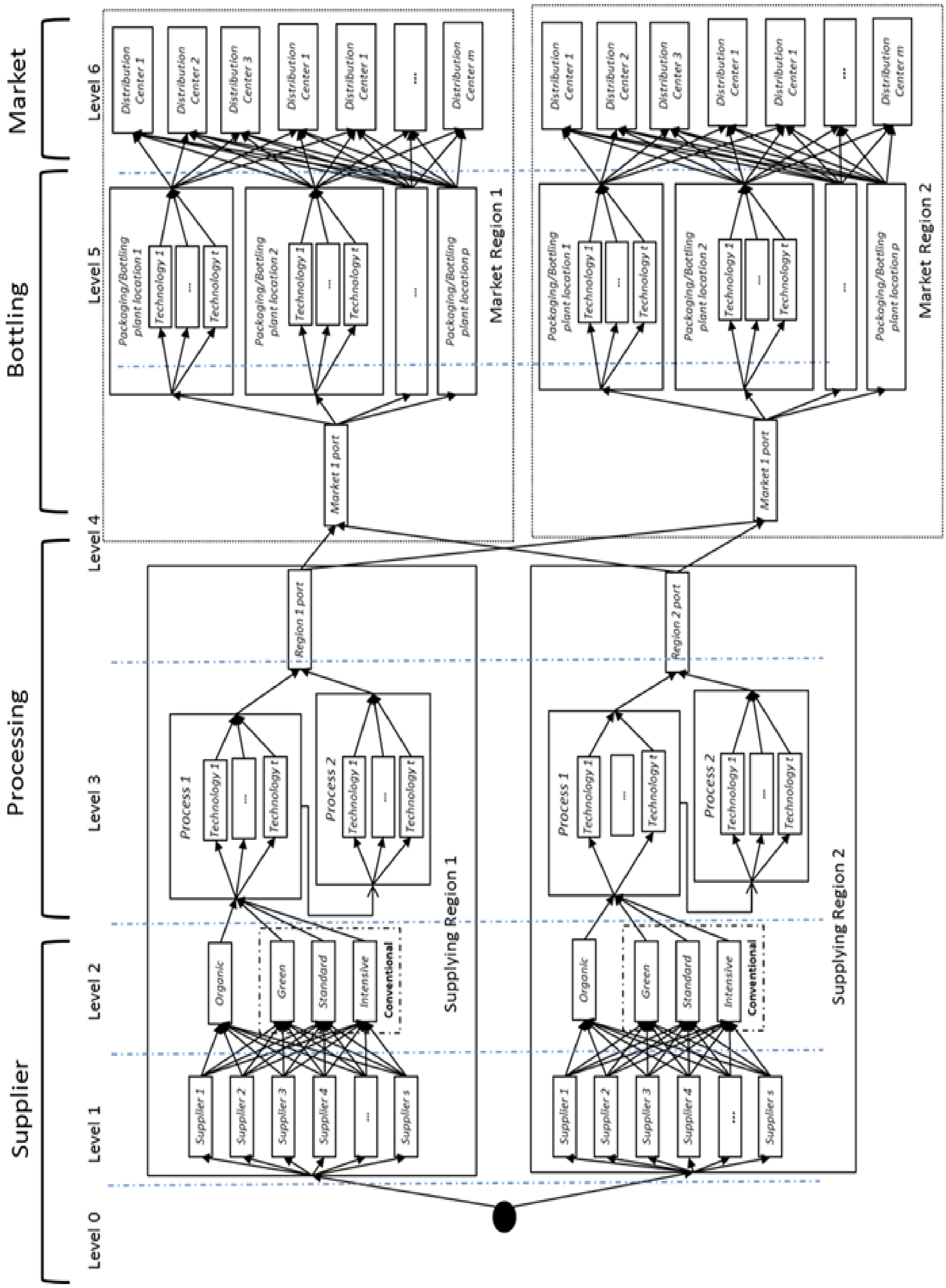


FIGURE 4-1 DECISION NETWORK OF THE SUPPLY CHAIN

4.2.1 DECISION LEVELS

Although the proposed approach has the ambition to be generic enough to be applied to a wide range of agro-food systems that have similar characteristics, the problem formulation is supported here by the case study of an orange juice cluster. Figure 4-1 presents the considered supply chain as a network of possible alternatives: each level involves supply chain design decisions that are developed in the following sections.

4.2.2 SUPPLIER ECHELON

4.2.2.1 SOURCING REGION SELECTION

Decision Level 0 models the selection of a single supplying region (e.g. a country). This decision level reflects the selection of the supplier set selection and processing plant location. The supplying region guarantees that suppliers are located near one another and share similar characteristics and behavior such as yield, resources, quality, etc, so that average values shared by clusters of suppliers, for long term planning purposes are considered. This selection level is rooted on the principles of developing a **Partnership for Sustainability** with the suppliers. By only selecting one region, information and technological resources are concentrated as a long-term planning project. After making this long-term planning commitment, more detailed studies can yet be performed in order to have better tactical and operational plans. This regional limitation also narrows the list of potential suppliers to those that can share a single initial processing plant (limiting capital investment). This condition is necessary because initial processing of food is carried out to minimize or eliminate spoilage of the raw material during handling and transportation. It becomes then a *de facto* plant location decision with its own components and connections to other decision levels. This is to say that other forces such as regional cost of resources (e.g. energy, water, etc.) needed to operate the processing plant and the distance of sourcing region to market regions are also connected as emphasized in Figure 4-2. Resources have an effect on the processing plant location decision, because depending on the location site, local energy and water cost will be more or less expensive.

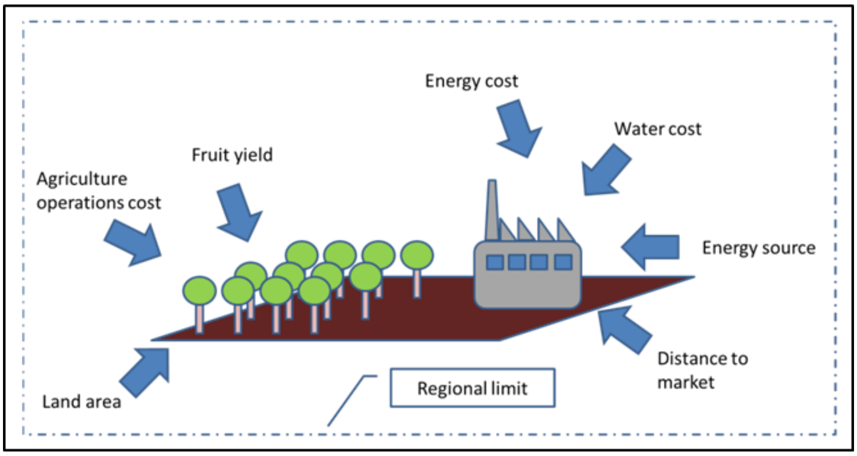


FIGURE 4-2 SOURCING REGION DECISION FACTORS

4.2.2.2 SUPPLIER SELECTION, AGRO PRACTICE & RAW MATERIALS CAPACITY

Decision Level 1 is a three-part nested decision, involving:

- the choice of suppliers: a set of suppliers with fixed land capacities are preselected to be considered within the region selected in Decision Level 0.
- the definition of capacity that will be contracted: once suppliers are selected, a portion or the full land capacity for each one can be contracted to guarantee raw material requirements for downstream processing.
- and the agricultural practice that will be used: the contract is formulated as a capacity guarantee contract-farming scheme. This contract scheme allows the Focal Company to define not only the land surface under contract but also the type of agricultural practice that is to be used.

The agricultural practice (as explained in Chapter 3) defines the quality and yield of the product output. The agricultural practices for the case study are divided into four categories based on the classification proposed by (Curti-Díaz et al., 1998):

1) *Organic*, where agrochemicals are not used;

2) *Green or quasi-organic*, where the use of agrochemical such as pesticides or fertilizers is limited;

3) *Standard* use of conventional types and quantities of agrochemicals;

4) *Intensive* use of agrochemicals and other agricultural technologies that enhance performance.

This family of 4 types of products will be considered in what follows.

Figure 4-2 illustrates this nested decision through an example of a set of 5 suppliers. Four are selected. For each supplier a percentage of the land is contracted (each supplier land is unique in size). Each supplier is assigned a specific agricultural practice (e.g. intensive agro practice is assigned to the farm with red histogram).

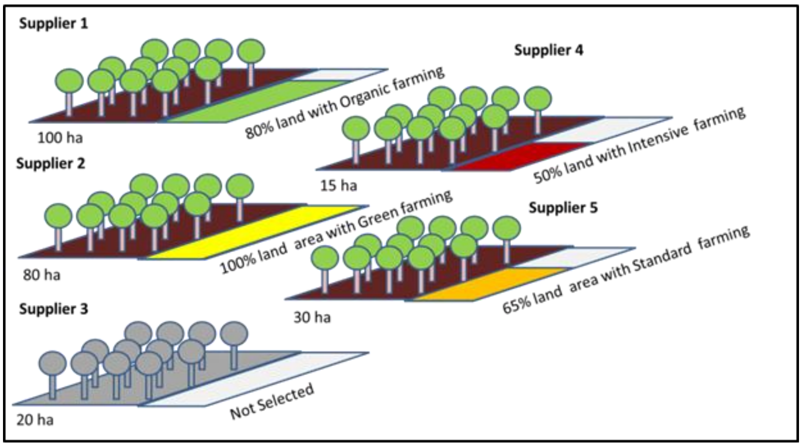


FIGURE 4-3 SUPPLIER SELECTION, AGRO PRACTICE AND RAW MATERIALS CAPACITY DECISIONS PROCESS ILLUSTRATION

4.2.3 PROCESSING ECHELON

Decision Level 3 integrates two important issues: technology selection and capacity setting.

Technology selection involves a choice among discrete values from a set of alternatives. For Pasteurization process two alternatives are proposed:

1) High Hydrostatic Pressure (HHP), (is also known as High Pressure Processing (HPP)) is a non-thermal pasteurization technique by applying high isotactic pressure.

2) Pulse Electric Field (PEF), a non-thermal pasteurization process based on applying high voltage pulsed electric fields.

For the Concentration Process three alternatives are proposed:

1) Multi-effect evaporators, is thermal method that by heat evaporates the water from the food product.

2) Freeze (concentration), is a separation method that removes heat from a mixture during which a component crystallizes, and then physically removed leaving a more concentrated liquid.

3) Reverse Osmosis, is a pressure driven membrane process that separates water from the food mixture by physically filtering.

The technology selection choice is interconnected with Decision Level 0, because depending on the region the economic and environmental cost of resources will be different. Each technology alternative involves distinctive operational requirements in addition to capital cost.

Figure 4-4 illustrates this decision structure.

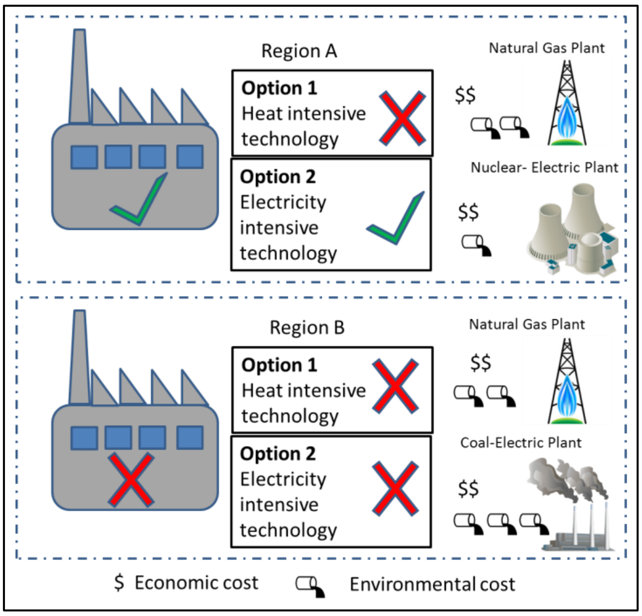


FIGURE 4-4 : PROCESSING PLANT TECHNOLOGY SELECTION DECISION PROCESS ILLUSTRATION

Let us consider two regions A and B (see Figure 4-4) where a pasteurization plant is to be installed. Two types of technologies are evaluated, option 1 is heat intensive, e.g. flash pasteurization, and option 2 electricity intensive, e.g. pulse electric field pasteurization technology. In region A, electricity is produced from nuclear energy (low GWP burden), and region B from coal burning (high GWP). Region A would be more attractive to install a plant if the technology selected is electricity intensive (in terms of GWP).

In addition, the operational performances of the processes are dependent on the technology used (e.g. orange juice can reach 66°Bx concentration with evaporators, but only 44°Bx with freeze or reverse osmosis concentration). The different concentration levels will then induce different transport costs.

Capacity setting influences other decision levels. It is not explicitly modeled as a decision variable, but depends on the demand coverage that is targeted in the Market Echelon (Decision Level 6). For the case study, two attributes are allocated to the family of the abovementioned 4 types of products, referring to label and process. The label can be either Organic or Conventional (connected to Decision Level 1); the process can involve either the concentration of orange juice (it will be denoted From Concentrate Orange Juice, FCOJ or FC) or no concentration (it will be denoted Not From Concentrate Orange Juice (NFCOJ or NFC)). The Processing Echelon in Decision Level 3 is influenced in the Market Demand coverage that is targeted in the Market Echelon.

Decision Level 4 between the supplying regions and the market region refers to raw material processing. The orange juice case study presents an illustrative example of the connection between the processing stages and the transport phase. As mentioned in Chapter 2 and illustrated in Figure 4-5, orange juice can be processed into a single strength (NFCOJ) or multi-strength (FCOJ) mode.

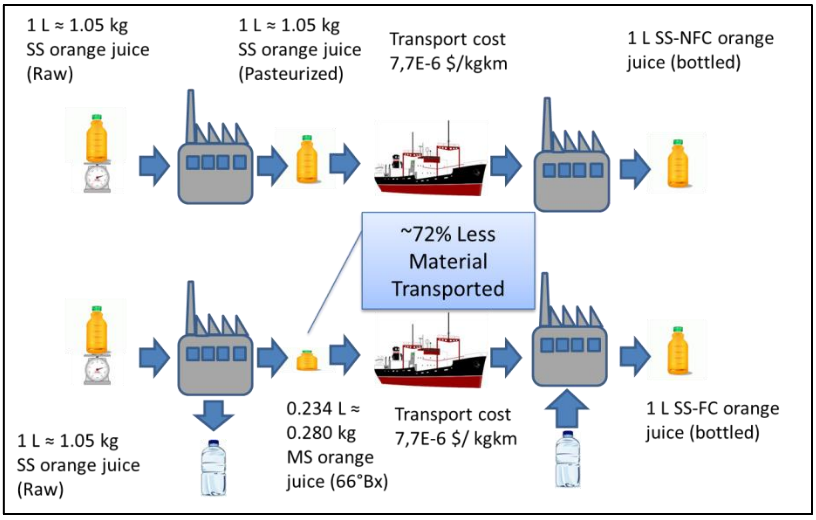


FIGURE 4-5 MATERIALS HANDLING OF NON CONCENTRATED (SS, SINGLE STRENGTH 11°BX) AND CONCENTRATED (MS, MULTI-STRENGTH 66°BX) ORANGE JUICE

When 1L of NFCOJ is transported, it weighs roughly 1.05kg. A fixed price per kg is allocated for transportation. It is then bottled near the consumer market in 1L presentation. A second alternative is to transform 1L of raw orange juice through a concentration process into roughly 0.280kg of FCOJ by basically removing water content. This reduces the quantity of material that needs to be transported by approximately 72% that is then transported at the same price rate, so there is a transportation cost reduction. It is then reconstituted by adding water to make it once more into a 1L single strength orange juice (concentration and reconstitution process costs and environmental impacts are also modeled). So processing can affect and be affected by other decision levels at different echelons in the SC.

It must be highlighted that one of the most important applications of the supply chain network design problem formulation is to determine logistical routes. Although it is possible to evaluate many distribution routing questions related to the distance between farmers and processing plants on the one hand and to the one between the processing plant and the port of departure on the second hand, these distances are not considered here as well as the selection of alternative ports of departure or arrival. This could yet easily be changed to accommodate different logistical distribution networks. This assumption is yet valid since their contribution is assumed to be low compared to those related to: (1) from port of departure to port of arrival; (2) from port of arrival to bottling plant; and (3) from bottling plant to market.

4.2.4 BOTTLING ECHELON

In Decision Level 5, two main issues are considered: 1) Packaging/bottling plant location and 2) packaging/bottling technology selection.

For the **plant location issue**, a set of possible packaging/bottling plant locations is considered, either as potential new installations or as capacity expansion of an existing plant. From this set of potential locations, only one can be chosen to serve all of the distribution centers located in major cities within the regional market. As abovementioned, the distances from the Port of Arrival to the Bottling Plant, as well as, the distances from the Bottling Plant to Markets are considered. The evaluation of distances between the chosen bottling plant location in relation to the port of arrival and to the distribution centers is reflected through the economic and environmental cost given the distance and quantity of raw material and product being distributed.

Furthermore, the **packaging/bottling technology** is evaluated as a technology selection problem similar to that described in the Processing Echelon section. The case study evaluates three different bottling technologies, i.e., glass bottles, plastic bottles and ascetic carton container, that are selected based on cost and environmental impact taken from Life Cycle Design study by the United States Environmental Protection Agency (Spitzley et al., 1997).

4.2.5 MARKET ECHELON

The modelling approach is based on a **market driven supply chain**. Decision Level 6 focuses mainly on market demand coverage, this is to say, production capacity allocation to satisfy each markets' needs of each product type. A set of targeted markets that represents the main cities in a region are considered illustrated in Figure 4-6.

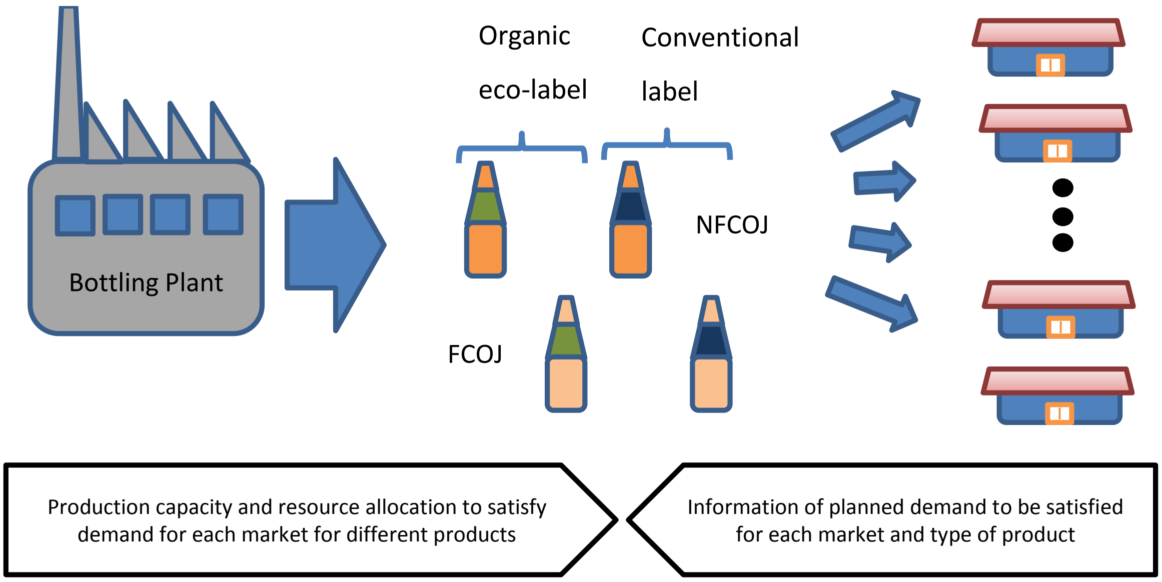


FIGURE 4-6 MARKET PRODUCT DISTRIBUTION ILLUSTRATION

Demand is defined as a decision variable that can take values between upper and lower demand constraints for each city (see Appendix A Table 1 and 2). The demand variables are used as production planning targets that define the capacities that are required in terms of raw materials production capacity, processing capacity and bottling capacity. By optimizing these demand coverage variables not only is the capacity set at each production stage defined, but also the allocation of the installed resources, since the planned production mix ratio between organic labeled and conventional label products as well as from FCOJ and NFCOJ is defined through these variables. Furthermore, these will condition the global environmental impact that the SC network design will yield.

In summary, the network design model is characterized by considering a long-term time horizon, lower and upper demand bounds, variable product pricing for each product type, fixed and variable investment costs associated with capacity installation or expansion of processing and packaging/bottling plants, variable transport costs on the economic side. In addition, the environmental impacts of each stage are captured through the GWP (kg CO_2 eq) measurement provided the agro practice, land use, energy consumption, water and material use. The objective is then to determine the optimal supply chain network considering simultaneously economic benefit and environmental impact.

4.3 MODELLING STRATEGY

4.3.1 PROBLEM FORMULATION

This section specifically deals with the modelling and optimization of a four-stage multi-echelon supply chain network architecture using a multi-objective optimization procedure. The supply chain architecture consists of four echelons, i. e. Supplier, Processing, Bottling and Market.

Each supply chain echelon has a set of control variables that affect the performance of each component that defines it. The optimization variables are all of integer types. These control or decision variables are:

1. Supplier Echelon Decision Variables (81)
    a. Raw materials sourcing region location
    b. Supplier selection
    c. Agro practice selection
    d. Land area contracted (Agricultural output capacity)
2. Processing Echelon Decision Variables (2)
    a. Processing technology selection
3. Bottling Echelon Decision Variables (4)
    a. Bottling plant location
    b. Bottling technology selection
4. Market Echelon Decision Variables (80)
    a. Demand coverage (product mix & system wide capacity)

These variables are subject to two main sets of constraints. The first set involves lower and upper bounds of the values that the decision variables can take during the optimization process. These bounds represent the operational capabilities or value limits evaluated during the genetic algorithm run. The second set of constraints represent the feasibility of the network, in other words the interdependencies and operational limitations of the process system under consideration, encompassing mass balance and demand constraints. In addition, the objective functions are constituted by a set of equations describing the system decomposed into three groups :

1. Operational and economic functions;
2. Environmental impact functions;
3. Transportation functions.

These constraints and set of function systems are developed in section 4.4. The general objective of this modelling approach is to capture all the complex interdependencies between the variables. The objective functions that will be considered are the following ones:

1. Maximization of the Net Present Value (NPV), defined as an indicator of the economic performance of a project as measured by the cumulative cash flows over time. It allows measuring the economic performance of the system in its full life cycle.
2. Minimization of Global Warming Potential (GWP): GWP is a measurement index that integrates the overall climate impact of an activity or system measured in a standardized form by CO_2 emissions equivalency.
3. Minimization of variable unit cost (VUC): VUC is defined as the cost incurred to produce and deliver a product to a store or retailer.
4. Minimization of investment: this capital cost is related to the purchase and installation of processing equipment and facilities.

These objective functions will be assessed in different combinations in order to evaluate independent or interconnected performances and behavior of the SC network design model (e.g. Customer focused, Focal Company centered, multiple stakeholder approach, etc.). The evaluations are needed to overcome difficulties in the decision-making process due to the problem complexity. The main difficulties that are overcome through this approach are:

a) **Multi-objective:** under the green supply chain paradigm, multiple objectives are involved.
b) **Multi-stakeholder:** the model is framed taking into account the objectives and preferences of the Focal Company, the natural environment and the customers.
c) **Multi-period:** the model evaluates the project in strategic terms through a 10-year time horizon reflecting the useful life cycle of equipment via NPV and operational performance (i.e. capacity, GWP, etc.) in per annum terms.
d) **Multi-echelon:** the scope of the supply chain network includes the interfaces between the four echelons mentioned before.
e) **Multi-product:** the model is developed to consider multiple products variations (organic labeled, conventional label, plastic bottle, glass bottle, etc.) with different process and material routes.
f) **Multi-location:** the problem is formulated for globally distributed supply chain networks with different locations and routes at different levels in the product's life cycle.

4.3.2 MATHEMATICAL MODELLING APPROACH

Within the process industry domain, the GSCND problem has mainly been tackled through bi-objective Mixed Integer Nonlinear Programs (MINLP) (Guillén-Gosálbez and Grossmann, 2009) following the principles developed in (Hugo and Pistikopoulos, 2004), in which nodes are activated in order to design the network through binary variables, while the other variables in the system can take integer and real variables (e.g. capacity of process).

The modelling approach proposed here is based on a multi-objective integer nonlinear formulation in agrofood systems. The final product is a discrete packaged product (i.e. 1L of bottled orange juice, 1 can (320mL) of tomato concentrate, etc.) and process capacity is thus estimated accordingly to the discrete final quantity of product that will be marketed. A formal definition in an abstract form is presented in (4-1). The set of minimization objective functions from 1 to ***n*** represents the set criteria (related to economic and environmental performance) that must be simultaneously optimized, subject to inequality and equality constraints represented by ***g*** and ***h*** functions. They represent the model framework via the interconnected and interdependencies between decision variables, dependent variables and parameters with respect to the feasibility of the system. The decision variables that are used are of binary and integer type represented by ***y*** and x respectively.

$$\begin{aligned} \min f_1\ x,y,z\ ,f_2\ x,y,z\ ,\ldots,f_n\ x,y,z \\ s.t.\ g\ x,y,z\ \leq 0 \\ h\ x,y,z\ = 0 \\ y\ \in\ 0,1\ ^m, x \in \mathbb{Z}^n \end{aligned} \tag{4-1}$$

Following the problem statement and abstract formulation, the formal mathematical model is proposed, using the general structure of the four-echelon supply chain. For the sake of illustration, a mathematical formulation is developed for each link in the chain and constructed in the abstract representation by using the case study of the orange juice production company as a support instance.

The historical and bibliographical data used for model implementation and validation are offered in the Appendix A section and throughout the case study description. The information that is provided is based on literature review from past and recent data on orange fruit and orange juice production (Curti-Díaz et al., 1998; Doublet et al., 2013; Knudsen et al., 2011; Spitzley et al., 1997). Additional data for environmental impact estimations is provided by using Simapro ® software and EcoInvent 2.2 databases.

4.3.3 GENERALIZATION TO SIMILAR PRODUCTION SYSTEMS

Table 4-1 presents the abstract form of the case study instance that could be generalized to other food systems.

TABLE 4-1 PRODUCT LIFE CYCLE ABSTRACT MODEL AND CASE STUDY REPRESENTATION

Abstract instance	Abstract nomenclature	Case study instance	Case study
Agricultural resource product	AR	Orange	Orange
Intermediate product 1	IP1	Raw orange juice	Juice
Intermediate product 2	IP2	Pasteurized orange juice	Past
Intermediate product 3	IP3	Concentrated orange juice	Conct
Intermediate product 4	IP4	Bottled orange juice	Bott
Final product 1	FP1	Not from concentrate orange juice	NFCOJ
Final product 2	FP2	From concentrate orange juice	FCOJ

These abstract representations can be applied to products that follow a similar life cycle (e.g. fruit juices, vegetable concentrates, milk products, dehydrated food products, etc.).

4.4 MATHEMATICAL MODEL FORMULATION

The model framework provides a means to represent the behavior the system. Section 4.3.1 has presented a brief description of the interconnected decisions that are involved in the GrSND problem. This section is now devoted to the mathematical formulation of the supply chain model related to materials flows and demand satisfaction is introduced. The case study serves here as a support of the methodology and each component and decision level is presented in detail.

4.4.1 MASS BALANCE AND DEMAND CONSTRAINTS

In terms of materials flow, the network of suppliers, production plants and markets are reflected in a set of constraints that insure production capacities at each level in the supply chain can meet market demand requirements.

4.4.1.1 DECISION LEVELS 0, 1 AND 2

First, production output has to match market demand. For this purpose, a necessary condition is the procurement of the raw materials from the suppliers, divided in our case study into organically and conventionally grown orange orchard fields. The first two echelons, i.e. supplier and processing are displayed in order to visualize the flow of raw materials along the two links in Figure 4-7.

The ***TotalCapacity$_t$*** variable refers to the total capacity of the supplier network and sums the total capacity of all suppliers capacities ***QC$_{r,s,t}$*** given the agricultural practice used ***t***. When agro practice ***t=1*** is used to produce organic raw material in terms of materials flow it is defined by an index ***i=org*** , and agro practice ***t=2,3,4*** are used to produce conventional raw material output at different agrochemical use levels; in terms of materials flow an index ***i=conv*** is assigned to these raw materials.

$$TotalCapacity_t = \underset{s}{\quad} QC_{r,s,t}\ ;\ \forall r,s,t \tag{4-2}$$

The capacity contracted from each supplier is calculated through the ***QC$_{r,s,t}$*** variable, that is related to the contracted land surface through the ***LandArea$_{r,s}$*** variable for each supplier ***s*** in each region ***r***, times the average output yield per land surface unit $\beta_{r,t}$ given the region ***r*** where the suppliers are located and the technology ***t*** used at each orchard***.***

$$QC_{r,s,t} = LandArea_{\,r,s} \times \beta_{r,t}\ ;\ \forall r,s,t \tag{4-3}$$

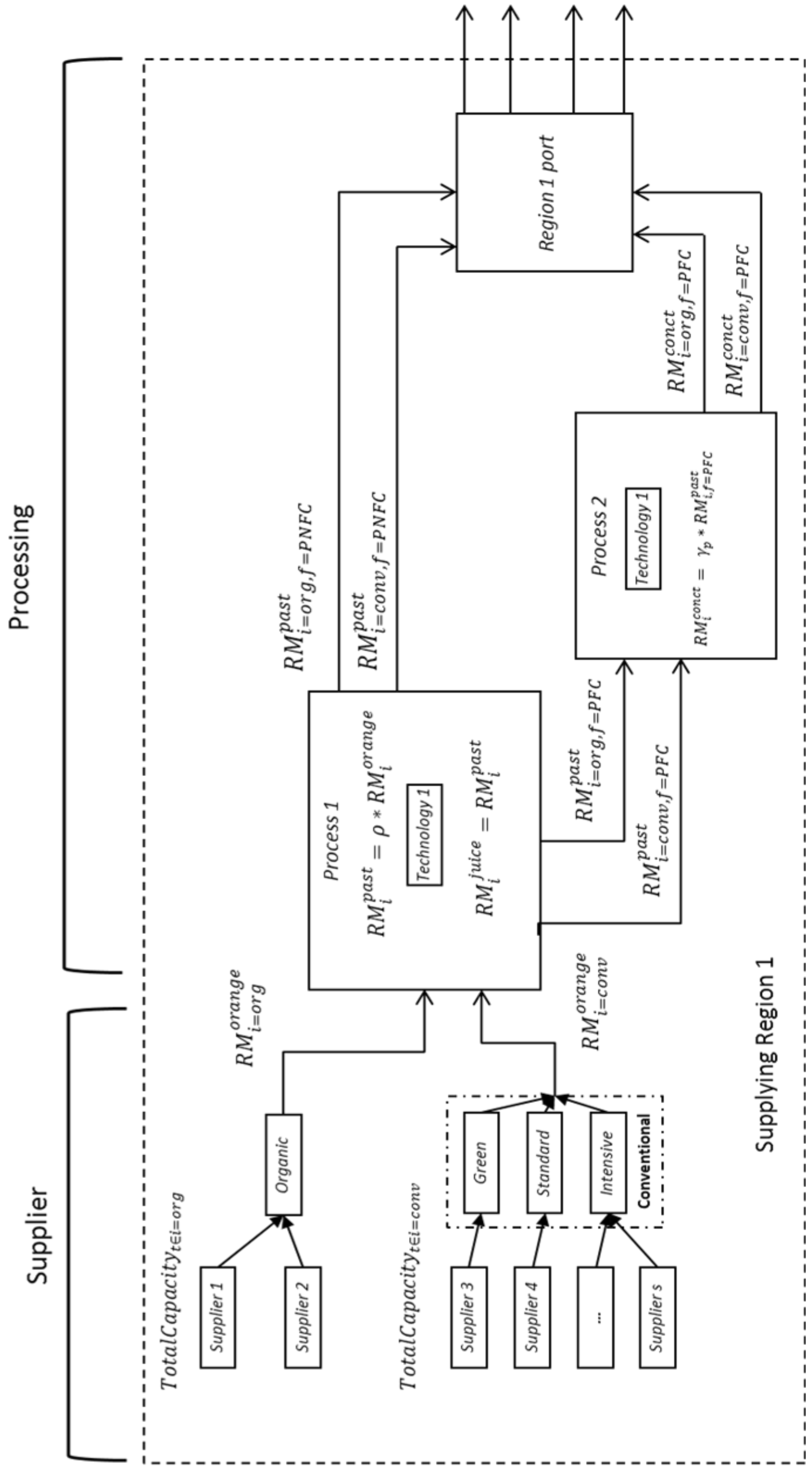


FIGURE 4-7 SUPPLIER AND PROCESSING PLANT MATERIALS FLOW DIAGRAM

Table 4-2 summarizes the average output, cost and environmental impact relative to the region and the agricultural practice being used for the case study. They have been established from the information given in (Consejo Citrícola Poblano A.C., 2004) for Mexico and in (Knudsen et al., 2011; Oelofse et al., 2010) for Brazil.

TABLE 4-2 AVERAGE OUTPUT, COST AND ENVIRONMENTAL IMPACT PER AGRO PRACTICE AND REGION SUMMARY TABLE

Parameter	Agro practice (t)	Mexico (r=1) (Consejo Citrícola Poblano A.C., 2004)	Brazil (r=2) (Knudsen et al., 2011; Oelofse et al., 2010)
Output ($\beta_{r,t}$; kg/ha/yr)	Organic (1)	5000	18000
	Quasi-organic (2)	8000	18660
	Standard (3)	15000	19320
	Intensive (4)	25000	20000
Cost ($\delta_{r,t}$; \$/ha/yr)	Organic (1)	284	1139
	Quasi-organic (2)	552	1065
	Standard (3)	820	991
	Intensive (4)	1096	914
GWP ($\phi_{r,t}$; kg CO_2 eq/ha/yr)	Organic (1)	633	1512
	Quasi-organic (2)	1307	1752
	Standard (3)	1981	1992
	Intensive (4)	2675	2240

The ***LandArea**$_{r,s}$* (4-4) is defined by the selection of the region ***r*** where the suppliers ***s*** are located, this selection is made through the product of the ***BR**$_r$* binary variable, the land size parameter $\boldsymbol{\omega_{r,s}}$ of each possible supplying orchard (in ha) (Table 4-3), the binary variable ***BS**$_{r,s}$* is used to be selected (activated) the suppliers ***s***, part of the subset of ***S*** that are located in region ***r*** .

TABLE 4-3 LAND SIZE PER SUPPLYING ORCHERD FROM BOTH MEXICO AND BRAZIL REGIONS

Supplier (s)	1	2	3	4	5	6	7	8	9	10
Mexico; r=1 ($\omega_{r,s}$; ha)	100	150	320	12	14	19	28	256	35	365
Brazil, r=2 ($\omega_{r,s}$; ha)	35	49	64	26	15	23	44	41	440	923
Supplier (s)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Mexico; r=1 (ωr,s; ha)	350	420	490	560	630	320	12	14	19	28
Brazil, r=2 (ωr,s; ha)	1060	53	13	66	17	67	23	29	21	14

This produces the total land area that can be guaranteed by the contract, in addition and in order to have more flexibility to determine the land capacity to be assigned an $\boldsymbol{IS_s}$ integer variable is used to determine the percentage of the total land area to be negotiated in the contract scheme.

$$LandArea_{\,r,s} = BR_r \times \omega_{r,s} \times BS_{r,s} \times \;\; IS_s;\; \forall r, s, t \qquad \text{4-4}$$

Equation 4 imposes that only one region can be selected for the reasons detailed in section 4.2.2.1:

$$\underset{r}{} BR_r = 1 \qquad \text{4-5}$$

An explicit lower limit of the land being considered of at least 50% of the total land is set in the case study to ensure a fair contract with a newly selected partner.

4.4.1.2 DECISION LEVEL 3

Two flows of types of oranges (see Figure 4-7) that come out of the Supplier Echelon enter the first process box (e.g. pasteurization). In our case study these are oranges to be passed through pasteurization process where the raw material requirements are denoted by $\boldsymbol{RM_{i=org}^{orange}}$ and $\boldsymbol{RM_{i=conv}^{orange}}$. They are used in (4-6) and (4-7) respectively to constrain the lower and upper limits of the contracted production capacity from the suppliers to be equal or 10% more than the raw materials required in order to guarantee sufficient raw materials for the production capacity to be installed. The superscript used (e.g. *i=org* and *i=conv*) denotes the raw material type, while the subscript t denotes the agro practice used. This nomenclature is used because we implement the same variable template for the raw material requirements along the different intermediate products throughout the full product life cycle. The subscripts denote the type of product being processed based on the raw material sourcing.

$$RM_{i=org}^{orange} \leq TotalCapacity_t \leq 1.1RM_{i=org}^{orange}; \text{when } t = 1 \qquad \text{4-6}$$

$$RM_{i=conv}^{orange} \leq \overset{4}{\underset{t=2}{}} TotalCapacity_t \leq 1.1RM_{i=conv}^{orange}; \text{when } t = 2{,}3{,}4 \quad \textbf{4-7}$$

$\boldsymbol{RM_i^{orange}}$ represents the quantity of oranges needed for juice extraction processing and $\boldsymbol{RM_i^{juice}}$ defined in (4-8) is the quantity of raw material required in the pasteurization process. $\boldsymbol{RM_i^{juice}}$ defined as the quantity of juice extracted, is the product of the constant $\boldsymbol{\rho}$ that represents the average yield of raw juice extracted per unit of oranges by the quantity of oranges procured $\boldsymbol{RM_i^{orange}}$**.** Additionally it is assumed that there is negligible or no mass loss during the pasteurization process.

$$RM_i^{juice} = \rho * RM_i^{orange} = RM_i^{past} \quad \textbf{4-8}$$

Distinctly $\boldsymbol{RM_i^{Past}}$ represents the quantity of pasteurized juice required for outgoing product given that pasteurized juice is sent as a raw material to the bottling plant *as-is* (Pasteurized Not for Concentrate or PNFC); it is also used as an input raw material for the following processing step, concentration (Pasteurized For Concentrate or PFC), as shown in (4-9). It involves raw materials targeted at different destinations.

$$RM_i^{past} = RM_{i,f=NFC}^{past} + RM_{i,f=FC}^{past} \quad \textbf{4-9}$$

$\boldsymbol{RM_i^{conct}}$ is the raw material requirement by the bottling plant to produce From Concentrate Orange Juice (FCOJ). It is defined in (4-10) as the product of the constant $\boldsymbol{\gamma_p}$ that represents the concentration ratio based on the average level of concentration that can be achieve using the selected technology $\boldsymbol{p}$ times the pasteurized juice assigned to be concentrated.

$$RM_i^{conct} = \gamma_p \times RM_{i,f=FC}^{past} \quad \textbf{4-10}$$

Table 4-4 presents the two concentration levels that are reached by different equipment technologies being evaluated for the concentration process for the case study. It shows the quantity of single strength orange juice (i.e. with the natural concentration level of the juice ~11°Bx) needed to produce a unit (measured in volume and weight) of multi-strength orange juice concentrate (i.e. orange juice that is concentrated to multiple times its Brix concentration, usually 44°Bx and 66°Bx).

TABLE 4-4 SINGLE STRENGTH TO MULTI-STRENGTH (>11°BRIXC) CONCENTRATION COEFFICIENTS

Concentration	γ_p (L single strength OJ/L FCOJ)	γ_p (kg single strength OJ/kg FCOJ)
44 $°\text{Brix}_c$	4.27	3.57
66 $°\text{Brix}_c$	7.08	5.35

Based on (Amador, 2011)

4.4.1.3 DECISION LEVELS 5 AND 6

Within the Packaging/Bottling and Market echelons, there are a series of characteristics that are modeled for the case study. Looking at the demand side, there are two market regions ***r'*** France and Germany, this is denoted by the dotted line boxes in Figure 4-7. Within each region, a single bottling plant is located and sized to satisfy the demand $D_{i,f,r',m}$ corresponding to a market of the 10 most populated cities ***m*** in each region ***r'*** denoted by the distribution centers (DC) boxes. A variable demand is allocated to each market within upper and lower limits. The demand to be covered by production capacity will be set as a decision variable. This allows the model to allocate the production output capacity to the most profitable and least environmentally damaging product types and markets (e.g. markets closer to a bottling plant may be more attractive). The lower limit for demand means that there is a minimum level to be satisfied while the upper limit represents an estimation of the market potential.

Four flows of bottled products from the bottling plant are connected to the market DC. The total capacity of the bottling plant is determined by the sum of the demands to be satisfied. These demands are divided by product type, based on the initial raw material sourcing ***i*** and on the other hand, on the fabrication steps it has gone through notably if it has been concentrated or not as indicated through ***f*** index.

More precisely, within the packaging/bottling plant, the input of raw materials coming from the market ***r'*** port of arrival is available in two forms, either single strength (or NFCOJ) form or multi-strength (or FCOJ) form for each raw material sourcing type ***i*** that is transformed using a given technology p. For the case of NFCOJ, no mass change is assumed, while for FCOJ, the addition of water serves to reconstitute the orange juice to its single strength form.

Mathematically these echelons involve $\boldsymbol{RM_i^{bott}}$, i.e., the quantity of bottling juice required by the market DC; it is equal to the demand (4-11). The demand coverage is denoted by the integer decision variable $\boldsymbol{D_{i,f,r',m}}$ that represent the number of final product units that are planned to be sold to the distribution center in market ***m*** within the region ***r'*** of products type based on concentration ***f*** , where f can be either NFCOJ or FCOJ, as well as based on the type of raw materials used ***i***.

$$RM^{bott}_{i,f,r\prime} = \underset{m}{\quad} D_{i,f,r',m}; \forall r' \tag{4-11}$$

The demand is restricted by an upper and lower bound expressed in (4-12), these limits are viewed as the minimum acceptable market demand satisfaction and the maximum market demand saturation limits.

$$LLD_{i,f,r',m} \leq D_{i,f,r',m} \leq ULD_{i,f,r',m} \tag{4-12}$$

The demand is satisfied by the inputs coming from the pasteurization process as $\boldsymbol{RM^{past}_{i,f=NFCOJ}}$(4-13) and through the reconstitution step by adding water to the concentrated raw material $\boldsymbol{RM^{const}_{i,f=FCOJ}}$ (4-14).

$$RM^{bott}_{i,f,r'} = RM^{past}_{i,f} \text{ ,} when\ f = NFCOJ \tag{4-13}$$

$$RM^{bott}_{i,f,r'} = \frac{1}{\gamma_p} RM^{conct}_{i,f} + \quad 1 - \frac{1}{\gamma_p} RM^{conct}_{i,f} \quad \times Q_{water}, when\ f = FCOJ \tag{4-14}$$

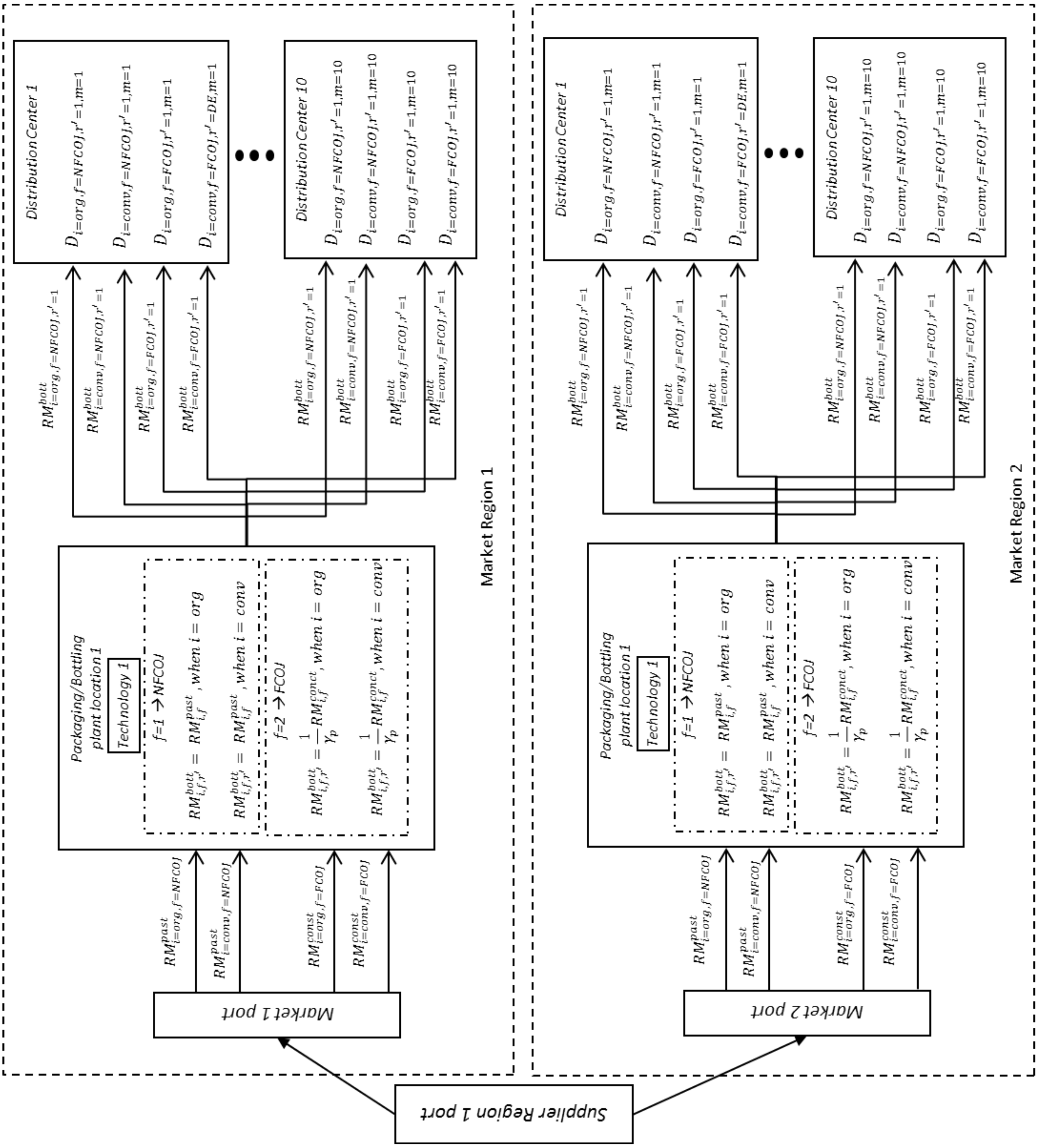


FIGURE 4-8 BOTTLING AND MARKET MATERIALS REQUIREMENT FLOW DIAGRAM

4.4.2 OPERATIONAL AND ECONOMIC FUNCTIONS

4.4.2.1 DECISION LEVELS 0, 1 AND 2

In order to evaluate the economic performance, we need to determine the cost at each stage of the production process. The production cost of each type of product is dependent on the conditions and costs that are relative to each echelon of the network. A similar nomenclature is used to the one adopted for the demand and mass balance constraints: a super-index is used to denote the stage in processing of the materials (e.g. orange to raw juice to pasteurize and so on) and the sub-index is used to denote the sourcing of raw material and the processing steps.

Figure 4-9 provides an overview of the input, process and output in terms of cost for the orchard production system. Each contribution is then presented in detail in what follows.

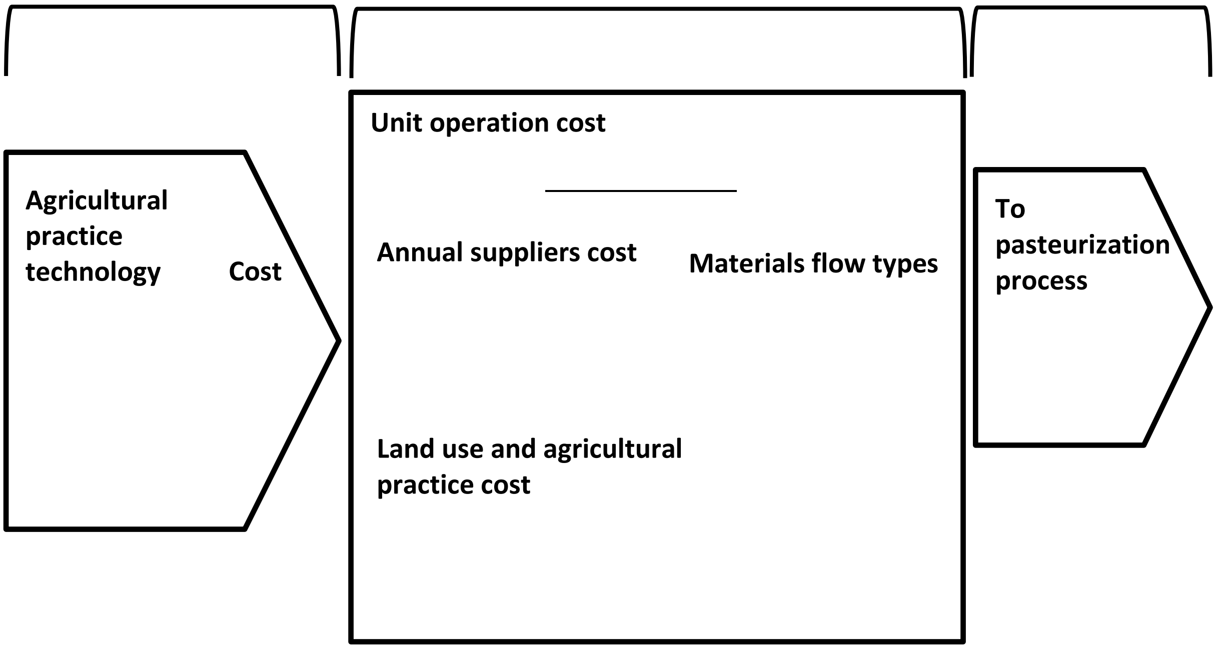


FIGURE 4-9 INPUT /OUTPUT DIAGRAM FOR THE ORCHARD PRODUCTION SYSTEM

The raw materials unit cost $\boldsymbol{RMUC_i^{orange}}$ represents the cost that is necessary to produce 1 kg of oranges based on which agricultural practice category $\boldsymbol{i}$ was used (organic or conventional). It is estimated by dividing the sum of the annual supplier operating cost $\boldsymbol{ASC_t}$ of all orchards that use technologies $\boldsymbol{t}$ that are in the $\boldsymbol{i}$ technology category (see Materials flows types in (Figure 4-9) and divided by the sum total of capacity contracted $\boldsymbol{TotalCapacity_t}$ for agro practice $\boldsymbol{t}$ that are in the $\boldsymbol{i}$ label category:

$$RMUC_i^{orange} = \frac{{}_t ASC_t}{{}_t TotalCapacity_t} \; ; \; \forall t \in i \tag{4-15}$$

The annual supplier operating cost $\boldsymbol{ASC_t}$ given a technology $\boldsymbol{t}$ is the sum of the annual operating cost $OpCost_{r,s,t}$ for all suppliers that were assigned agro practice $\boldsymbol{t}$:

$$ASC_t = \underset{s}{\quad} OpCost_{r,s,t} \forall t \tag{4-16}$$

$\boldsymbol{OpCost_{r,s,t}}$ is the annual operational cost of each supplier $\boldsymbol{s}$ in region $\boldsymbol{r}$ assigned to use agricultural practices $\boldsymbol{t}$ in terms of land area contracted. It is defined as the product of the contracted land surface $\boldsymbol{LandArea_{r,s,t}}$ and of the average operational cost of managing a unit of farm land $\boldsymbol{\delta_{r,t}}$ based on the region $\boldsymbol{r}$ and agro practice $\boldsymbol{t}$ being applied.

$$OpCost_{r,s,t} = LandArea_{r,s} \times \delta_{r,t} ; \forall r, s, t \tag{4-17}$$

Two types of oranges, i.e., organic and conventional are considered in the case study, thus leading to two distinct raw material unit costs. For organic oranges, it is referred as $\boldsymbol{RMUC_i^{orange}}$ where type ***i=org***, and is calculated given that the agro practice to obtain organic fruit is only one type (***t=1***).

$$RMUC_{i=org}^{orange} = \frac{{}_t ASC_t}{TotalCapacity_t} \; ; \; when \, t = 1 \in i = Organic \subset T \tag{4-18}$$

For conventional production, the other 3 types of agro practices can be applied. These are summed and averaged in (4-19)

$$RMUC_{i=conv}^{orange} = \frac{{}_t ASC_t}{TotalCapacity_t} \; ; \; when \;\; t = 2{,}3{,}4 \in i = Conventional \subset T \tag{4-19}$$

4.4.2.2 DECISION LEVELS 3

Pasteurization

The raw material unit cost is used to compute the unit variable costs in the processing of the materials along the next processing steps. The processing of the materials is firstly carried out near the raw materials source that usually consists of pasteurization and concentration.

It is considered as a single black-box process where the unit operating cost $\boldsymbol{RMUC_i^{past}}$ for fabrication step ***f=1*** or past using technology $\boldsymbol{p}$ is the unit cost estimated as the quotient of the annual operation cost $\boldsymbol{AOC_{f,p}}$ of that step $\boldsymbol{f}$ using technology $\boldsymbol{p}$ divided by the total output capacity required $\boldsymbol{Cap_{f,p}^{OUT}}$. The cumulative cost of this quantity and the raw materials unit cost required for that step $\boldsymbol{RMUC_i^{orange}}$ is then represented by Equation 22 (two flows, one for each $\boldsymbol{i}$).

$$RMUC_{i,f=past}^{past} = \frac{AOC_{f=past,p}}{Cap_{f=past,p}^{OUT}} + RMUC_{i}^{orange};\ \forall i \qquad \text{4-20}$$

The annual operating costs include the variable costs incurred related to materials and energy resources in order to operate a processing plant are defined. The annual operation cost $\mathbf{AOC}_{\boldsymbol{f,p}}$ is the product of the average cost of the resource $\boldsymbol{\varepsilon_{r,e}}$ given the region ***r*** of location of processing plant and the resource being consider ***e*** by the average resource requirement $\boldsymbol{\lambda_{f,e,p}}$ in units of resource ***e*** per unit of product for fabrication step ***f*** (e.g. pasteurization) using technology ***p*** (e.g. pulse electric field pasteurization), ***p*** technology is selected through a integer variable that is selected from a list of technology possibilities, and the input quantity to be processed $\boldsymbol{Cap_f^{IN}}$**.**

$$\mathrm{AOC}_{f=past,p} = \underset{e}{\quad} \varepsilon_{r,e} \times \lambda_{f,e,p} \times Cap_f^{IN} \qquad \text{4-21}$$

So, for example if technology ***p=PEF*** is selected, only energy is needed and is consumed at a rate of $\lambda_{f,e,p} =$ 0.0278 kWh/kg in the form of ***e=electricity***; in ***r=Mexico*** cost $\boldsymbol{\varepsilon_{r=Mexico,e=electricity}} =$ 0.1093 \$/kWh, and the calculated annual capacity required to satisfy demand for this equipment is $\boldsymbol{Cap_f^{IN}}$ =2 250 000 kg, thus the annual operating cost for this configuration would be $\mathbf{AOC}_{\boldsymbol{f,p}}$ =6838 \$/yr.

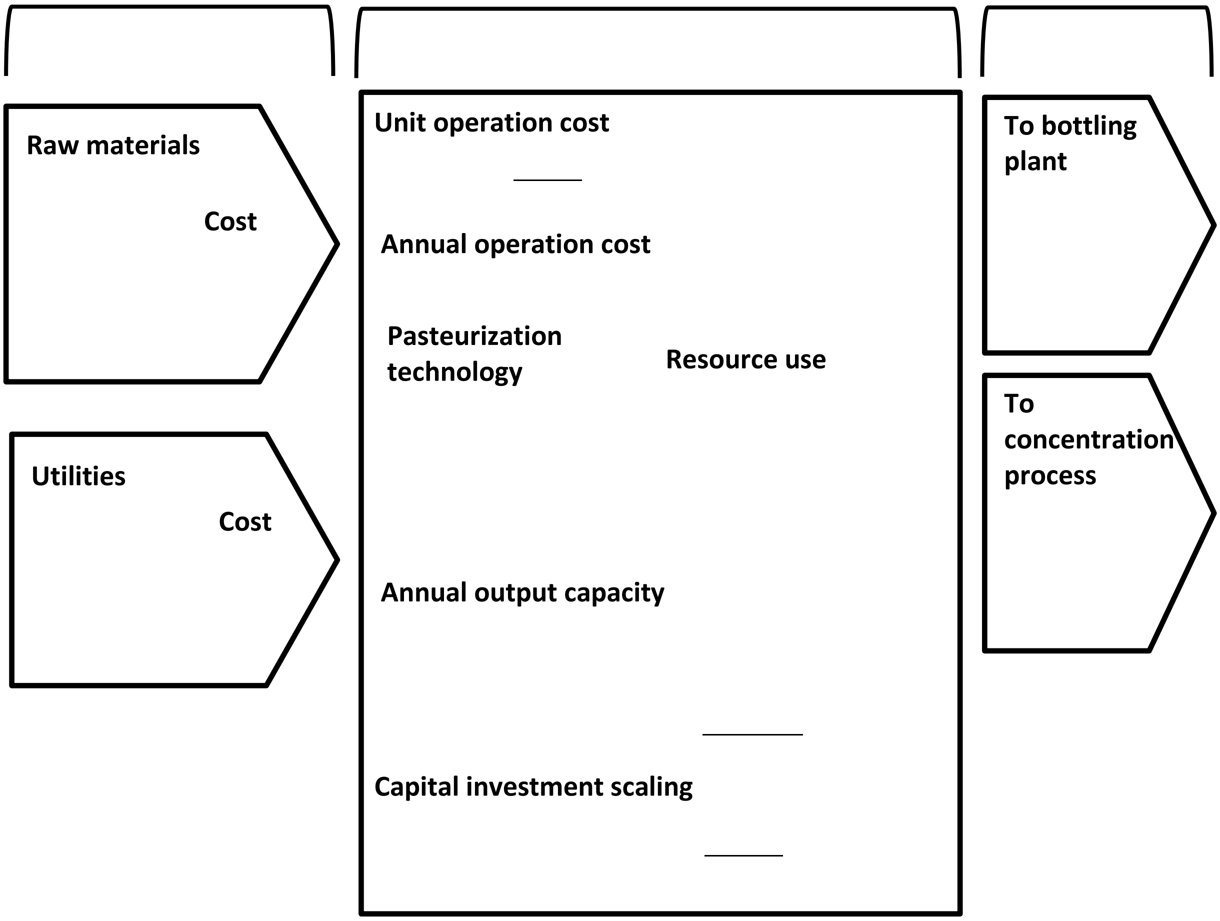


FIGURE 4-10 INPUT/OUTPUT DIAGRAM FOR PASTEURIZATION PROCESS

TABLE 4-5 COST AND ENVIRONMENTAL IMPACT EMISSIONS BY COUNTRY REGION

	$\varepsilon_{r,e}$			$\varphi_{r,e}$		
Region	*e*=electricity	*e*=gas	*e*=water	*e*=electricity	*e*=gas	*e*=water
(r,r')	(\$/kWh)	(\$/kWh)	(\$/kg)	(kgCO2eq/kWh)	(kgCO2eq/kWh)	(kgCO2eq/kg)
France	5.92E-02	4.78E-02	4.56E-02	9.21E-02	6.98E-02	2.44E-06
Germany	1.08E-01	5.36E-02	5.36E-02	6.77E-01	6.98E-02	2.44E-06
Mexico	1.09E-01	2.74E-02	6.98E-02	5.73E-01	6.98E-02	2.44E-06
Brazil	1.03E-01	2.53E-02	6.98E-02	2.26E-01	6.98E-02	2.44E-06

Source:

- Gas cost for France and Germany taken from Eurostat website retrieved 11-03-2014 link (http://epp.eurostate.ec.europa.eu:tgm/table.do?tab=table&init=1&pluin=0&language=en&pcode=ten00112)
- Gas cost for Mexico based on Section 3.5 in (Secretaría de Energía, Mexico, 2012)
- Gas cost for Brazil source of data (MATHIAS and CECCHI, 2009)
- Electricity data for all from International Energy Agency, Energy Prices & Taxes – Quarterly Statistics, Fourth quarter 2009, Part II Section D, Table 21 and Part III, Section B, Table 18, 2008.
- Water data for Mexico and Brazil from The International Benchmarking Network for Water and Sanitation Utilities retrieved 16-04-2014 (http://www.ib-net.org/en/production/?action=country)
- Water data for France and Germany from Global Water Intelligence retrieved 16-04-2014 (http://www.globalwaterintel.com/archive/12/9/market-profile/global-water-tariffs-continue-upward-trend.html)
- GWP emissions taken from (Santoyo-Castelazo et al., 2011) and the SimaPro EcoInvent 2.2 (May 2010) database.

$\boldsymbol{Cap_f^{IN}}$ is the input capacity necessary to satisfy demand in the next processing step, i.e. the quantity of pasteurized juice needed for bottling NFCOJ and for the concentration process (4-22). It is calculated by using a standard input-output capacity ratio given the technology $\boldsymbol{p}$ selected for this fabrication step $\boldsymbol{f}$ in order to scale the materials input capacity.

$$Cap_{f=past}^{IN} = Cap_{f=past}^{OUT} \times \frac{StdCap_{f,p}^{IN}}{StdCap_{f,p}^{OUT}} \qquad \textbf{4-22}$$

TABLE 4-6 PASTEURIZATION AND CONCENTRATION TECHNOLOGY CHARACTERISATION SUMMARY TABLE

		Pasteurization (f=past)		Concentration (f=conct)		
Parameter	Unit	HHP (p=1)	PEF (p=2)	Multieffects evaporator (p=1)	Freeze (p=2)	Reverse (p=3)
$StdCap_p^{IN}$	(kg / yr)	1,62E+07	3,75E+07	1,28E+08	5,63E+07	3,75E+07
$StdCap_p^{OUT}$	(kg / yr)	1,59E+07	3,68E+07	2,38E+07	1,58E+07	1,05E+07
Concentration	(°Brix)	-	-	66	44	44
e=gas	(kWh/kg)	-	-	8.41E-04	-	-
e=electricity	(kWh/kg)	1,71E-01	2.78E-02	-	9.33E-03	1.18E-03
e=water	(kg water/kg)	-	-	6.6	-	-
$StdCC_{f,p}$	$ (2010)	1875000	2500000	1272006	2750712	2303523

Source:

- Pasteurization data from (Balda et al., 2012; Pereira and Vicente, 2010; Toepfl et al., 2006) and Hiperbaric Co. Equipment catalog retrieved 03/2014 from web page http://www.hiperbaric.com/media/uploads/equipos/documentos/Hiperbaric_Range_2015_ENG_opt_internet1.pdf
- Concentration data from (Bomben et al., 1973)

Additionally, for each fabrication step an equipment investment cost is required, this capital investment is estimated in the same way for each of the processing steps: pasteurization, concentration and bottling. It is calculated based on capacity scaling comparison from a known similar technology that has been characterized following the *six-tenth factor rule* (Peters, 2003). Using the known standard capital cost $\boldsymbol{StdCC_p}$ for a given technology $\boldsymbol{p}$ and its standard capacity $\boldsymbol{StdCap_p}$ the estimated capital cost investment $\boldsymbol{InvCost_f}$ is a function of the output capacity requirement $\boldsymbol{Cap_f^{OUT}}$

$$InvCost_f = StdCC_p \, \frac{Cap_f^{OUT}}{StdCap_p}^{3/5} \quad ; \forall f \tag{4-23}$$

Concentration

The next process is the concentration process for the case study. It is located at the same plant location than the pasteurization process. Figure 4-11 gives an overview of the modelling of concentration process: the input flows come from the pasteurization process (organic and conventional). The concentration process consists of removing water through a selected concentration technology $\boldsymbol{p}$ from a list of candidates: evaporation, freezing, osmosis. Each technology has a different energy consumption profile defined by the type and quantity of energy resource used with a specific operation cost. The output of the system is constituted of two flows, organic and conventional FCOJ for the bottling plants.

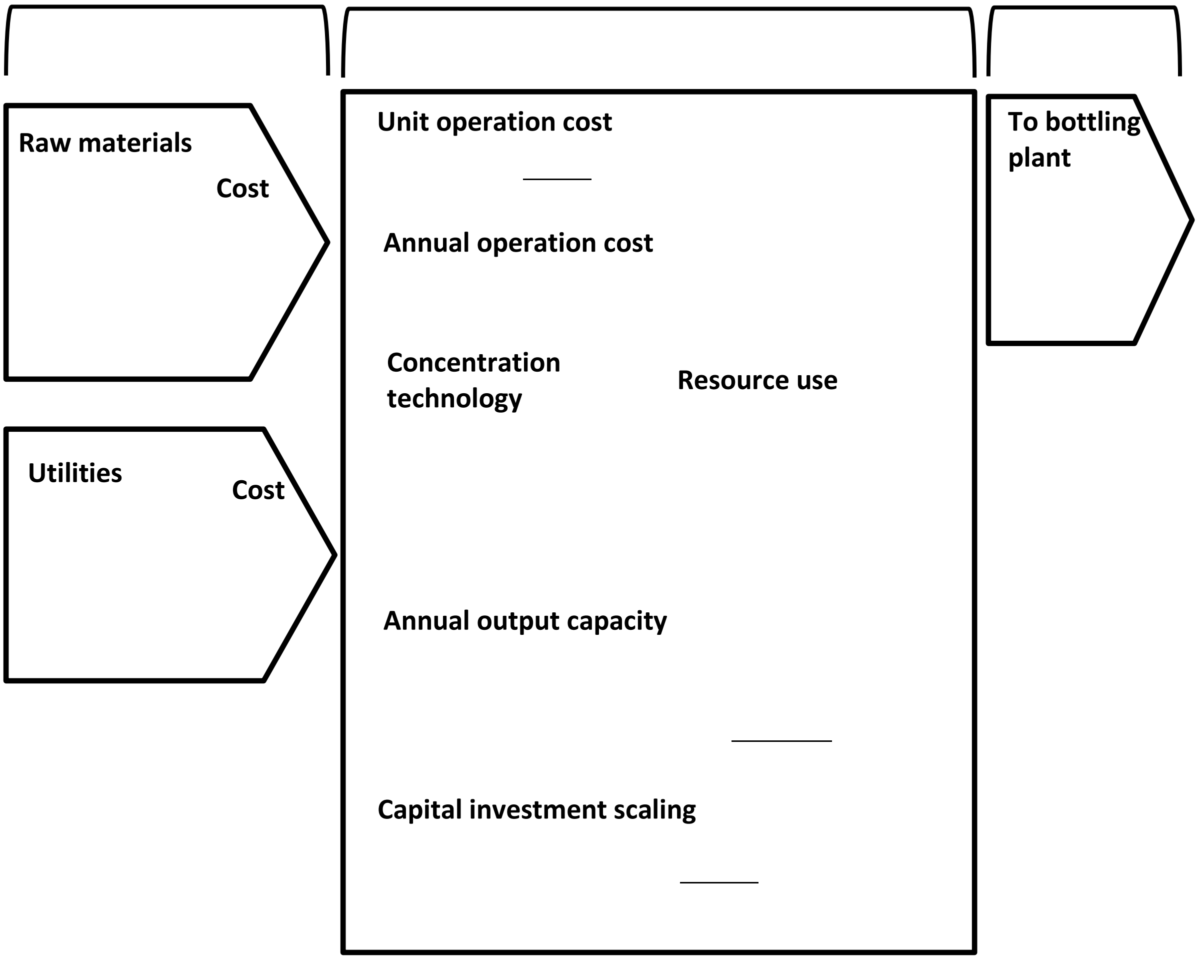


FIGURE 4-11 CONCENTRATION PROCESS INPUT OUTPUT DIAGRAM

The cost constraints of this system are mathematically represented by two components: first, the raw materials unit cost of concentrated juice $\boldsymbol{RMUC_{i,f}^{const}}$ as a function of the annual operating cost $\boldsymbol{AOC_{f=const,p}}$ to concentrate juice given technology ***p*** divided by the output capacity of this equipment ***(f,p)*** giving a per unit operational cost to this raw materials unit cost; second, the product of $\boldsymbol{RMUC_{i}^{past}}$ by the ratio of pasteurized juice to obtain one unit of concentrated juice $\boldsymbol{\gamma_p}$ given the technology ***p*** capacity.

$$RMUC_{i,f=const}^{const} = \frac{AOC_{f=const,p}}{Cap_{f=const,p}^{OUT}} + (\gamma_p * RMUC_i^{past}) \qquad \textbf{4-24}$$

The annual operating cost is calculated in the same manner as the pasteurization process but using the specific values for the concentration process instance (see 4-24, Table 4-5 and Table 4-6).

In addition similar to the pasteurization process we calculate the capital investment for the equipment through (4-24).

2.1.1.1 Decision Levels 5

Bottling

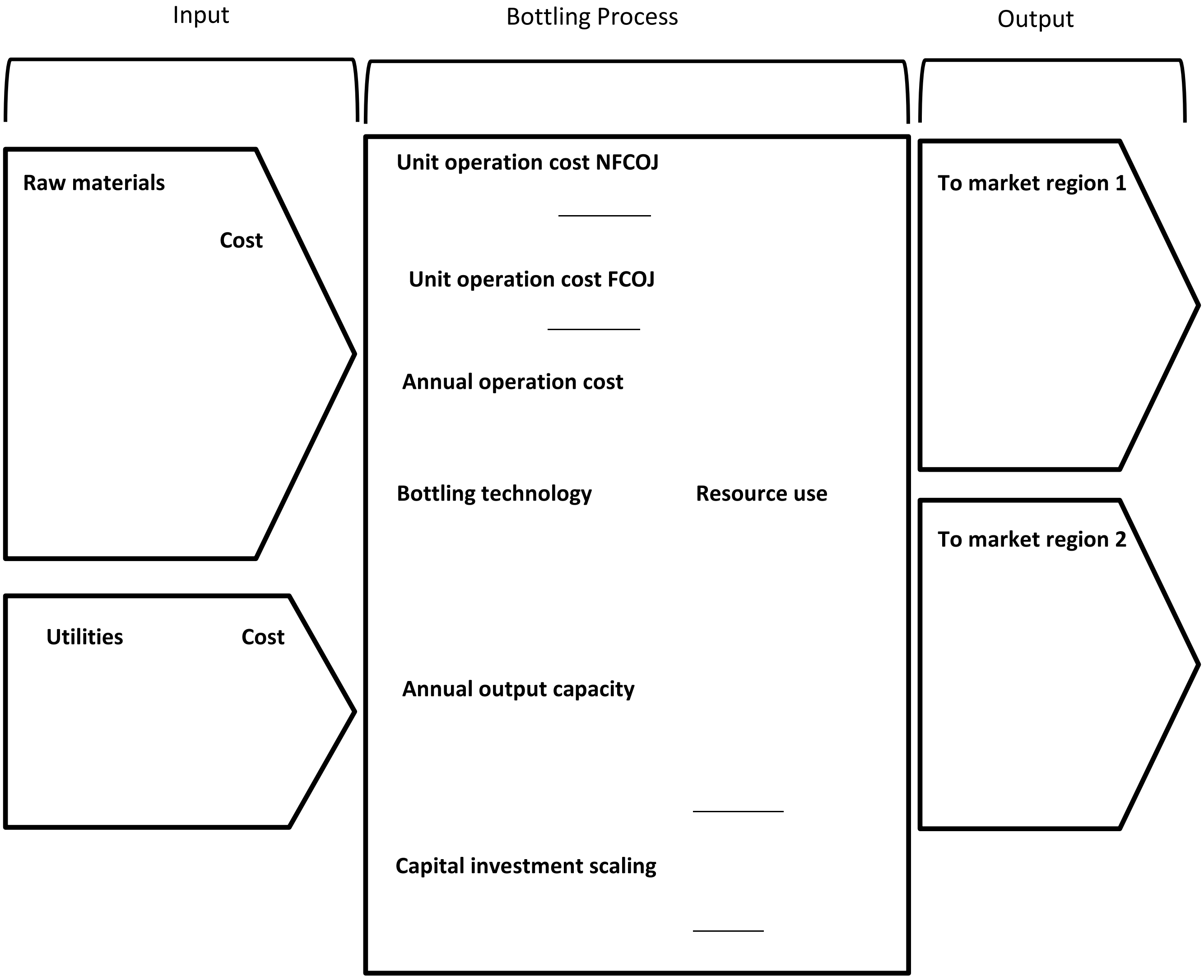


FIGURE 4-12 CONCENTRATION PROCESS INPUT OUTPUT DIAGRAM

For unit cost estimation of the raw materials relative to the bottling process, a different approach is used given that the annual operations cost per unit is fixed (see Table 4-7). In addition there are two materials streams based on mass that require different resources. One is the unit cost for processing NFC orange juice $\boldsymbol{RMUC^{bott}_{i,f=NFCOJ}}$ and is defined by two components the bottling operation process cost BMC_p that is fixed given the technology used $\boldsymbol{p}$ and the resource materials used taking in single strength pasteurized juice as raw material $RMUC^{past}_{i,f=past}$

$$RMUC_{i,f=NFCOJ}^{bott} = BMC_p + RMUC_{i,f=past}^{past} \tag{4-25}$$

For FC *orange juice* materials flow in addition to the raw materials unit cost, the water needed to reconstitute the *for concentrate orange juice* is considered through the last term in brackets.

$$RMUC_{i,f=FCOJ}^{bott} = BMC_p + RMUC_{i,f=const}^{const} + \quad 1 - \frac{1}{\gamma_p} \quad \times \varepsilon_{r',e=water} * \lambda_{f,e,i} \tag{4-26}$$

In addition, similar to the pasteurization process, the capital investment is calculated by scaling the equipment through (4-23) using information from Table 4-7.

TABLE 4-7 BOTTLING TECHNOLOGY CHARACTERIZATION SUMMARY TABLE

p	Technology	BMC_p	$\lambda_{f=NFCOJ,e=water,p}$	$\lambda_{f=FCOJ,e=water,p}$	$\lambda_{f,e=electricity,p}$	$stdCC_p$	$StdCap_p^{OUT}$
		$/L bottling juice	L water/L bottled juice	L water/L bottled juice	kWh/L bottling juice	$ (2010)	L / per year
1	PET bottle	0.02747	0.66924	0.66924	0.66924	275 000	3 170 409
2	Glass bottle	0.1025	1.37957	1.37957	1.37957	275 000	3 170 409
3	Aseptic carton	0.07714	0.39039	0.39039	0.39039	430 000	3 170 409

Source: (Spitzley et al., 1997) actualized to 2010

4.4.3 ENVIRONMENTAL IMPACT FUNCTIONS

The same basic modelling structure is used for the definition of the environmental impact functions. The environmental impact is focused on global warming potential as expressed in kgCO$_2$eq/kg.

Orchard Production

At the supplying orchards a raw material unit environmental impact $RMUEI_i^{orange}$ for each type of agricultural technology ***t*** is used, aggregated in two groups ***i=organic*** when ***t=1*** and ***i=conventional*** when ***t=2,3,4***. It is estimated by summing all of the annual environmental emissions per supplier $OpEI_{r,s,t}$ given the region, and technology being used and dividing it by the sum of the total capacity in terms of the technologies being evaluated:

$$RMUEI_i^{orange} = \frac{{}_t\, ASEI_t}{{}_t\, TotalCapacity_t}\ ;\ \forall t|i \tag{4-27}$$

The annual supplier environmental impact $\boldsymbol{ASEI_t}$ given a technology ***t*** is the sum of the annual operating emissions $OpEI_{r,s,t}$ for all suppliers that use technology ***t :***

$$ASIE_t = \underset{s}{} OpEI_{r,s,t}\,;\ \forall t \tag{4-28}$$

where $\boldsymbol{OpEI_{r,s,t}}$ is the annual operational environmental impact emissions of each supplier $\boldsymbol{s}$ in region $\boldsymbol{r}$ using agricultural practices $\boldsymbol{t}$ in terms of land area contracted $LandArea_{r,s,t}$ times the average environmental impact output per land unit $\boldsymbol{\psi_{r,t}}$ that is determined as a function of the region and technology being used:

$$OpEI_{r,s,t} = LandArea_{r,s,t} \times \psi_{r,t}; \forall r, s, t \tag{4-29}$$

Pasteurization

The environmental impact for each unit of juice pasteurized is calculated as an average. This is to say, the annual (operations) environmental impact $\boldsymbol{AOEI_{f,p}}$ of fabrication step $\boldsymbol{f}$ using technology $\boldsymbol{p}$ divided by the total output $\boldsymbol{Cap_{f,p}^{OUT}}$ and by adding the environmental impact per unit of orange $\boldsymbol{RMUC_{i}^{orange}}$ needed for production of the juice (adjusted by multiplying the orange to juice ratio constant ρ)

$$RMUEI_{i,f=past}^{past} = \frac{AOEI_{f=past,p}}{Cap_{f=past,p}^{OUT}} + (\rho \times RMUEI_{i}^{orange}) \tag{4-30}$$

Annual operations environmental impact is defined by resources used (energy and water) for one year of operation. This is estimated by the sum of the environmental impacts calculated for each resource used $\boldsymbol{e}$ (i.e. gas, electricity, water). These impact per resource are estimated by the product of the average environmental impact of the resource $\boldsymbol{\varphi_{r,e}}$ times the average resource requirement $\boldsymbol{\lambda_{f,e,p}}$, times the input quantity to be processed $\boldsymbol{Cap_{f}^{IN}}$

$$\mathrm{AOEI}_{f,p} = \underset{e}{} \varphi_{r,e} \times \lambda_{f,e,p} \times Cap_{f}^{IN} \tag{4-31}$$

So, for example, using the case study values from

Table 4-5, say technology ***p=PEF*** is selected and it has only one resource need mainly ***e=electricity*** energy, that is consumed at a rate of $\boldsymbol{\lambda_{f,e,p}} = 0.0278$ kWh/kg produced, the electricity in ***r=Mexico*** emitting $\varphi_{r=\boldsymbol{Mexico},e=\boldsymbol{electricity}} =$ 6.90E-04 kgCO$_2$eq/kWh, and the calculated annual capacity required to satisfy demand for this equipment is $\boldsymbol{Cap_f^{IN}}$ =2 250 000 kg, thus the annual operation environmental impact for this configuration would be $\mathbf{AOEI}_{f,p}$ =43.16 kgCO2eq/yr.

Concentration

The concentration process environmental impact per unit is estimated much the same way as the pasteurisation's, where term $\boldsymbol{AOEI_{f=const,p}}$ is divided by the output $\boldsymbol{Cap^{OUT}_{f=const,p}}$ that is then added to the emission given the raw materials input, the main difference is that the input raw material is pasteurised juice material which is multiplied by the average pasteurised to concentrated juice ratio $\boldsymbol{\gamma_p}$ given the technology ***p*** used

$$RMUEI^{const}_{i,f=const} = \frac{AOEI_{f=const,p}}{Cap^{OUT}_{f=const,p}} + (\gamma_p \times RMUEI^{past}_i) \qquad \textbf{4-32}$$

Bottling

In a similar way to how unit cost were estimated for the bottling process the environmental impact is calculated taking into account the fixed environmental impact emission $\boldsymbol{BMEI_p}$ based on the technology ***p*** and the raw materials used unit environmental impact that for NFCOJ is $RMUEI^{past}_{i,f=NFCOJ}$

$$RMUEI^{bott}_{i,f=NFCOJ} = BMEI_p + RMUEI^{past}_{i,f=past} \qquad \textbf{4-33}$$

For FCOJ raw materials bottling additionally we have to take into account the water consumption impact

$$RMUEI^{bott}_{i,f=FCOJ} = BMEI_p + RMUC^{const}_{i,f=const} + \quad 1 - \frac{1}{\gamma_p} \quad \times \varphi_{r',e=water} * \lambda_{f,e,i} \qquad \textbf{4-34}$$

4.4.4 TRANSPORTATION FUNCTIONS

The transportation activities involved through the supply chain have an economic and environmental cost. The four intermediate product types, i.e., pasteurized single strength (NFCOJ) organic and conventional orange juice, and concentrated multiple strength (FCOJ) organic and conventional orange juice differ from their production cost, related to their operations but share the same transportation cost in terms of kilogram kilometer (kgkm) per mode of transport. These intermediate products are transported in bulk by different modes and route; for our case study, transport is limited to sea freight transport from the port of departure of the region r selected, with two arrival port destinations. These ports service two main market regions, mainly France and Germany, the two largest consumers of fruit juice in Europe. Within each market region, a set of markets (10 in the case study) made up of the most populated cities (10 in the case study). This configuration is shown in Table 4-8 and in Figure 4-13 where the economic cost from one location to its destination is denoted by $\boldsymbol{\vartheta}_{A\rightarrow B}$ where A is the current location and B is the destination for each echelon connection in the network in \$/kgkm; while $\boldsymbol{\psi}_{A\rightarrow B}$ represents the environmental impact of each transport trajectory measured in kg of CO_2 eq / kg.km (as abovementioned).

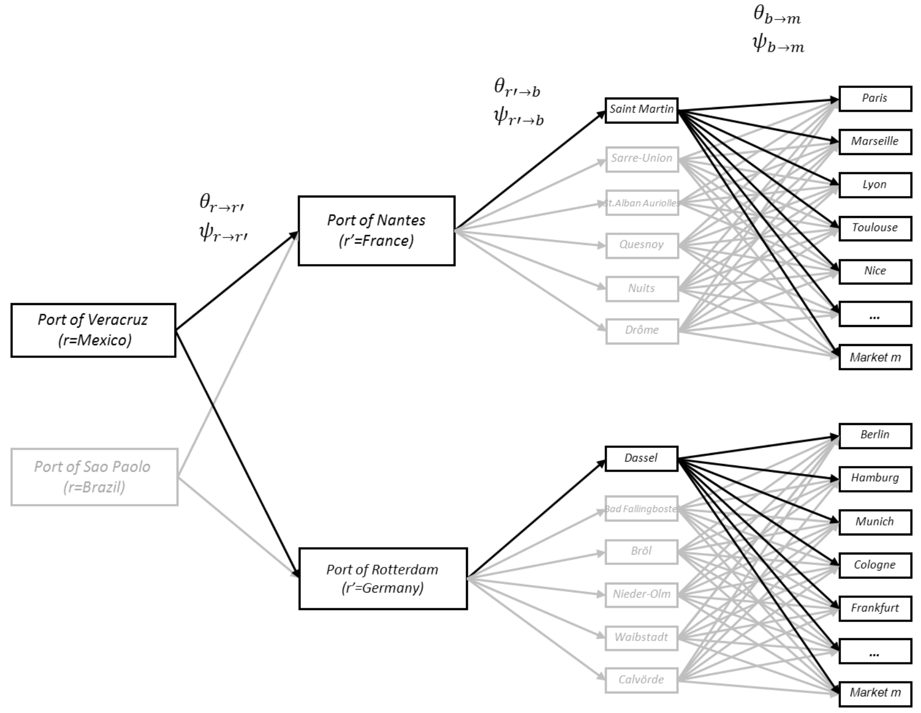


FIGURE 4-13 TRANSPORT ROUTE NETWORK CASE STUDY EXAMPLE

Table 4-8 presents the values that are used for the case study for the sea freight transport concerning economic and environmental impact constants used to measure the performance of the transportation activities from ***r→r'***. Appendix A Table 3 to 6 present in more detail the values for the two other main transportation trajectories that are included in the case study model, mainly port of arrival to bottling plant and bottling plant to market city.

TABLE 4-8 ECONOMIC AND ENVIRONMENTAL IMPACT COST FOR TRANSPORTATION FROM DEPARTURE TO ARRIVAL PORTS

Port of arrival	$\theta^{r\rightarrow r'}$ (\$/kgkm)	$\psi^{r\rightarrow r'}$ EI (kg CO_2 eq / kgkm)	Distance (km)

	(Brown et al., 2004)		(SimaPro Eco-invent database)			
	Mexico	Brazil	Mexico	Brazil	Mexico	Brazil
Nantes(FR)	0.08171	0.08945	0.08498	0.09303	10623	11628
Rotterdam(NL)	0.08839	0.09613	0.09193	0.09998	11491	12497

The general mathematical representation of the transport cost is through the multiplication of the intermediate product quantity to be transported $Q_{A\rightarrow B}$ that is a measurement in kg of material equivalent to the weight needed to produce one unit of the final product and the standard cost $\theta_k$from location A to B in \$/kgkm.

$$TUC_{i,f,m,r'}^{A\rightarrow B} = Q_{i,f,m,r'}^{A\rightarrow B} \times \theta^{A\rightarrow B}; A\ initial\ location\ and\ B\ final\ location \tag{4-35}$$

For the environmental impact the coefficient chances to the standard emission ψ_k from location A to B in kgCO$_2$eq/kgkm.

$$TUEI_{i,f,m,r'}^{A\rightarrow B} = Q_{i,f,m,r'}^{A\rightarrow B} \times \psi^{A\rightarrow B};\ A\ initial\ location\ and\ B\ final\ location \tag{4-36}$$

4.4.5 OBJECTIVE FUNCTIONS

In order to evaluate the performance of the supply chain network, different criteria are developed. Initially one needs to empirically or through an “objectives and preferences study” choose a set of criteria of interest, which reflect the economic and environmental performance of the SC. The model considers four possible objectives NPV, GWP, average VUC and I.

4.4.5.1 NPV AND INVESTMENT

One of the most widely used KPIs is the net present value (NPV) of a project. The advantage of this indicator is that it looks at the long-term plan taking into consideration the effect of time. Additionally, it considers the operational and the fixed capital cost within a single framework in contrast to single facets of a project such as Sales Revenue, Project Cost, among others KPIs. It is defined in its objective function form as follows

$$\max NPV = -I + \sum_{j=1}^{nj} \frac{(V_j - C_j - A_j) * (1-\alpha) + A_j}{(1+ir)^j} \tag{4-37}$$

Investment ***I*** is calculated by summing the equipment cost and multiplying by the *Lang factor* (f_L) for the type of production system

$$I = f_L \sum_{f} InvCost_f \tag{4-38}$$

Sales revenue (V_j) in a period is the product of sales price by the demand and satisfies:

$$V_j = \sum_{i}\sum_{f}\sum_{m}\sum_{r\prime} SP_{i,f,m,r\prime} \times D_{i,f,m,r\prime} \;\; ; \forall i,f,m,r',\mathrm{j} \tag{4-39}$$

The sales price (SP) is calculated in function of the variable unit cost $VUC_{i,f,m,r\prime}$, a sales margin M_i . Price setting strategies are evaluated in detail in Chapter 5.

$$SP_{i,f,m} = VUC_{i,f,m,r\prime} * M_i;\ \forall i,f,m,r' \tag{4-40}$$

The Cost ***C*** is defined by sum of the products planned to be produced defined by the product of the demand coverage (***D***) for each product at each market by its unit Variable unit cost (***VUC***)

$$C_j = \sum_{i}\sum_{f}\sum_{m}\sum_{r\prime} VUC_{i,f,m,r\prime} \times D_{i,f,m,r\prime} \;\; ; \forall i,f,m,r' \tag{4-41}$$

The variable unit cost is defined by the sum of all the operational cost incurred to produce and deliver each final product to each market. In general it considers raw materials, processing and bottling costs, and transport variable costs for each product based on the type of product type and the market it is sent to (for the case study 80 VUCs are estimated in total: 2 labels (***i***) * 2 process routes (***f***) * 10 markets (***m***) * 2 regions (***r'***))

$$\begin{aligned} VUC_{i,f,m,r'} = \sum_{i}\sum_{f}\sum_{m}\sum_{r'} & RMOC_{i,f,m,r'}^{bottl} + TUC_{i,f,m,r'}^{r\to r'} + TUC_{i,f,m,r'}^{r'\to b} \\ & + TUC_{i,f,m,r'}^{b\to m} \;\; ; \forall i,f,m,r' \end{aligned} \tag{4-42}$$

The investment, previously defined, is used to estimate the amortization *A* by divining ***I*** by ***n*** periods of operation (i.e. strength line method).

$$A_j = \frac{I}{n} \tag{4-43}$$

For the case study, a time period n equal to 10 years, an interest rate of 12% and a tax rate α equal to 0.322 and $\mathrm{f_L} = 2.02$ for Orange Juice Concentration equipment (Saravacos and Maroulis, 2007) are considered.

4.4.5.2 GWP

Simultaneously environmental impact measurements are also developed for each optimization instance. The proposed approach takes into account the GWP indicator. It is defined as the sum of the environmental impact output per unit given the type of product and market to which it is transported to (i.e. each of the 20 market destinations demanding the 4 types of products, 80 unique ***UnitEnvImp***) times the number of product produced to cover each demands

$$\min \text{Global GWP} = \sum_{i}\sum_{f}\sum_{m}\sum_{r'} \text{UnitEnvImp}_{i,f,m,r'} \times \text{D}_{i,f,m,r'} \quad ; \ \forall i,f,m,r' \tag{4-44}$$

The environmental impact is calculated by aggregating the environmental impact at each stage in the production lifecycle per unit of product type *i* destined for market *m* standardized for one year of fixed production capacity. The production at orchard is aggregated during the first steps in the processing plant stage, this is because normally the first stage of processing of food stuff is done to conserve and/or separate materials components, which is done near the raw food stuff supplier, to later be sent to stages further downstream, for example to a bottling or packaging plant. Unit environmental impact is thus the sum of measured impacts added in each stage and route needed to satisfy a specific market, it is defined as

$$\begin{aligned}\text{UnitEnvImp}_{i,f,m} &= \sum_{i}\sum_{m} \text{RMEI}^{\text{bottl}}_{i,f,m} + \text{TUEI}^{r\to r'}_{i,f,m,r'} + \text{TUEI}^{r'\to b}_{i,f,m,r'} \\ &+ \text{TUEI}^{b\to m}_{i,f,m,r'} \quad ; \ \forall i,f,m,r'\end{aligned} \tag{4-45}$$

4.4.5.3 AVERAGE VARIABLE UNIT COST

The sum of the product of each ***VUC*** times the quantity that is produced (***D***) for each type of product given ***i*** label, ***f*** fabrication steps and marketed to ***m*** in region ***r'*** divided by the sum of all the production output planned for all products to all markets gives the average variable cost.

$$A\text{VUC} = \frac{\sum_{i}\sum_{f}\sum_{m}\sum_{r'} \text{VUC}_{i,f,m,r'} \times \text{D}_{i,f,m,r'}}{\sum_{i}\sum_{f}\sum_{m}\sum_{r'} \text{D}_{i,f,m,r'}} ; \ \forall i,f,m,r' \tag{4-46}$$

4.5 MULTI-OBJECTIVE OPTIMIZATION

The problem formulation is based on a two-stage process: Multi-objective Optimization (MOO) and Multiple Criteria Decision Making (MCDM) process as illustrated in Figure 4-14. The development principle of each procedure was presented in detail in Chapter 2.

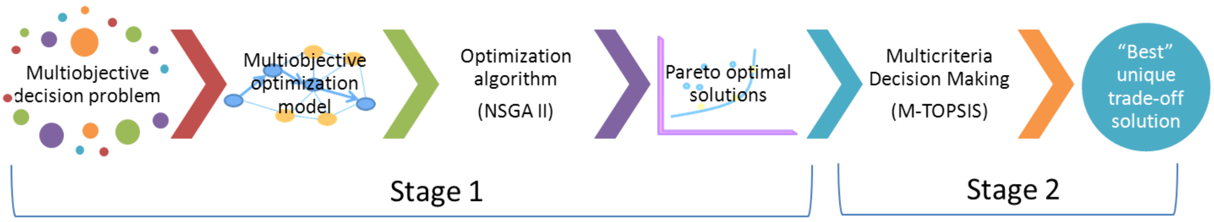


FIGURE 4-14 INTEGRATED MULTI-OBJECTIVE OPTIMIZATION AND MULTIPLE CRITERIA DECISION MAKING PROCESS

The former stage, MOO, can be solved through a limited number of techniques. The weighted sum method, utility method, lexicographic, epsilon-constraint (De-León Almaraz et al., 2013) are among the most cited MOO solving methods. A very interesting alternative is to use metaheuristic methods, in particular genetic algorithms (Cortez, 2014; Yang, 2008). These techniques allow to find feasible heuristic solutions, (Collette and Siarry, 2003; Cortez, 2014). For a monocriterion viewpoint, the main disadvantage is that when using these techniques there is no guarantee of finding solutions that are near the global optimal; the quality of the solution is generally dependent on the implementation, analysis and intuition of the modeler to overcome local optima. This trade-off strategy has yet proven to be valuable when modelling complex SCND problems (Miranda-Ackerman et al., 2014). Recent publications in the context of green chain design show a recurrent use of GA (Ahumada and Villalobos, 2009; Arkeman and Jong, 2010; Yeh and Chuang, 2011). The solving method used here is based a multi-objective genetic algorithm through the Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al., 2002). This algorithm is a population based stochastic search algorithm that produces Pareto non-dominated solutions. In contrast to other techniques such as weighted sum or lexicographic methods, that are *a priori* technique (i.e. a weight or order of the objectives as a matter of choice prior to the execution is needed), multi-objective GA referred as an *a posteriori* method produces a set of solutions (the so-called Pareto front) to choose from (Cortez, 2014), this is to say, without prior judgment or decision making. The NSGA-II is implemented through the so-called MULTIGEN library developed by (Gomez et al., 2010a) that allowed to perform evaluations, data analysis and visualization for the case study presented in Chapter 5.

4.6 MULTICRITERIA DECISION MAKING STRATEGY

The GA approach leads to a set of Pareto optimal (non-dominated) alternative solutions. These solutions represent SC network design configurations that produce equivalently good outcomes in terms of the multiple objectives. The aim of MCDM is to aid the decision-maker to select the best alternative. The objectives and preferences of the decision makers and stakeholders play a role in choosing the model structure and characteristics, but a non-bias and systematic approach should be taken when choosing the final solution alternative. This is especially important in multi-objective formulations, also known as, multicriteria decisions, because it is difficult to make judgments on complex higher dimensional solution alternatives. To aid the decision maker, there is a wide range of MCDM tools one can access. Methods such as ELECTRE, PROMETHEE, AHP, TOPSIS , thoroughly evaluated by (Zanakis et al., 1998), provide a systematic and dimension independent ranking framework to compare and order solutions based on multiple criteria.

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), according to (Eraslana, 2015; Kim et al., 1997) has advantages over the other main methods, mainly: 1) it provides a scalar value that accounts for best and worst alternatives concurrently; 2) a logical approach that represents the human choice process; 3) the performance measurements for all alternatives can be visualized on a polyhedron, at least for any two dimensions; 4) simple to implement algorithm. In addition we use the M-TOPSIS a modified version of the TOPSIS method outlined by (Ren et al., 2010). This method helps to overcoming some evaluation failures that occur in the original TOPSIS method such as top rank reversal (Eraslana, 2015; Zanakis et al., 1998).

The implementation of M-TOPSIS as an algorithm was coded through the Excel® environment. Because the GA output is given as Excel® worksheet tables, it was natural to couple the optimization output to the decisions analysis technique through this environment.

4.7 CONCLUSION

This modelling framework presented in this chapter has been developed to guide the modeler on the key issues that have to be incorporated for GSCN modelling, and provides examples on how to overcome situations that occur frequently in agrofood systems. The orange juice case study serves as an illustration case and the solution strategy is developed in detail in the next chapter. A set of scenarios are now explored to find the best solution strategy for the case study instance taking into account the various stakeholders of the supply chain.

Chapter 5 Solution strategy for Green Supply Chain Network Design problem: application to an integrated agrofood chain

Résumé

Ce chapitre présente la stratégie de résolution de la conception d'une chaîne logistique verte qui s'appuie sur les approches de modélisation énoncées dans le chapitre précédent. Il *est consacré au développement de stratégies d'optimisation, basées sur le modèle de conception de chaîne logistique, selon des scénarios différents qui reflètent les objectifs spécifiques des parties prenantes impliquéess. Trois stratégies d'optimisation principales sont proposées: (1) Un schéma séquentiel, impliquant une optimisation en deux étapes considérant d'abord le point de vue des clients ciblant le produit moins cher et le plus respectueux de l'environnement puis celui de l'entreprise visant rentabilité et performance environnementale; (2) Un schéma d'optimisation simultané, basé sur une optimisation intégrée où les objectifs des parties prenantes principales sont simultanément optimisés, pour trouver les chaînes logistiques qui produisent des produits respectueux de l'environnement et rentables; (3) un schéma d'optimisation basé sur la différenciation de produits de qui considère non seulement les objectifs des parties prenantes principales, mais aussi la valeur ajoutée d'écolabels biologiques (organiques) et le prix de vente des produits finis.*

Une analyse comparative des différentes stratégies est effectuée..

Abstract:

This chapter presents the solution strategy for GrSCND that binds to the modelling approaches laid out in the previous chapter. It is devoted to the development of optimization strategies, based on the supply chain design model, following different scenarios that reflect the specific targets of the interconnected stakeholders. Three main optimization strategies are proposed: (1) Sequential Optimization Scheme, involving a two-stage optimization process first reflecting customers' aims for cheaper and more environmentally friendly product, and then followed by company's aims related to profitability and environmental performance; *(2)* Concurrent Optimization Scheme, based on an integrated optimization where the objectives of the main stakeholders' are simultaneously optimized, in order to find SC networks that produce environmentally friendly and profitable products. *(3)* Differentiated-Product Optimization Scheme encompassing an integrated optimization approach that similarly considers not only the main stakeholders' objectives, but also the added value of *organic* eco-labels and the sales price of the final products.

A comparative analysis of the different pricing and objective function configurations through the three main strategy configurations.

Acronyms

AVUC	AVERAGE VARIABLE UNIT COST
DC	DISTRIBUTION CENTRE
FCOJ	FROM CONCENTRATE ORANGE JUICE
GrSCM	GREEN SUPPLY CHAIN MANAGEMENT
GSCND	GREEN SUPPLY CHAIN NETWORK DESIGN
GWP	GLOBAL WARMING POTENTIAL
HHP	HIGH HYDROSTATIC PRESSURE
INLP	INTEGER NONLINEAR PROGRAM
KEPI	KEY ENVIRONMENTAL PERFORMANCE INDICATORS
KPI	KEY PERFORMANCE INDICATORS
LCA	LIFE CYCLE ASSESSMENT
MINLP	MIXED INTEGER NONLINEAR PROGRAM
MS	MULTIPLE STRENGTH
NFCOJ	NOT FROM CONCENTRATE ORANGE JUICE
NLP	NONLINEAR PROGRAM
NPV	NET PRESENT VALUE
PEF	PULSE ELECTRIC FIELD
PfS	PARTNERSHIP FOR SUSTAINABILITY
SC	SUPPLY CHAIN
SCM	SUPPLY CHAIN MANAGEMENT
SCND	SUPPLY CHAIN NETWORK DESIGN
SP	SALES PRICE
SS	SINGLE STRENGTH
VUC	VARIABLE UNIT COST

5.1 INTRODUCTION

Chapter 4 was dedicated to the development of a framework in order to represent the different aspects of an agrofood Supply Chain (SC), taking into account the different perspectives and preferences of the principal stakeholders, mainly suppliers, focal company, customers and natural environment. Chapter 4 highlighted that the supply chain is not a chain of businesses with one-to-one, business-to-business relationships, but a network of multiple businesses and relationships. The Green Supply Chain Network Design (GrSCND) approach that was previously presented allows the modeler to use different techniques to formulate, experiment, evaluate and analyze the types of problems that are related to the supply chain issue. This chapter is devoted to the development of optimization strategies, based on the supply chain design model, following different scenarios that reflect the specific targets of the interconnected stakeholders. For this purpose, three main optimization strategies are proposed:

(1) Sequential Optimization Scheme, involving a two-stage optimization process first reflecting customers' aims for cheaper and more environmentally friendly product, and then followed by company's aims related to profitability and environmental performance using the breakeven point deduced from the first step.
(2) Concurrent Optimization Scheme, based on an integrated optimization where the objectives of the main stakeholders' are simultaneously optimized, in order to find SC networks that produce environmentally friendly and profitable products.
(3) Differentiated-Product Optimization Scheme encompassing an integrated optimization approach that similarly considers not only the main stakeholders' objectives, but also the added value of *organic* eco-labels and the sales price of the final products.

These alternative strategies are applied to the case study and compared to one another. The results are presented in terms of the Pareto front solutions produced by the GA. Additionally, a multiple criteria decision making (MCDM) technique, i.e., M-TOSPSIS is applied to find single trade-off solutions. All the optimization strategies that are proposed are carried out following the Life Cycle Optimization process that is introduced in Chapter 1 and illustrated in Figure 5-1: information of environmental performance is integrated into a multi-objective supply chain model as additional optimization criteria following the guidelines proposed in (Yue et al., 2014) and in (Ouattara et al., 2012). A final solution is then obtained by application of the MCDM technique.

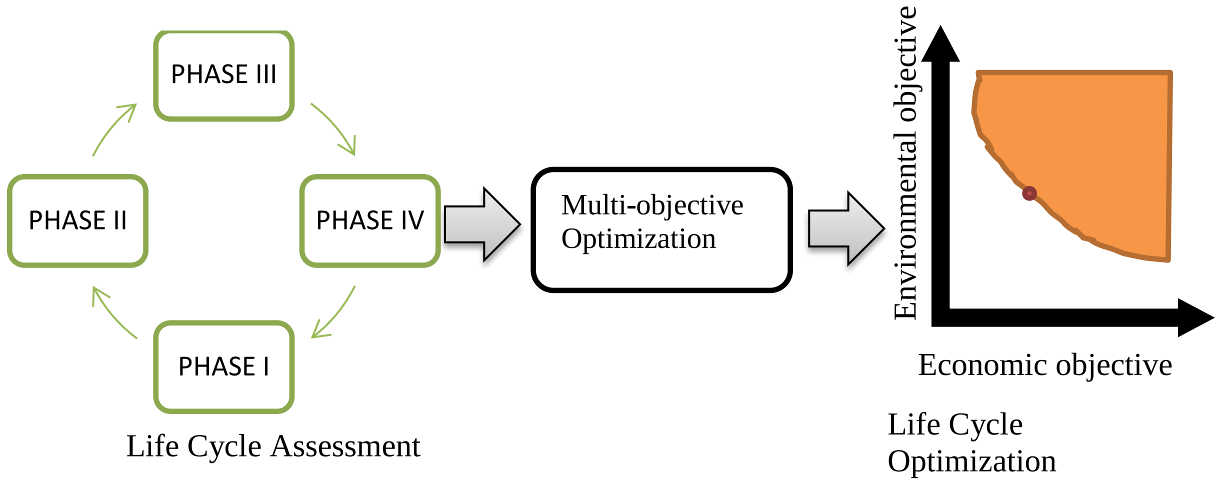


FIGURE 5-1 LIFE CYCLE OPTIMIZATION APPROACH ADAPTED FROM (YUE ET AL., 2014)

Thinking behind the agrofood GrSC network design paradigm

In Chapters 1 and 2, a theoretical framework presents the different approaches that GrSCM uses to frame and solve problems. The adaptation of these paradigms to the context of an agrofood chain is central, due to the increasing interest in higher quality foods. The *organic* eco-label becomes an attribute that defines this higher quality, and can be marketed respectively. Furthermore, food products have the special characteristic that eco-labels are mostly based on the way the raw materials used to make the product are obtained and also transformed. The GrSCM involves many different decisions in many different levels as nested choices, thus requiring an integrated and holistic approach that helps reflect reality in the decision making process of a large scale strategic project.

Furthermore, the Life Cycle Optimization process outlined in Chapter 1 is founded on the idea of adaptability. The solution approach, based on the coupling of Multi-objective Genetic Algorithms and Multicriteria Decision Making, is flexible enough to allow the modeler to evaluate different strategies based on the specification of the food system under consideration. This is possible due to the proposed solving techniques, mainly, Genetic Algorithms and Multicriteria Decision Making. This approach helps overcome many of the restrictions that limit other solution strategies. The choice of an evolutionary algorithm (EA) as a multi-objective optimization procedure is mainly influenced by the following items that make them preferable over classical optimization strategies:

- EAs have some advantages over traditional OR techniques. For example, considerations for convexity, concavity, and/or continuity of functions are not necessary in EAs;
- Their potential of finding multiple Pareto-optimal solutions in a single simulation run. This feature can be considered as greatly beneficial over deterministic procedures (see chapter 2 presenting the methods and tools used in this work)

- Nonlinear constraints and criteria can be tackled by such algorithms;
- They are known to be efficient to tackle combinatorial problems. In the supply chain design problem encountered in this work, integer variables are considered representing the decisional choices relative to the existence or absence of a node in the network as well as the operational variables of the supply chain.

The use of NSGA-II as the stochastic search algorithm was justified in Chapter 2. This algorithm, as detailed in section 2.2.3, requires a set of parameters. Table 5-1 summarizes the values used for these parameters. They are fixed based on both empirical trial-and-error experience and on the sensitivity analysis described in Chapter 2 (Dietz et al., 2006). The higher number of individuals in the population associated with a higher number of generations used for scenario 1 compared to that used for scenarios 2-6 (i.e. a double value) is used to overcome the difficulties encountered in stochastic search methods involving equality constraints. It must be highlighted that a relatively high value for mutation rate (i.e. 0.5) was adopted which can be considered inconsistent compared to what occurs in natural evolution. This phenomenon was already observed in mixed integer problems similar to the pure integer problem treated in this work (Dietz et al., 2006; Gomez et al., 2010a).

TABLE 5-1 : PARAMETER SET FOR MULTI-OBJECTIVE GA

	Scenario 1	Scenario 2-6
Population size	200	400
Number of generations	400	800
Cross-over rate	0.9	0.9
Mutation rate	0.5	0.5

At the final step of the strategy, the MCDM strategy then provides a way to find a solution in the diversity of the solution space represented by the Pareto front. It allows the decision maker to rank solutions with the flexibility to reflect different values and preferences among the best solutions that were identified by the optimization procedure. In this work, the M-TOPSIS method is used. It has a set of weight parameters that can be used to assign importance to each criterion. Unless explicitly mentioned, the same weight is allocated to each criterion. It must be yet highlighted that different values can also be used reflecting the preference of a stakeholder in real world decision-making environment.

Key elements concerning the case study

Before going further presenting the different optimization schemes, let us briefly recall the key elements of the case study presented in Chapter 4. It illustrates a globally distributed orange juice supply chain. The Focal Company that manages this chain needs to select a project to increase capacity. The potential market demand is assumed to be known. The main assumptions are the following ones:

1. Two potential raw material supplying regions are considered, i.e., Mexico and Brazil, to meet raw material requirements.
2. Only one region has to be selected, from which a set of suppliers are contracted in order to satisfy the capacity level as required by the demand and the quality of oranges.
3. The oranges will be processed at a plant located near the supplier. A selection of technologies and capacities has to be carried out to best satisfy market needs.
4. The final products are of four types, combining the label attribute (*organic* labeled[2] and conventionally labeled) and the processing attribute (from concentrate and not from concentrate).
5. The market target is composed of ten principal cities in two countries (France and Germany).
6. A set of 6 potential sites to locate a bottling/distribution site for each country is considered.

The parameter values used for this case study, which are presented in Chapter 4, are taken from relevant literature and adapted to this example.

5.2 SEQUENTIAL OPTIMIZATION SCHEME

Figure 5-2 illustrates the Sequential Optimization Scheme that consists of a two-stage solution strategy. In all the optimization runs, two or three criteria are optimized. In all the cases, the environmental component is always factored in through Global Warming Potential indicator optimization while the economic viewpoint varies targeting fixed capital cost and operational expenditures.

In the first stage, Scenario 1 (Sc1) uses a customer-centered optimization in order to find the best Average Variable Unit Cost (AVUC), while minimizing GWP. AVUC is defined as the cost to produce and deliver a product before adding profit (Sales Price is calculated based on AVUC). For this purpose, Net Present Value (NPV) is set to equal zero, this is to say, the Focal Company preference of profitability is neglected. Let us recall that NPV is a measurement of the difference between the present value of forecasted cash inflows and outflows of a project. It is used to analyze the

---

[2] Recalling that eco-label is used throughout the document as product that can hold the “organic” or “bio” certification labeling under the EU regulation on food and beverage labeling. (See Chapter 1section 1.3.1)

profitability of a project considering time. This baseline scenario (Sc1) is used to obtain an estimate of the Sales Price that will then be used in the second stage of the approach.

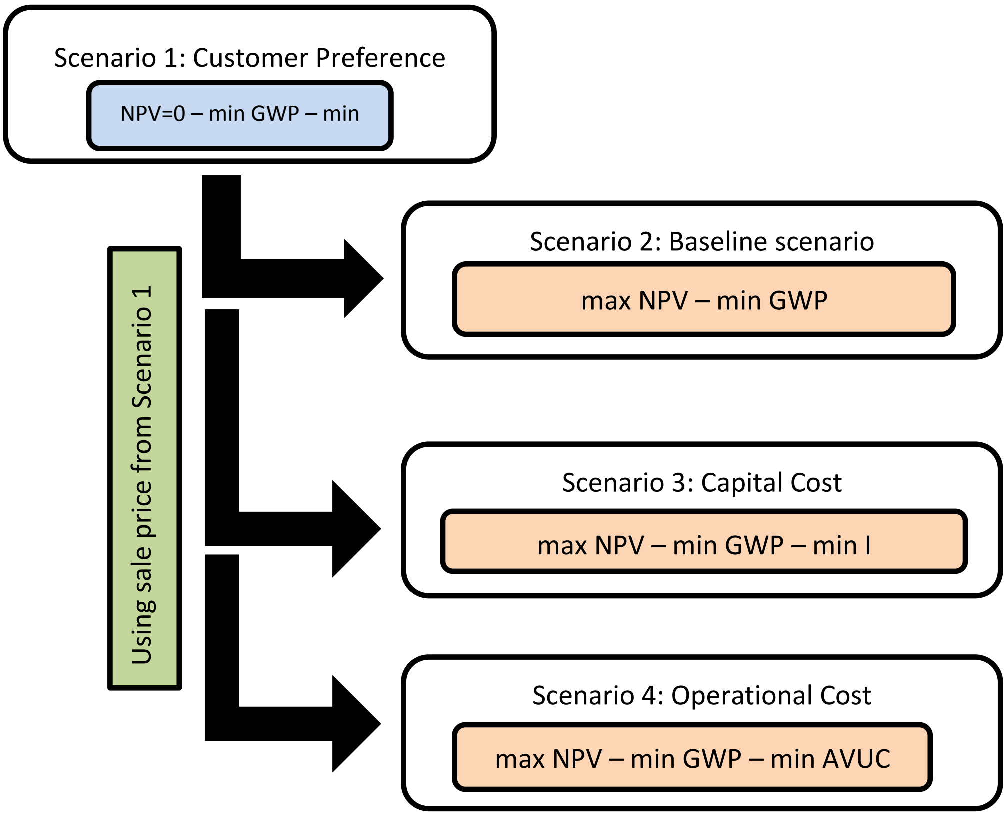


FIGURE 5-2 SEQUENTIAL OPTIMIZATION SCHEME

The second stage (Sc2 to Sc4) is based on a profit strategy reflecting the focal company's preference. The Sales Price (SP) of each product is defined by a profit margin over the Average Variable Unit Cost (AVUC) values found in Sc1: a value of 25% is considered in the simulation scenario for illustration purpose. It must be highlighted that the current gross profit margin reported in the business literature for orange juice is at 9-60% and depends on multiple factors (Neves et al., 2011). The 25% markup was selected as a representative average value to be used in the case study but could easily be modified without contradicting the essence of the analysis. In this second stage, the SP obtained in Sc1 is used as a fixed parameter that indirectly represents the customers' preferences. To reflect the company's preference as the other principal stakeholder, different indicators are evaluated. These strategies explore a combination of Key Performance Indicators from a business perspective.

5.2.1 SCENARIO 1: CUSTOMER-ORIENTED MODEL

Scenario 1 is formulated from the point of view of the customer. The objective is to minimize simultaneously GWP and CP, in order to reflect the consumer preference for environmentally sound and low cost products. For this purpose, CP is computed by constraining NPV to be equal to zero in order to find breakeven point. It serves two main objectives; the former consists to favor the customers prerogative before any other stakeholders', the latter gives a reference value for the price that can be competitive with market prices.

Figure 5-3 illustrates the layout and materials flows of the supply chain. The proposed legend will be used throughout the chapter. For this purpose, the symbols are presented in detail for their first occurrence in this manuscript so that the reader can be familiar with such representation.

Supplying regions:

The supplying regions, Mexico and Brazil, and their sets of suppliers are represented by two types of symbols, i.e. triangles and circles respectively. The triangle denotes the selection of the region if filled, a two-digit number denotes the technologies selected. The first digit refers to the pasteurization process and the second to the concentration process. Let us recall that each process can be carried out by a set of technologies (as characterized in Chapter 4 in Table 4-6), each technology can also be operated by different operational conditions, i.e. energy and water requirements, amounts of raw materials, thus leading to different output flows. In the example case, the Mexico region is selected. Technology 2 (PEF) for pasteurization and technology 1 (Multi-effect evaporator) for concentration process are selected at the initial processing site. In addition, a set of 4 suppliers producing by organic agro practice, 2 using quasi-organic and 2 with intensive agro practice (See Table 4-2 in Chapter 4) are selected to meet raw materials requirements. The circles symbolize the suppliers that can be selected. The circles are color coded (see code table in Figure 5-3), representing the type of agro practices assigned to selected suppliers.

Pie charts are then proposed to represent the nature of the raw materials that are exported from the supplier region to the customer region to be bottled. The upper two (i.e. NFC – DE and FC – DE) represent the amounts of raw materials that flow, from Mexico to Germany; the information is separated based on processing steps applied to the raw materials (i.e. non concentrated (NFC), concentrated (FC)) and the pie segments symbolize the raw materials used through the color code (see code table in Figure 5-3). In addition, reference values are provided for each slice of the pie in kilograms of raw material. In Scenario 1, conventionally produced raw materials in both concentered and non-concentrated forms are mainly sent to Germany (DE). The lower two pie charts on the left hand corner represent the flow from Mexico to France (FR). The flow of organic and conventionally sourced raw materials is mixed.

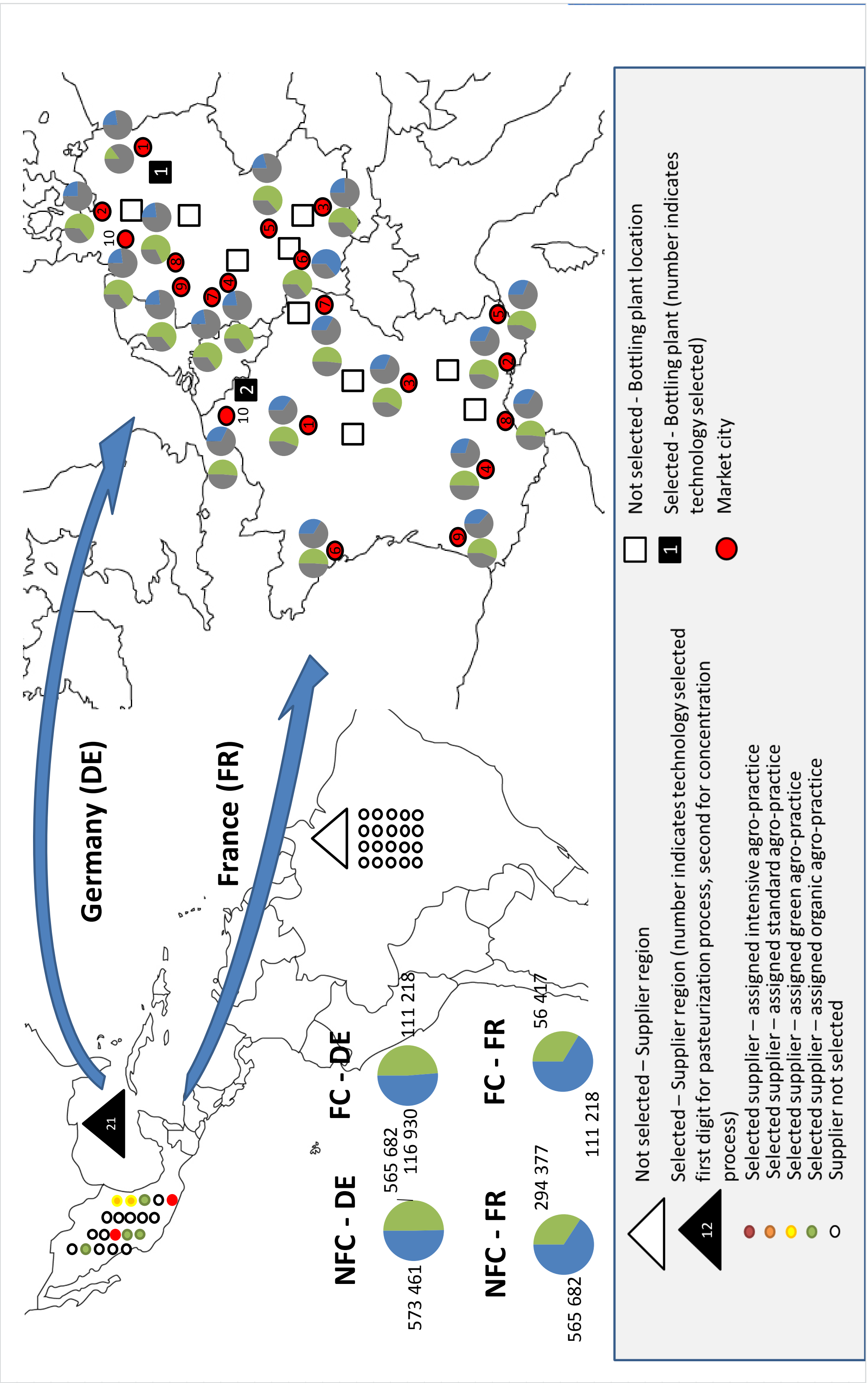


FIGURE 5-3 SCENARIO 1: SUPPLY CHAIN NETWOR DESIGN AND MATERIALS FLOW

Customer regions:

Concerning the market regions, France and Germany, four symbols are involved. The red circles indicate the location of a market city. Two pie charts are allocated for each city, i.e., green for organic label demand and blue for conventional product. Each pie symbolizes the fraction of the market that is covered with the optimized values for capacity and allocations of final product to market. The coverage is a little over half for *organic* products and roughly a third for conventional products in both countries. In addition, each country has six alternative locations for the bottling plant symbolized by the squares (see Figure 1 in Appendix A). Going back to Figure 5-3, the filled square is the selected bottling site location; it contains a digit representing the technology selected for the bottling process. In France, the bottling location is location 4 (St. Alban Auriolles) and technology 2 (glass bottle) is assigned. Germany bottling plant is also located in site 2 and technology 1 (PET bottle) is involved.

Table 5-2 presents some Key Performance Indicators and some Key Environmental Performance Indicators of interest.

TABLE 5-2 KPI AND KEPI SUMMARY FOR SCENARIO 1

NPV ($)	GWP (kgCO_2eq)	Average GWP/L (kgCO_2eq/L)	AVUC ($/L)	Investment ($)
0	2 011 882	0.6121	0.6490	2 174 893

Figure 5-4 presents a summary of the sales price values found through Sc1 that are used for Sc2 through Sc4. In addition a reference value is presented from an LCA case study developed by (Becceli et al. 2009). The reference values are lower because they do not include bottling and final transportation costs; but they do serve to validate that the behavior between NFC and FC for Sc1, i.e. FC being much more expensive than NFC, is consistent with the related literature.

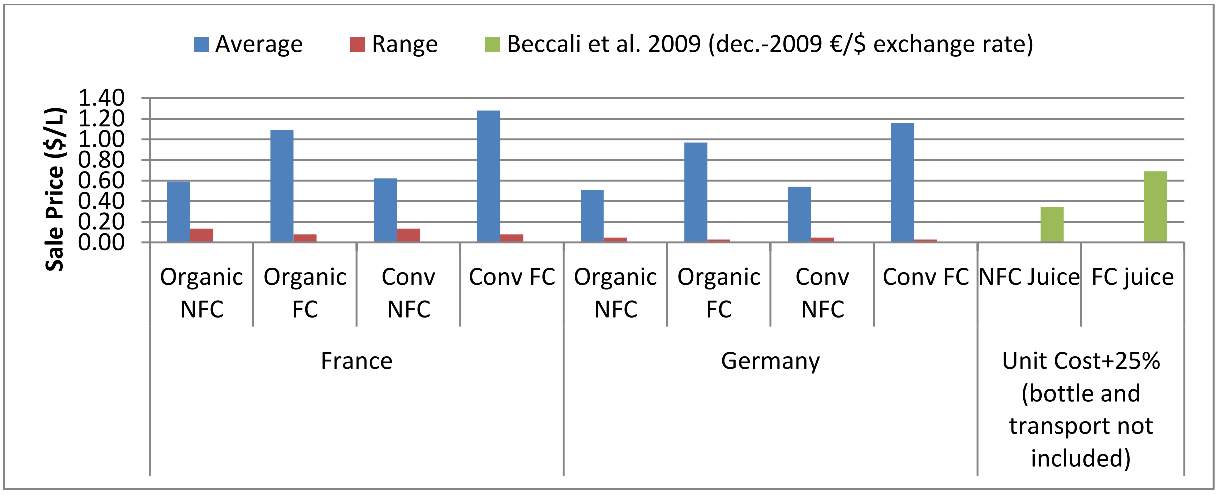


FIGURE 5-4 SCENARIO 1: SALES PRICE AVERAGE SUMMARY AND REFERENCE VALUE FROM (BECCELI ET AL. 2009)

5.2.2 SCENARIO 2: ENVIRONMENTALLY CONSCIOUS COMPANY PERSPECTIVE

Scenario 2 (Sc2) is formulated from the point of view of the environmentally friendly company. The objective functions are to maximize NPV and minimize GWP. This approach has been the most widely used strategy in the relevant literature and serves as a baseline model.

Sc2 uses a fixed sales price strategy (FSPS). In other words, the values for sales prices found in Sc1 optimization are used as fixed parameters in Sc2. The objective of this approach is to evaluate the effectiveness of integrating the competing preferences of the main stakeholders, mainly the consumer and the company. A secondary objective is to evaluate the antagonistic behavior resulting from the well-established NPV vs. GWP optimization approach with one centered on the consumer. The output of this optimization is a set of Pareto optimal solutions (see Figure 5-5 to Figure 5-7): the green triangle represents the unique solution found in Sc1, while the blue dots represent the Pareto front made up by Sc2. The red square represents the top ranked solution by M-TOPSIS method for Sc2. These figures give the evolution range of each criterion and the potential gain that could be obtained for the system under study.

Figure 5-5 presents the Pareto front output for Sc2. It forms a curve with an inflection point in the higher NPV values. In this area the M-TOPSIS method locates the top ranked solution (red square). These solutions fall beneath Sc1 values. This is because Sc1 was limited to the (NPV=0) constraint limiting the solutions range, while Sc2 optimization process was not constrained to any NPV bound. Furthermore, by using the Sales Price from Sc1, Sc2 is forced to find solutions that are equal or better in terms of operational economic performance than that of Sc1 in order to maximize economic benefit.

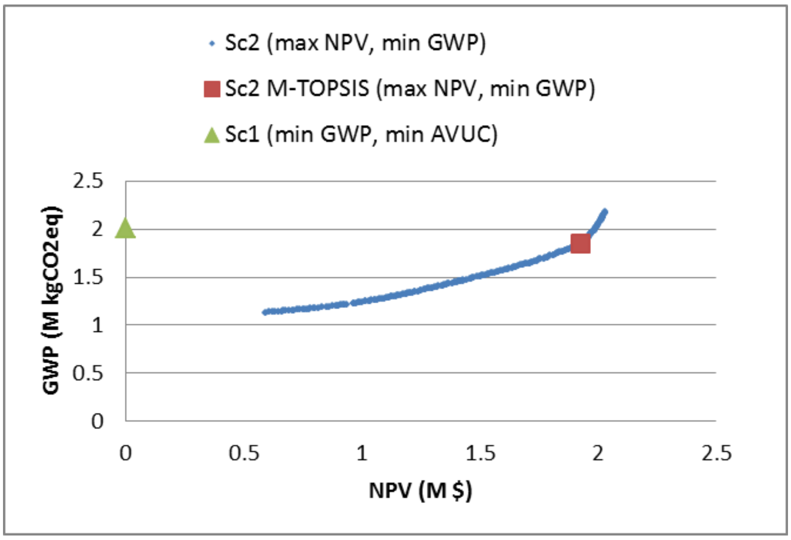


FIGURE 5-5 NPV AND GWP 2D PARETO FRONT OUTPUT FOR SC2 WITH M-TOPSIS SOLUTION AND SC1 SOLUTION

Figure 5-6 shows the Average Variable Unit Cost (AVUC) that was reached by the different optimal solutions found. Although AVUC is not explicitly optimized by an objective function, it is indirectly optimized because SP is a fixed parameter in Sc2. So, in order to optimize economic performance (i.e. NPV) the AVUC has to be minimized to have a larger profit margin. It must be noted that the improvement in performance compared to Sc1 in terms of AVUC can be explained by the equality constraint on NPV used in Sc1 that different from all other scenarios. The demand to be satisfied and capacity installed also changes between Sc1 and all other; this is in addition to the SP change.

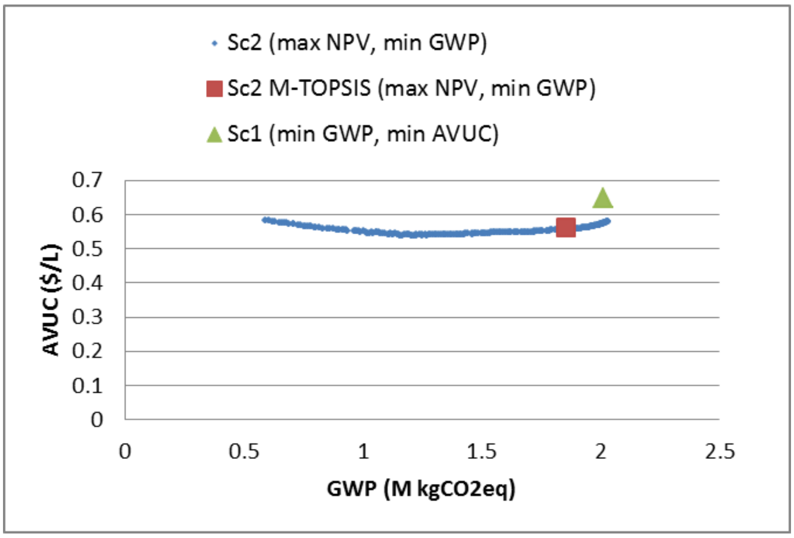


FIGURE 5-6 AVUC AND GWP 2D PARETO FRONT OUTPUT FOR SC2 WITH M-TOPSIS SOLUTION AND SC1 SOLUTION

Again, it must be highlighted that investment (see Figure 5-7) is not optimized in this scenario. This KPI is only presented as a reference value since it will be explicitly included in the set of criteria in the following scenario optimization.

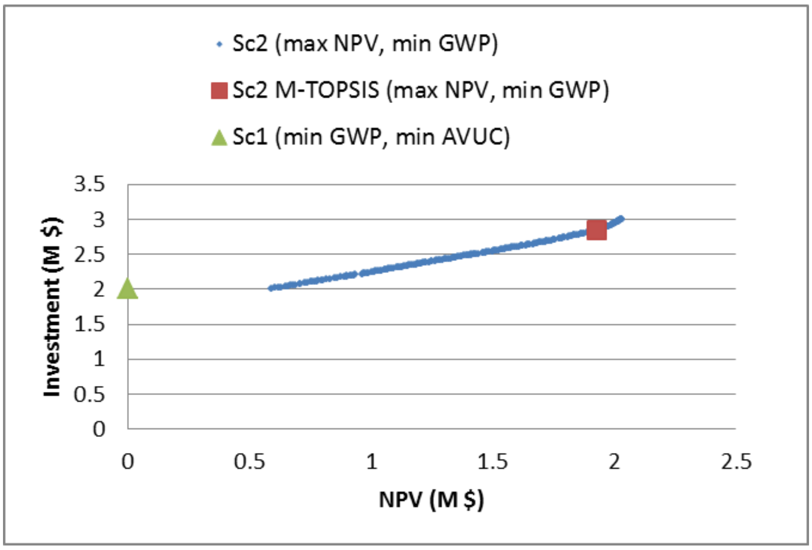


FIGURE 5-7 NPV AND I 2D PARETO FRONT OUTPUT FOR SC2 WITH M-TOPSIS SOLUTION AND SC1 SOLUTION

Figure 5-8 represents the supply chain corresponding to the top-ranked solution using the M-TOPSIS method of Scenario 2 optimization. Mexico is again selected, with a larger number of suppliers (6 organic and 2 quasi-organic production). The pasteurization uses now technology 2 (PEF), while concentration is carried out in technology 2 (Freeze). Two important observations can be made by looking at the proportions of *organic* and conventional for FCOJ and NFCOJ - shown in the lower left side pie charts. First, proportions are similar to those of Sc1 (see Figure 5-3). Second, the quantity has significantly increased, this is to say, that production and market demand coverage is much higher in Sc2, since one of the objective functions is to maximize economic benefit. Furthermore, the bottling plant locations have changed in Sc2 compared with Sc1 for France and Germany as well as the bottling technology used (i.e. PET). An explanation on what drives these changes is given in Section 5.5.

All these observations illustrate and highlight the significant differences between the two optimization scenarios. In order to insure that the Focal Company objectives are widely considered, other objective functions are now evaluated within the same Sequential Optimization Scheme. Scenario 3 incorporates investment as a third objective function, in order to favor project initiation while searching for more profitable alternatives. Scenario 4 targets operational costs by minimizing the Average Variable Unit Cost (AVUC) of final products.

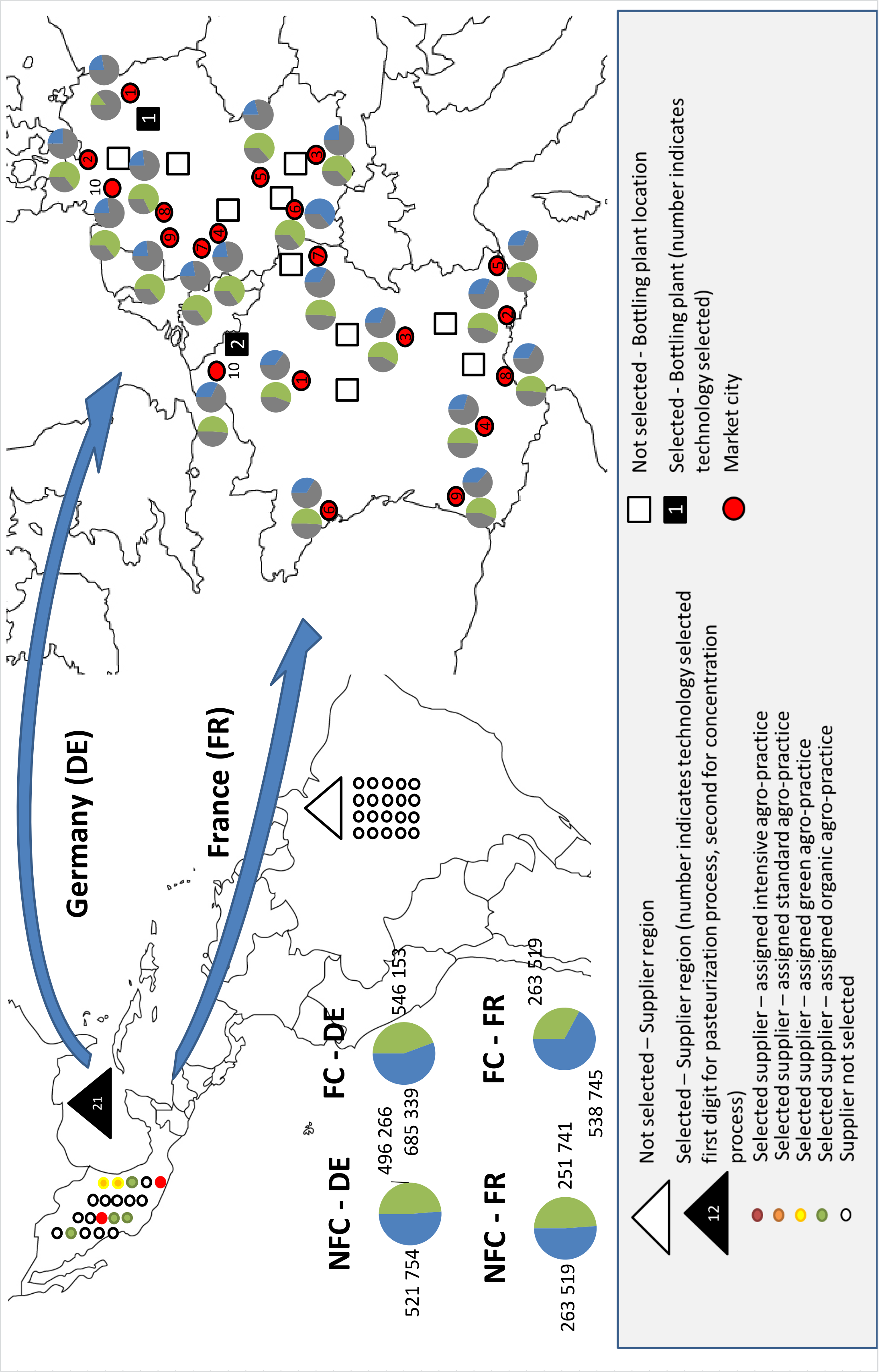


FIGURE 5-8 SCENARIO 2: SUPPLY CHAIN NETWORK DESIGN AND MATERIALS FLOW

5.2.3 SCENARIO 3: FOCAL COMPANY PERSPECTIVE WITH INVESTMENT CONSIDERATION

Scenario 3 (Sc3) is formulated considering the Investment cost (I) taken by the company to carry out the project. The objective functions are to maximize NPV while minimizing GWP and I. The investment, as defined in Chapter 4, is the total capital investment for each of the three main processing steps (pasteurization, concentration and bottling) multiplied by the corresponding *Lang factor* (Saravacos and Maroulis, 2007). The consideration of investment as an objective function gives an additional weight to economically performing SC network designs, favoring risk-aversion.

The output of Sc3 in terms of NPV and GWP is shown in Figure 5-9. The M-TOPSIS solution found in Sc2 as well as the set of Pareto optimal and M-TOPSIS solution for Sc3 are displayed. Compared to the results for Sc2 in Figure 5-5 that form a single curve, Figure 5-9 shows two curves that form the Pareto front, one in the lower NPV range of ~0.2 to 1.3 M$ and a second around 1.3 to 2.3M$ NPV. The M-TOPSIS solution falls in the latter region.

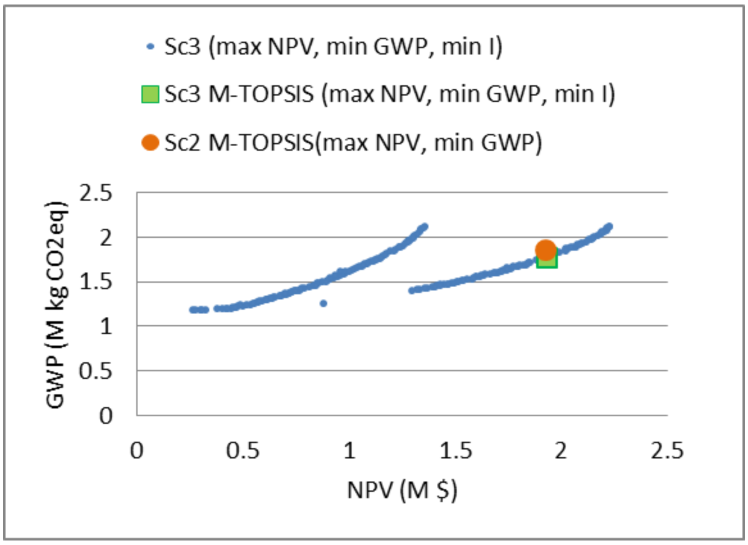


FIGURE 5-9 NPV AND GWP 2D PARETO FRONT OUTPUT FOR SC3 WITH M-TOPSIS SOLUTION AND SC2 M-TOPSIS SOLUTION

The formation of two groups of solutions is mainly due to one variable: concentration technology selection. Figure 5-10 shows the Pareto front output in terms of NPV and GWP per liter of orange juice colored by the technology selected. The red square represents the solutions that selected Multiple-effect evaporator concentration technology while the blue triangles are solutions involving freeze concentration technology. A strong relationship between the NPV and GWP/L values exists as exhibited by the Pareto front: solutions with multiple-effect evaporator technology have lower NPV solutions than those with freeze concentration technology. In terms of GWP/L they are roughly in the same range, given that they both have a similar energy consumption range based on the case study. And exhibit “U” shaped patterns reflecting the influence of Demand coverage variation.

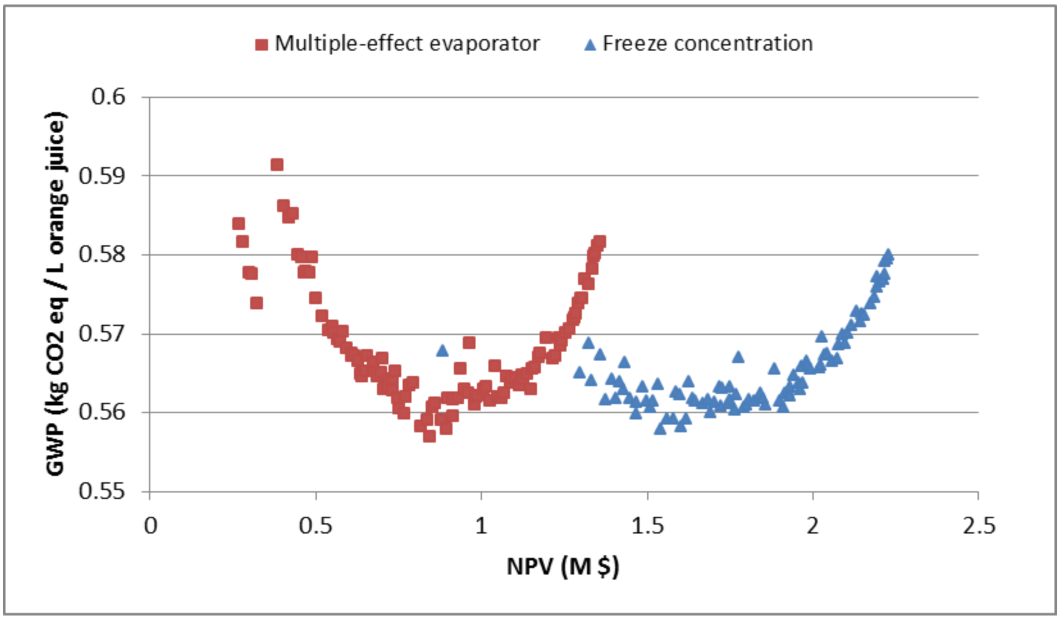


FIGURE 5-10 NPV AND GWP 2D PARETO FRONT OUTPUT FOR SC3 WITH CONCENTRATION TECHNOLOGY SELECTION VARIABLE

In terms of AVUC shown in Figure 5-11, a slight improvement can be observed in terms of M-TOPSIS top solutions. The top ranked M-TOPSIS solution is located in the same vicinity as that of Scenario 2 in terms of NPV, while it is lower (better) in terms of AVUC criterion. Furthermore, a similar pattern to that shown in Figure 5-10 where the concentration technology selected has an important influence on the outcome is seen. This is to say that AVUC has two main clusters of solution points. One cluster that ranges below ~1.3M $ NPV and the other above this threshold. This difference in outcomes is related to the capital and operational cost related to each concentration technology. This highlights the importance of the technology selection variable in terms of both criteria.

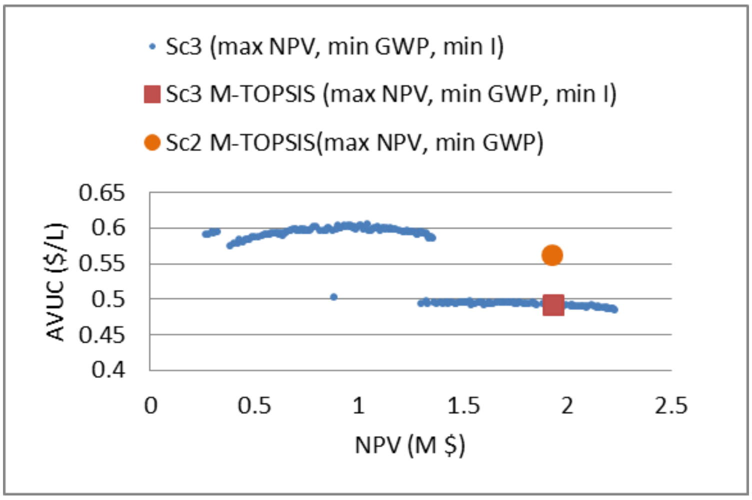


FIGURE 5-11 AVUC AND NPV 2D PARETO FRONT OUTPUT FOR SC3 WITH M-TOPSIS SOLUTION AND SC2 M-TOPSIS SOLUTION

The relation between NPV and Investment (see Figure 5-12) is roughly linear and similar to the trend already observed in Sc2. A computation of the internal rate of return (IRR) corresponding to each solution is also carried out. **Internal rate of return (IRR)** is the interest rate at which the net present value of all the cash flows (both positive and negative) from a project or investment equals zero. Internal rate of return is used to evaluate the attractiveness of a project or investment. If the IRR of a new project exceeds a company's required rate of return, that project is desirable. If IRR falls below the required rate of return, the project should be rejected.

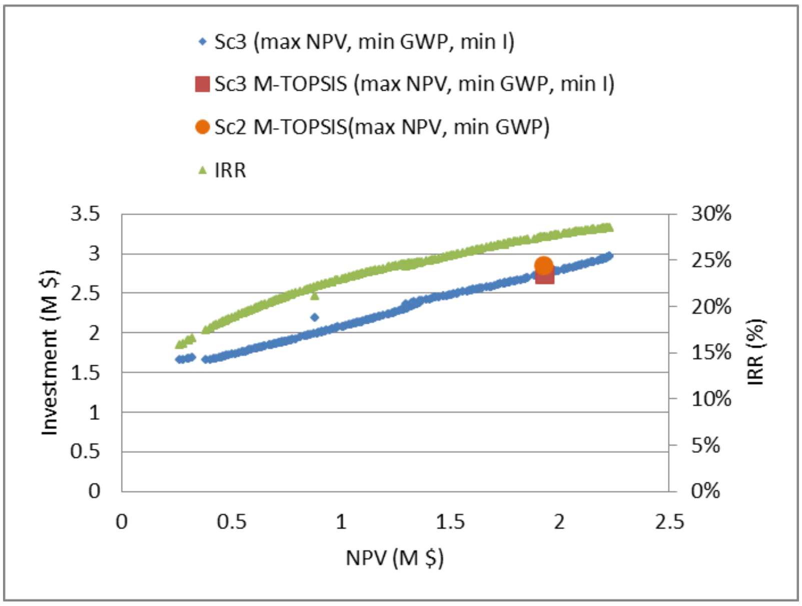


FIGURE 5-12 INVESTMENT AND NPV 2D PARETO FRONT OUTPUT FOR SC3 WITH M-TOPSIS SOLUTION AND SC2 M-TOPSIS SOLUTION

IRR is shown in Figure 5-12, it has a slight curvature but does not have a peak to aid the decision making process. It grows basically linearly while NPV grows. The IRR for the M-TOPSIS solution is roughly 27% which is above the industry standard that ranges from 20 to 25% (Brookes, 2007). Both optimization strategies (i.e. Sc2 and Sc3) produce solutions in the same search space, and the solutions proposed by the M-TOPSIS method are in the same vicinity. It is important to note that although Sc2 and Sc3 have similar outcomes, Sc3 is the best performing yet.

5.2.4 SCENARIO 4: FOCAL COMPANY PERSPECTIVE WITH VARIABLE UNIT COST CONSIDERATION

Scenario 4 (Sc4) takes a different approach to guaranty maximum performance for the focal company, by maximizing NPV and minimizing GWP and Variable Unit Cost (AVUC). Given that Sales Price (SP) is fixed based on the Sc1 values, minimizing AVUC helps insure that the solutions that are found during the optimization process are the best in terms of operational costs, improving profit. The output of this scenario is presented in Figure 5-13 to Figure 5-15.

Several comments can be made for each scatter plot. On the one hand, the solutions that are found (see Figure 5-13) including the M-TOPSIS solution (orange circle) are dominated in terms of NPV compared to the M-TOPSIS top ranked solutions found in scenarios 2 and 3 (purple and red squares respectively). The highest NVP is around 1.7 M$ while for Sc2 & Sc3 they are just below 2 M$.

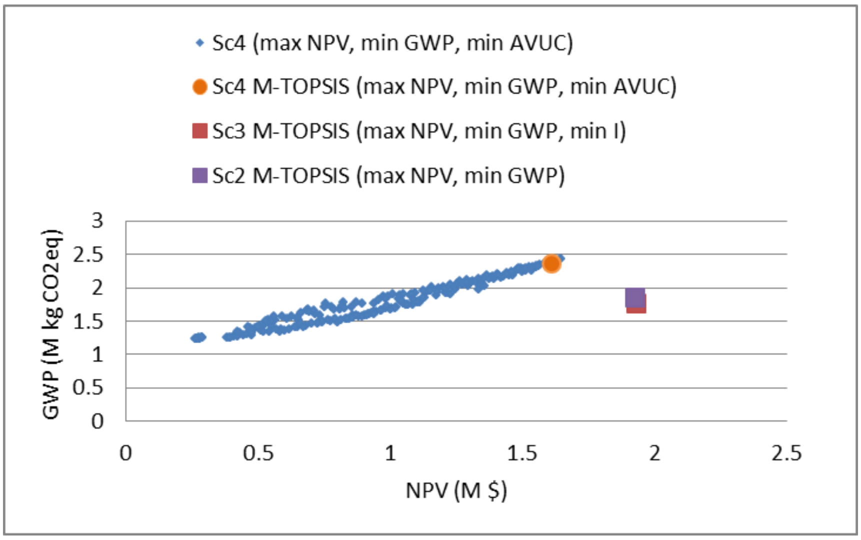


FIGURE 5-13 NPV AND GWP 2D PARETO FRONT OUTPUT FOR SC4 WITH M-TOPSIS SOLUTION AND SC2 AND SC3 M-TOPSIS SOLUTIONS

On the other hand, looking at Figure 5-14, AVUC has largely increased compared to Sc3, and the values reached are similar to those from Sc2. This is interesting because compared to that of Sc2 and Sc3 the values are far more dispersed, creating a wider set of solutions to choose from. The lowest value for AVUC is under 0.48$/L. But the M-TOPSIS solution in Sc4 (Orange circle) still falls short compared to the solution found in Sc3 (red square). This is to say Sc4 did not improve over Sc3.

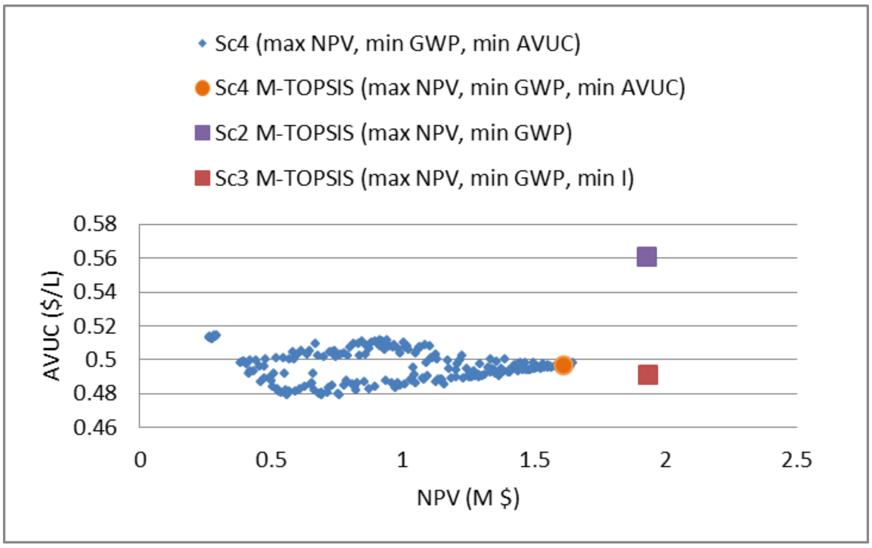


FIGURE 5-14 NPV AND AVUC 2D PARETO FRONT OUTPUT FOR SC4 WITH M-TOPSIS SOLUTION AND SC2 AND SC3 M-TOPSIS SOLUTIONS

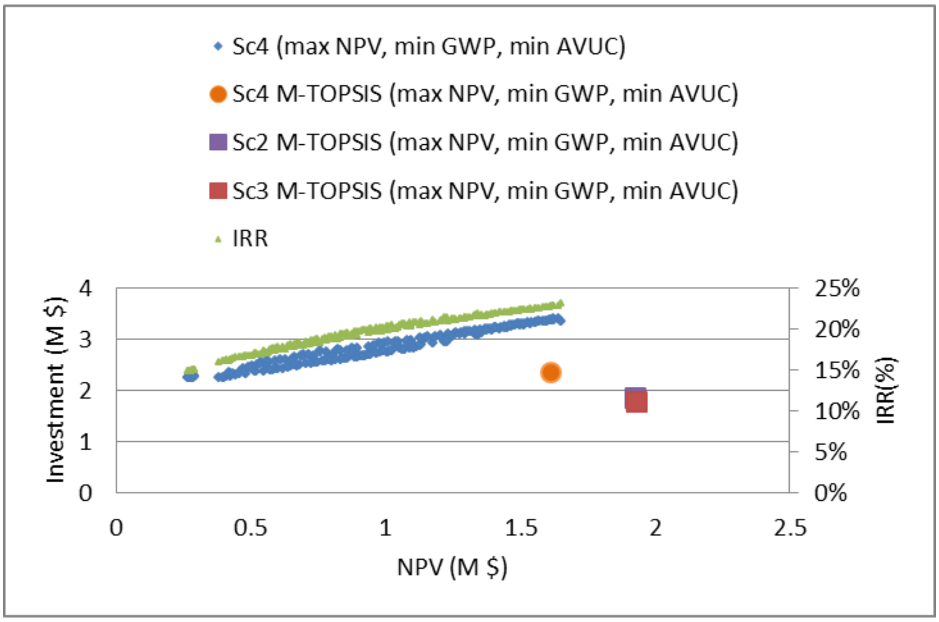


FIGURE 5-15 NPV AND I 2D PARETO FRONT OUTPUT FOR SC4 WITH M-TOPSIS SOLUTION AND SC2 AND SC3 M-TOPSIS SOLUTIONS

Figure 5-16 presents a summary of the different scenarios evaluated under the Fixed Price Strategy (FPS) to the GSCND problem - illustrating the four objectives that were evaluated. Overall, these cases support the view that: 1) even with the restrictive Fixed Pricing Strategy (FPS) - in all cases profitable project alternatives are found i.e. positive NPV values and IRR values above 15% for all scenarios. 2) The different scenarios provide insight on the sensitivity of the model to different objective function definitions under the FPS. 3) The best performing strategies are Sc2 and Sc3. Sc2 provides the lowest GWP value for the M-TOPSIS solution at 1.85 M kgCO_2eq outperforming Sc3 by a very low margin (Sc3 has a GWP of 1.96 M kgCO_2eq). Both scenarios exhibit very similar values for NPV with 1.92M$ and 2.14M$ for Sc2 and Sc3 respectively (Sc3 holding a slight edge). The decision to select an optimization strategy is not easy to make. A simultaneous or concurrent optimization approach is then carried out to see if it produces better outcomes.

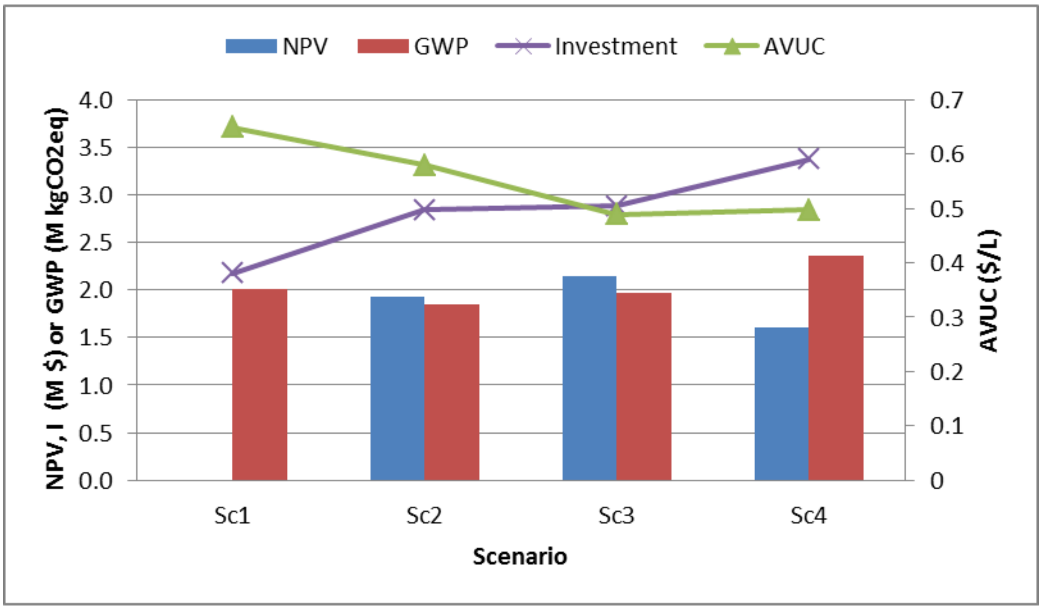


FIGURE 5-16 SEQUENTIAL OPTIMIZATION SCHEME: M-TOPSIS TOP RANKED SOLUTIONS OUTCOME SUMMARY

Table 5-3 is a summary of the different scenarios evaluated under the Sequential Optimization Scheme; it is presented in order to simplify referencing these outcomes when evaluating the two other optimization schemes going forward.

TABLE 5-3 SUMMARY OF THE RESULTS FOR SCENARIOS 1 TO 4

Scenario	Model	Description & Key results
Scenario 1 (Sc1)	$\min GWP\ \ x,y\ \ ,AVUC(x,y)$ $s.t.\ g\ \ x,y,z\ \ \le b_i$ $NPV\ \ x,y,z\ \ = 0$ $y\ \in\ \ 0,1\ \ ^m, x \in \mathbb{Z}^n, z \in \mathbb{R}$ $SalesPrice_i = VUC_i *\ \ 1 * Margin\ \ , \forall i \in I$ $where\ Margin = 25\%$	Fixing NPV to zero to find minimum Variable Unit Cost at lowest GWP output in order to reflect the customers' preference; also used to estimate a base Sales Price to be used in other Scenarios.
Scenario 2 (Sc2)	$\min -NPV\ \ x,y\ \ ,GWP(x,y)$ $s.t.\ g_i\ \ x,y\ \ \le b_i$ $y\ \in\ \ 0,1\ \ ^m, x \in \mathbb{Z}^n$ $SalesPrice_i(from\ Scenario\ 1)$	Integrating fixed Sales Price for all products to the value found in Scenario 1 while maximizing NPV and minimizing global GWP. Used as a baseline model.
Scenario 3 (Sc3)	$\min -NPV\ \ x,y\ \ ,GWP\ \ x,y\ \ ,I(x,y)$ $s.t.\ g_i\ \ x,y\ \ \le b_i$ $y\ \in\ \ 0,1\ \ ^m, x \in \mathbb{Z}^n$ $SalesPrice_i(from\ Scenario\ 1)$	Adding the Investment cost as a minimization objective function to consider a second economic criterion to favour project initiation phase. Sc 3 produces the best trade-off results yet.
Scenario 4 (Sc4)	$\min -NPV\ \ x,y\ \ ,GWP\ \ \ x,y\ \ ,AVUC(x,y)$ $s.t.\ g_i\ \ x,y\ \ \le b_i$ $y\ \in\ \ 0,1\ \ ^m, x \in \mathbb{Z}^n$ $SalesPrice_i(from\ Scenario\ 1)$	Poor performing solutions compared to scenarios 2 and 3.

5.3 CONCURRENT OPTIMIZATION SCHEME

In this set of exploratory optimization scenarios, sales price is modeled as a variable that is dependent on the Variable Unit Cost of each product. In this strategy, the two-stage approach that was proposed in the previous scenario is integrated into a single stage, following the idea that a better trade-off solution could be achieved, because sales price is no longer a restrictive force but rather one that allows the model to reflect improved configurations and combinations, this is to say, alternatives that might not otherwise be evaluated in the optimization process will be assessed.

5.3.1 SCENARIO 5: VARIABLE SALES PRICE WITH INVESTMENT CONSIDERATION

Scenario 5 (Sc5) is formulated with the same objectives as scenario 3, i.e. max NPV, min GWP and Investment with a Variable Sales Price Strategy (VSPS). Sales Price is calculated by adding a 25% cost margin to the AVUC for each product type and market, 80 prices in total. The idea behind this strategy is to allow the search algorithm to find profitable and feasible solutions that were not considered given the fixed sales price restriction of prior scenarios, thus expecting a different set of outcomes. Figure 5-17 to Figure 5-19 show the Pareto front solution output in scatterplots. It is worth noting that all of the Pareto optimal solutions from this scenario, including the M-TOPSIS solution are well dominated in terms of all three objective functions by the results from Sc3. This strategy underperforms compared to Sc3 even though they include the same objective functions.

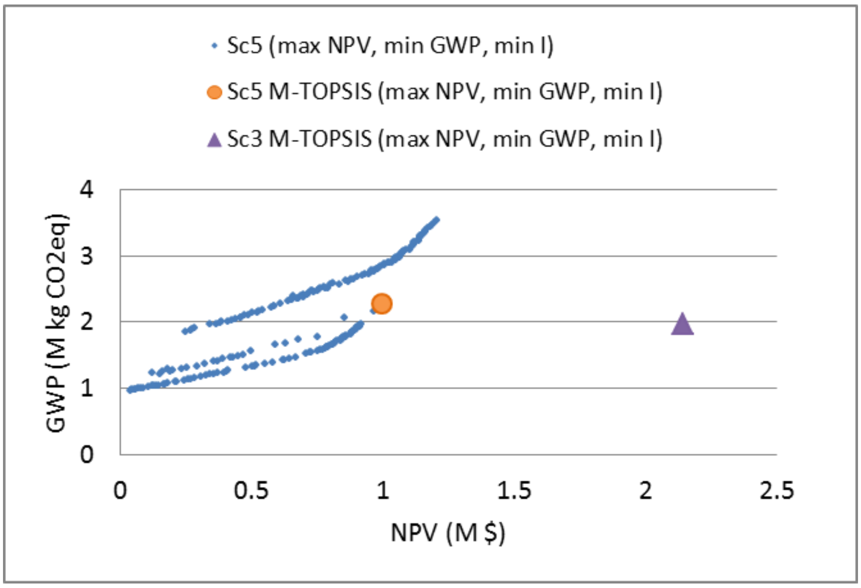


FIGURE 5-17 NPV AND GWP 2D PARETO FRONT OUTPUT FOR SC5 WITH M-TOPSIS SOLUTION AND SC3 M-TOPSIS SOLUTIONS

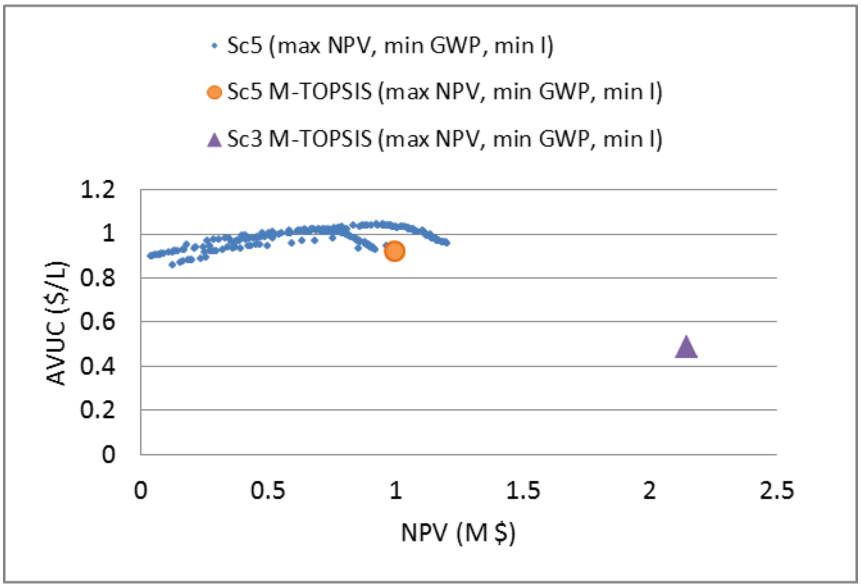


FIGURE 5-18 NPV AND AVUC 2-D PARETO FRONT OUTPUT FOR SC5 WITH M-TOPSIS SOLUTION AND SC3 M-TOPSIS SOLUTIONS

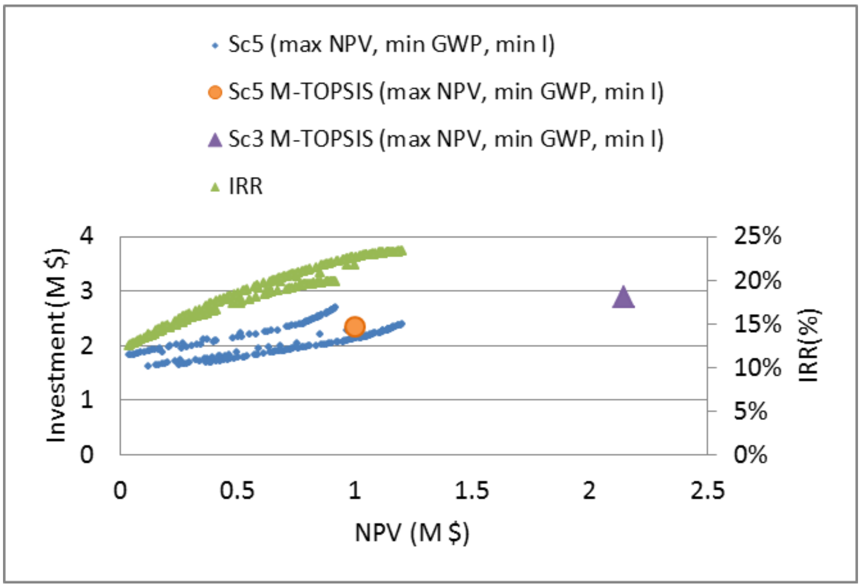


FIGURE 5-19 NPV AND I 2D PARETO FRONT OUTPUT FOR SC5 WITH M-TOPSIS SOLUTION AND SC3 M-TOPSIS SOLUTIONS

5.3.2 SCENARIO 6: VARIABLE SALES PRICE WITH VARIABLE UNIT COST CONSIDERATION

Scenario 6 (Sc6) is formulated with the same objectives as scenario 4 (but different from Sc5), i.e. maximize NPV, minimize GWP and average AVUC with a Variable Sales Price Strategy (VSPS). In the same way as for Sc5, Sales Price is calculated by adding a 25% cost margin to the AVUC for each product type and market. The idea behind this strategy is to improve the quality of solution space found through Sc5. Although one could expect a similar result than that found in Sc4 (poorer result than Sc3), it is important to thoroughly explore the possibility that the VSPS could produce a different result.

As previously, all the Pareto optimal solutions from this scenario configuration, including the M-TOPSIS solution are mostly dominated in terms of NPV and AVUC objective functions, compared to Scenarios 3 and 4., while performing equally well in absolute terms measuring GWP. Although Investment was not explicitly optimized as an objective function, the performance of this KPI was good, as for scenario 5.

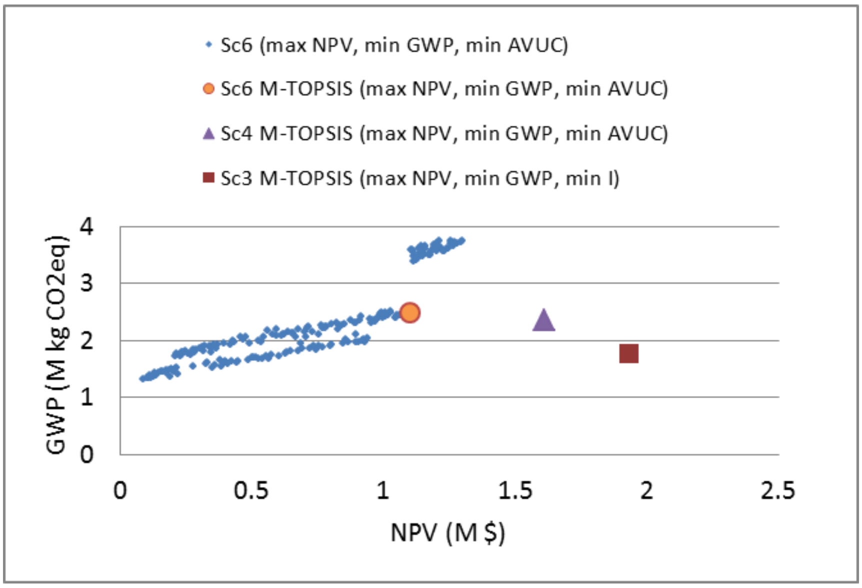


FIGURE 5-20 NPV AND GWP 2D PARETO FRONT OUTPUT FOR SC6 WITH M-TOPSIS SOLUTION AND SC3 AND SC4 M-TOPSIS SOLUTIONS

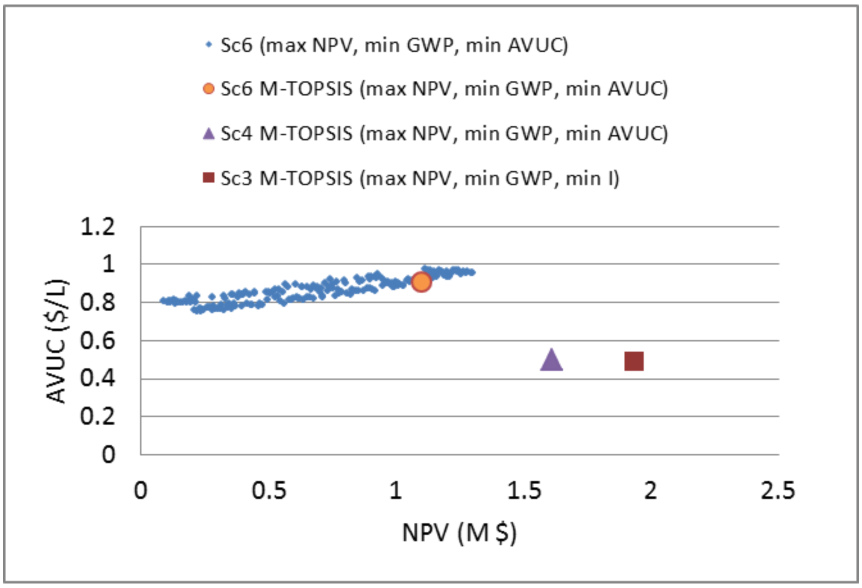


FIGURE 5-21 NPV AN D AVUC 2D PARETO FRONT OUTPUT FOR SC6 WITH M-TOPSIS SOLUTION AND SC3 AND SC4 M-TOPSIS SOLUTIONS

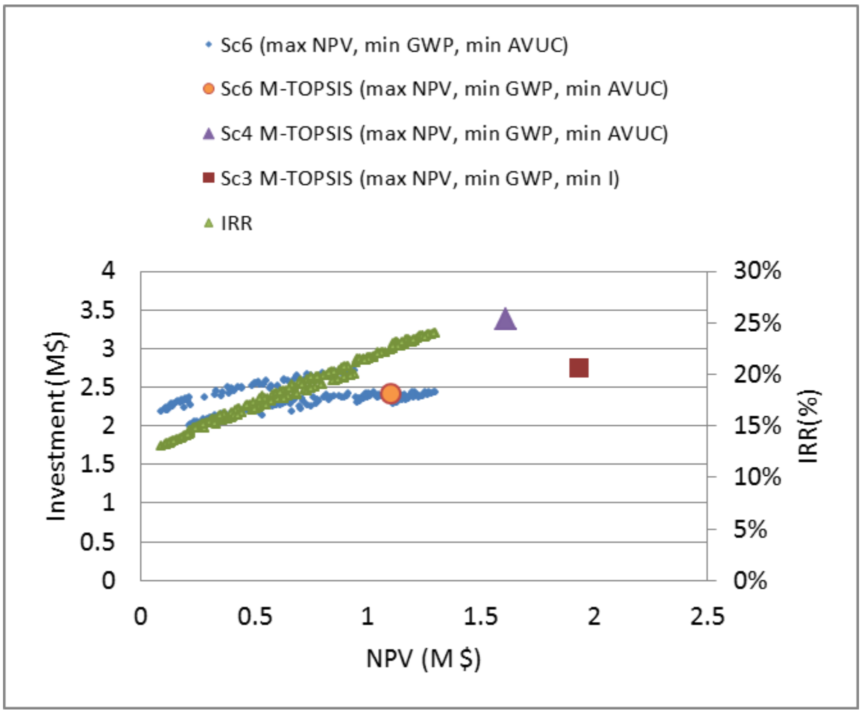


FIGURE 5-22 NPV AND I 2D PARETO FRONT OUTPUT FOR SC6 WITH M-TOPSIS SOLUTION AND SC3 AND SC4 M-TOPSIS SOLUTIONS

This result was unexpected given that the intuition was that by freeing the SP a wider range of configurations that have lower AVUC values could have been found. It is interesting to see that because SP is dependent on the AVUC - the search algorithm has difficulty to find solutions that are more profitable, i.e. higher NPV values. Furthermore, the search space was much more limited, solutions being less dispersed than other scenarios. The main observation from this alternative approach is that, by freeing the Sales Price and deducing it from the Variable Unit Cost, a very different behavior and optimization search space is found (compared to Sequential Optimization results). Furthermore, the values obtained are dominated by those found when using the Fixed Sales Price approach. Table 5-4 is a summary of the results of the Concurrent Optimization Scheme.

TABLE 5-4 SCENARIO 5 & 6 SCENARIO SUMMERY

Scenario	Model	Description & Key results
Scenario 5	$\min -NPV\ x,y\ ,GWP\ x,y\ ,I\ x,y\ \ ;$ $s.t.\ g_i\ x,y\ \le b_i;\ y\ \in\ 0,1\ ^m, x \in \mathbb{Z}^n$ $SalesPrice_i = CostPrice\ _i$ $*\ \ 1 + Margin\ ,\forall i \in I$ $where\ Margin = 25\%$	The objective functions used is the same as for Scenario 3. Sales Price is a variable dependent on the AVUC for each product, with a 25% sale margin. The outcome was poor, compared to the solution found using the Sequential Optimization Scheme.
Scenario 6	$\min -NPV\ x,y\ ,GWP\ x,y\ ,CP\ x,y\ \ ;$ $s.t.\ g_i\ x,y\ \le b_i;\ y\ \in\ 0,1\ ^m, x \in \mathbb{Z}^n$ $SalesPrice_i = CostPrice\ _i$ $*\ \ 1 + Margin\ ,\forall i \in I$ $where\ Margin = 25\%$	The objective functions evaluated are the same as in Scenario 4. The same variable sales price policy used for Scenario 5 is used. No improvement from Scenario 5 was achieved.

5.4 DIFFERENTIATED-PRODUCT OPTIMIZATION SCHEME

Scenarios 7 and 8 focus on a differentiated pricing policy based on *organic* eco-label quality attribute. This strategy consists of assigning a 50% sale margin for eco-labeled (i.e. *organically certified*) products and a 25% sales margin for conventional (illustrated in Figure 5-23). The idea is to reflect consumer willingness to pay a 25% premium for higher quality *organic* product (Rousseau and Vranken, 2013). This premium payment acts as a force that counteracts some of the extra cost that maybe related to greener supply chain network designs. This optimization strategy attempts to mimic real market pricing strategies. It reflects a more optimistic formulation of the acceptance of the product despite higher SP values.

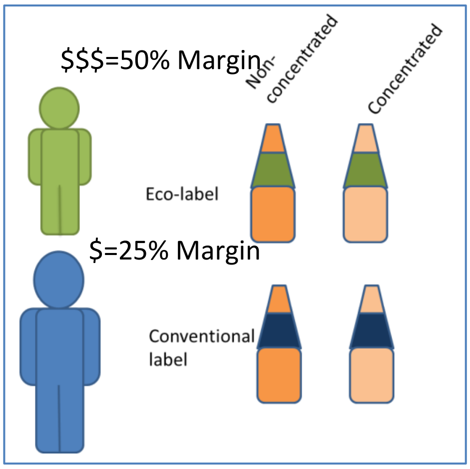


FIGURE 5-23 ILLUSTRATION OF CONSUMER DIFFERENTIATED BY PRODUCT PREFERENCE

5.4.1 SCENARIO 7: LABEL BASED SALES PRICE WITH INVESTMENT CONSIDERATIONS

Scenario 7 integrates the same three objective functions used in Scenarios 3 and 5 (i.e. NPV, GWP and Investment) with the important difference of Sales Price based on *organic certification*. It is formulated this way under the assumption that NPV will improve or remain constant while more eco-friendly products are produced. The price premium for the *organic* products is expected to overcome the poor outcome found under Sc5 and Sc6, shifting the solution space towards more profitable solutions that are congruent with the 25% premium.

Figure 5-24 to Figure 5-26 present the results obtained, i.e., Pareto optimal solutions and the corresponding M-TOPSIS solution from this optimization strategy. Additionally it includes the M-TOPSIS solutions for scenarios 3 and 5 that have the same objective functions but have different pricing policies. Figure 5-24 shows how the solutions found in this scenario are very different from those found in Sc5.

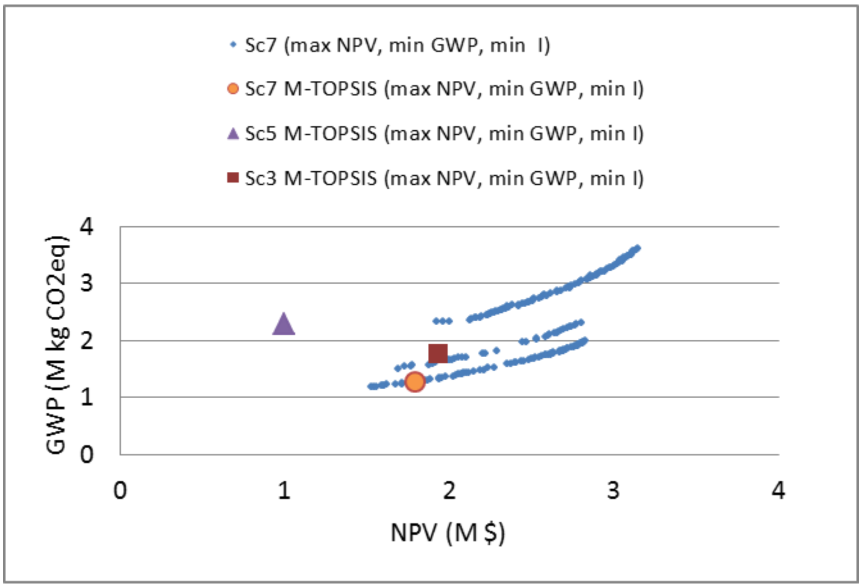


FIGURE 5-24 NPV AND GWP 2-D PARETO FRONT OUTPUT FOR SC7 WITH M-TOPSIS SOLUTION AND SC3 AND SC5 M-TOPSIS SOLUTIONS

In Figure 5-17 for Sc5, the range for NPV values of the Pareto optimal solutions found is between ~0.2 to 1.2 M$, while for this scenario (Sc7) lies much higher at roughly between 1.5 to over 3 M$ (see Figure 5-25). This is not explained solely by adding the 25% premium to the *organic* product to solutions in Sc5. This is rather a reflection of the sensitivity of model and optimization process to a combination of factors mainly criteria and pricing policies. But it is clear that there is an increase in AVUC compared to Sc3 and Sc5 M-TOPSIS solutions in order to find this higher NPV value solutions.

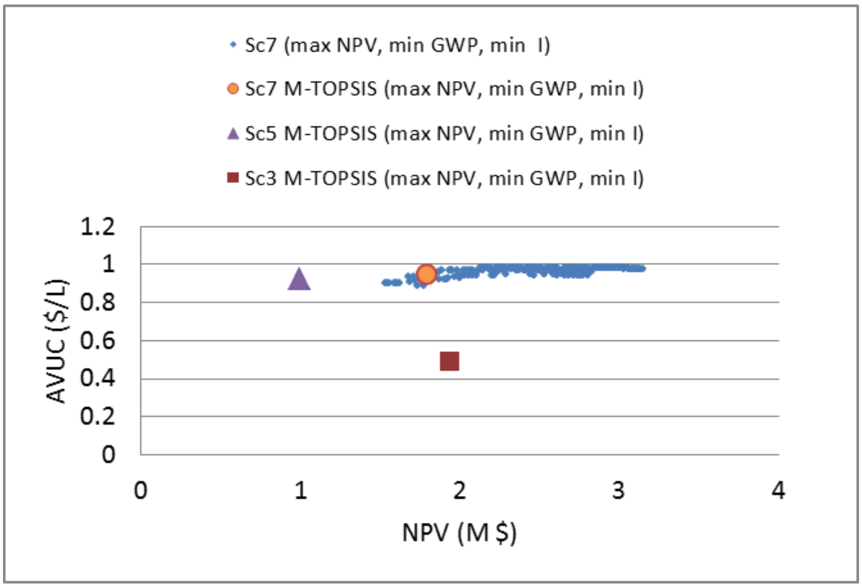


FIGURE 5-25 NPV AND AVUC 2-D PARETO FRONT OUTPUT FOR SC7 WITH M-TOPSIS SOLUTION AND SC3 AND SC5 M-TOPSIS SOLUTIONS

This poor AVUC performance is partially compensated by the good performance in minimizing the Investment cost and high return on investments shown in Figure 5-26. Scenario 8 is then formulated in order to overcome the deficiency of Sc7, in order to find solutions with better AVUC values.

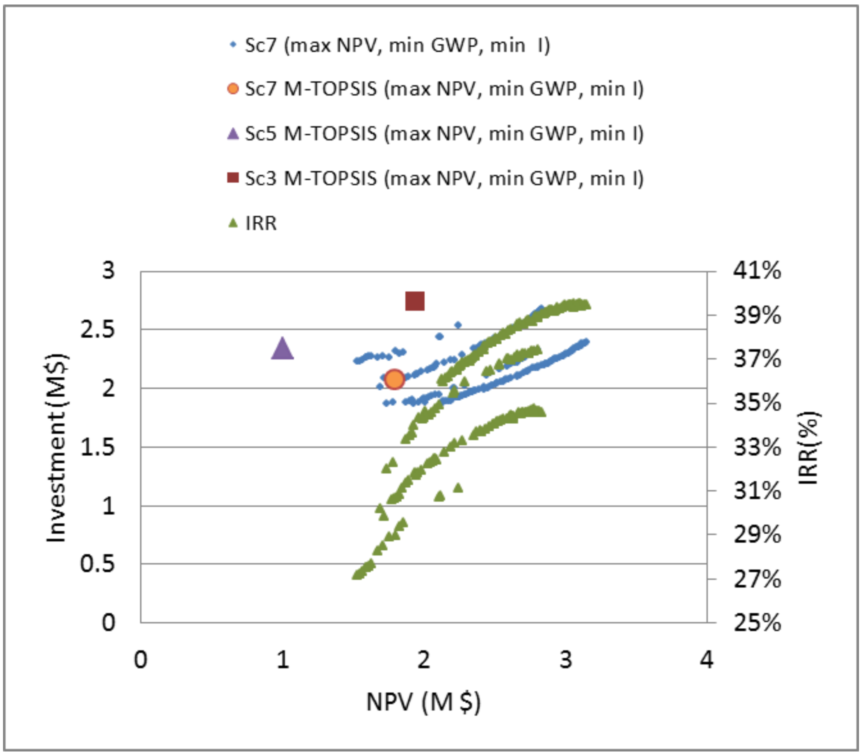


FIGURE 5-26 NPV AND I 2D PARETO FRONT OUTPUT FOR SC7 WITH M-TOPSIS SOLUTION AND SC3 AND SC5 M-TOPSIS SOLUTIONS

5.4.2 SCENARIO 8: LABEL BASED SALES PRICE WITH VARIABLE UNIT COST CONSIDERATIONS

Scenario 8 is formulated using the same objective functions that Scenario 4 and 6 use (i.e. NPV, GWP and AVUC) under the assumption that similarly good solutions in relation to NPV can be found with lower AVUCs than those of Sc7. Figure 5-27 shows the output of the optimization process. The M-TOPSIS solutions for Scenarios 4 and 6 are also plotted. The Pareto front once more reaches NPV values of up to 2.7M$, similar to those found in the Sequential Optimization Scheme. The M-TOPSIS solution is very low in terms of GWP, outperforming Scenarios 4 and 6.

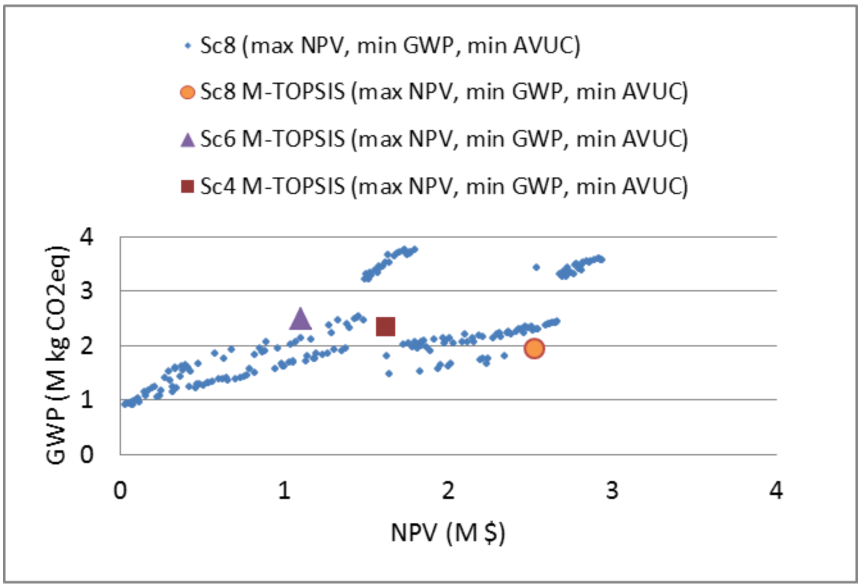


FIGURE 5-27 NPV AND GWP 2D PARETO FRONT OUTPUT FOR SC8 WITH M-TOPSIS SOLUTION AND SC4 AND SC6 M-TOPSIS SOLUTIONS

Although the AVUC was set as an objective functions AVUC value for the M-TOPSIS solutions is still high. Furthermore, Pareto optimal solutions do reach AVUC values under 0.6$/L, they are yet in the lower NPV value range.

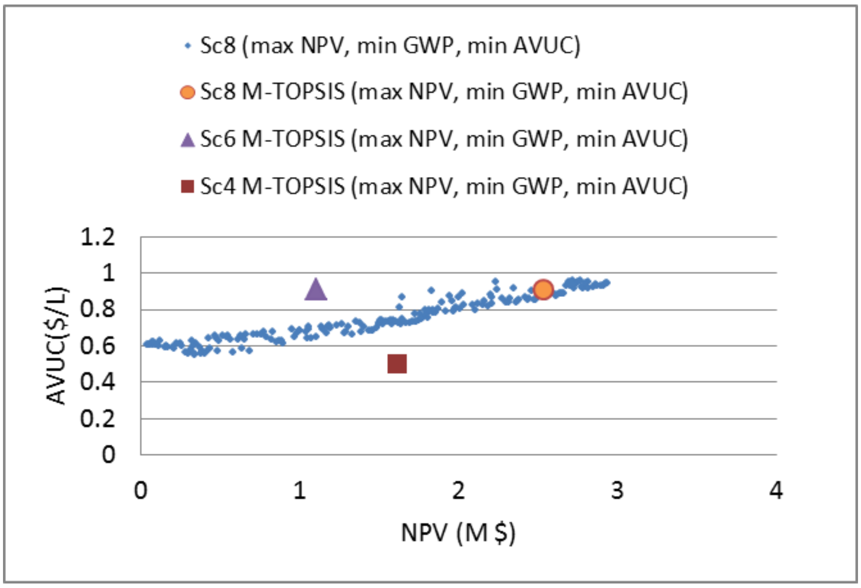


FIGURE 5-28 NPV AND AVUC 2D PARETO FRONT OUTPUT FOR SC8 WITH M-TOPSIS SOLUTION AND SC4 AND SC6 M-TOPSIS SOLUTIONS

Looking at Figure 5-29, most surprisingly, even while investment is not explicitly being optimized, the Investment values obtained outperformed Scenarios 4 and 6, reaching values that are similar to those found in Scenario 7 (in which investment is an optimization criterion).

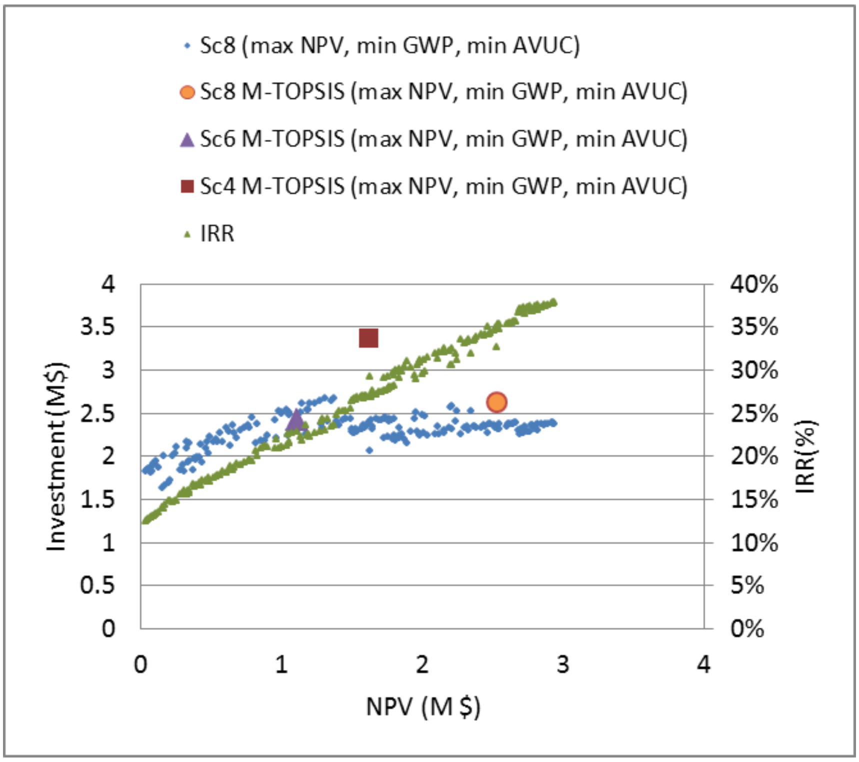


FIGURE 5-29 NPV AND I 2D PARETO FRONT OUTPUT FOR SC8 WITH M-TOPSIS SOLUTION AND SC4 AND SC6 M-TOPSIS SOLUTIONS

Table 5-5 presents a summary of the optimization strategy for scenarios 7 and 8 as well as the general model used and pricing strategy.

TABLE 5-5 DIFFERENTIATED-PRODUCT OPTIMIZATION SCHEME SCENARIO SUMMARY

Scenario	Model	Description & Key results
Scenario 7	$\min -NPV\ \ x,y\ \ ,GWP\ \ x,y\ \ ,I\ \ x,y\ \ \ ;$ $s.t.\ g_i\ \ x,y\ \ \leq b_i;\ \ y\ \in\ \ 0,1\ ^m, x \in \mathbb{Z}^n$ $SalesPrice_i = CostPrice\ _i *\ \ 1 + Margin_i\ \ , \forall i \in I$ $Margin_{i \in Conv} = 25\%\ and\ Margin_{i \in Eco} = 50\%$	Objective functions focus on investment. A sales price premium is attributed to *organic* products. NPV outcome is greatly improved, while AVUC reaches comparable values with Sc6.
Scenario 8	$\min -NPV\ \ x,y\ \ ,GWP\ \ x,y\ \ ,AVUC\ \ x,y\ \ \ ;$ $s.t.\ g_i\ \ x,y\ \ \leq b_i;\ \ y\ \in\ \ 0,1\ ^m, x \in \mathbb{Z}^n$ $SalesPrice_i = CostPrice\ _i *\ \ 1 + Margin_i\ \ , \forall i \in I$ $Margin_{i \in Conv} = 25\%\ and\ Margin_{i \in Eco} = 50\%$	Same pricing strategy as on Sc7. NPV and Investment perform similarly to Sc7. AVUC is not significantly improved unexpectedly.

5.5 RESULTS AND DISCUSSION

Aggregating the results obtained in each scenario gives a clearer understanding of the advantages and disadvantages of each strategy. The M-TOPSIS solution for each scenario is considered in Figure 5-30 where the values for the main objective functions, mainly NPV, GWP, AVUC and Investment are indicated. The left Y axis is used to measure the NPV (blue bar), GWP (red bar) and Investment (purple line with exes); the right Y axis is used to measure the average AVUC (green line with triangles). Looking only at the NPV bars, Sc8 is the best performing. The worst performing scenario in terms of NPV is Sc5. Looking only at GWP, Sc7 is the best performing, while Sc6 is the poorest. In terms of AVUC Sc3 followed closely by Sc4 is the best performing, while Sc7 is the worst. The main idea to take away from these observations is that the results are mixed and a clear trade-off solution is not evident. The most promising solution strategy is Sc3 that provides a compromise between all three criteria while finding the best AVUC values overall. A second important observation that can be made is that, even though the scenarios are performed under different conditions, there is a clear relation between the Investment cost and the Variable Unit Cost. Scenarios 2, 3 and 4 perform better in relation to AVUC, but have higher Investment costs; and the contrary is true for scenarios 5, 6, 7 and 8. These last four clearly have much higher AVUC costs.

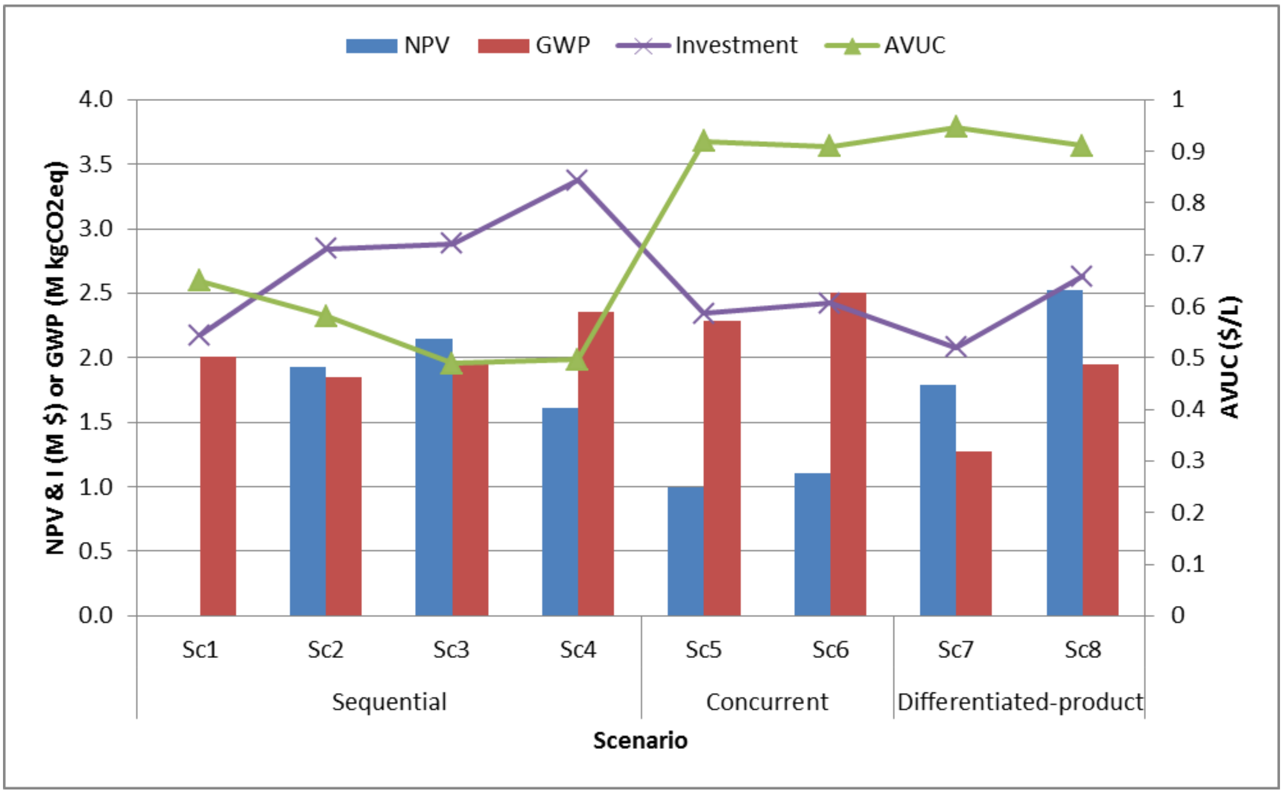


FIGURE 5-30 RESULTS FOR THE MAIN CRITERIA PER SCENARIO

In the current literature, the most common approach to multi-objective GSCD is to only consider NPV and GWP as the objective functions. By evaluating the different ways that the solution strategy can be formulated, different outcomes are achieved. The methods shown here provide a roadmap to fine tuning the modelling and optimization strategy through different approaches reflecting the different stakeholders' preferences and objectives, with special emphasis on capturing the customers' preferences.

Supply Chain Network Design Outcomes

Some insights can also be extracted by reviewing the differences in the SC network design that the optimization process suggests, referring to the values taken by the decision variables for each solution strategy. This allows us to understand how different elements of the SC have a strong or weak effect on the outcomes. Table 5-6 presents a summary of the main decision variable values chosen (for M-TOPSIS solutions). These values describe the SC configurations in terms of the variables that describe each echelon (e.g. Supplier Echelon: supplier region, supplier selected and agro practice assignment). A first impact is the pattern in relation to the supplying region selection. For the Fixed Price Strategy (FPS) (Scenarios 1) Mexico was selected and was also consequently in Scenarios 2 to 4: naturally, the search algorithm finds solutions in the space restricted by the SP found in Sc1, which then plays a decisive and restrictive role on what best configurations could be found given the fixed price parameters in subsequent scenarios. Even if this behaviour can be viewed as restrictive, it also provides “targets” for the algorithm to reach, effectively representing the customers’ objectives during the optimization process.

TABLE 5-6 DECISION VARIABLE SUMMARY FOR M-TOPSIS SOLUTIONS FOR EACH SCENARIO

	Supplier region	Organic farmers	Conventional farmers	Pasteurization technology	Concentration	Plant location		Bottling technology	
						France	Germany	France	Germany
Sc1	Mexico	4	4	PEF	Multieffect evaporator	4	6	Glass	PET
Sc2	Mexico	6	2	PEF	Freeze	1	1	PET	PET
Sc3	Mexico	6	1	PEF	Freeze	1	3	PET	PET
Sc4	Mexico	1	1	HPP	R.Osmosis	1	3	PET	PET
Sc5	Brazil	8	6	PEF	Multieffect evaporator	2	6	PET	PET
Sc6	Brazil	2	8	PEF	Multieffect evaporator	6	6	Glass	PET
Sc7	Brazil	1	5	PEF	Multieffect evaporator	5	6	Glass	Carton
Sc8	Brazil	7	6	PEF	Multieffect evaporator	6	6	Glass	Carton

The second observation is related to the numbers of organic and conventional farmers that supply raw materials shown in Figure 5-31. They are different in all scenarios from one another. There is no direct relationship between the number of suppliers of one or another type. This is because of the different sizes of land that each supplier has (ranging from 12ha for the smallest land to 1060 ha for the largest) can compensate for the number of suppliers selected. Let us consider for example Scenario 4, it has only two suppliers selected, but these two are some of the biggest (from the set of 20) that can be selected, reaching almost 900 ha of land. In addition almost the entire land is selected for each supplier, while in Scenario 5 many small land size suppliers are selected and only a portion of their land is contracted.

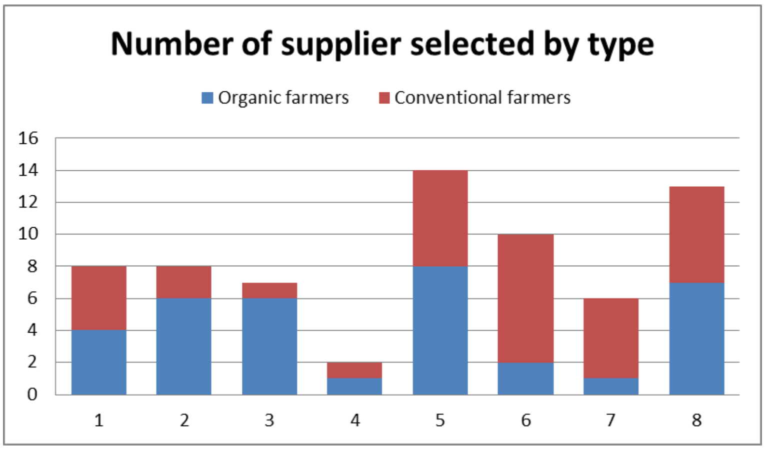


FIGURE 5-31 NUMBER OF SUPPLYING FARMERS PER TYPE OF AGRO PRACTICE

As far as processes are concerned, on the one hand, the selection of technology for the pasteurization process is consistently Pulse Electric Field (Table 5-6). On the other hand, the concentration process has more diversity. A clear tendency for heat intensive Multi-effect Evaporation technology can be observed when selecting the Brazil region (to install the processing plant). This is mainly due to the lower price of natural gas, while for scenarios that select the Mexican supply region all three technologies are selected at least once. This is partly due to the trade-off between price and environmental impact gas and electric energy sources have in Mexico.

Table 5-6 shows plant location for both France and German bottling sites. For France, many different locations are selected, which can be attributed to several factors, mainly the location of the targeted markets and the port of arrival of raw materials. The plant location is optimized to minimize the economic and environmental cost to service the target markets and to be serviced by the raw materials arrival port. Let us consider for illustration the case of Germany (see the distribution of potential plant location sites and marketed cities shown in Figure 5-32 as white boxes and red circles respectively (see Appendix A Figure 1). For the German market region, the sites that were selected in the set of scenarios presented in Table 5-6 are locations 1, 3 and 6. Locations 1 and 3 are selected because they are near a cluster of 4 main cities that make up a large bulk of the total market that is targeted. They are also located near the port of arrival of raw materials compared to other sites, reducing transportation cost of raw materials from the port to the bottling site. In contrast, bottling plant location 6 is selected as the nearest to the largest market city i.e. Berlin (circle 1), and not far to the second largest city Hamburg (circle 2). These reasons explain why these 3 locations are attractive in terms of logistical cost and environmental impact.

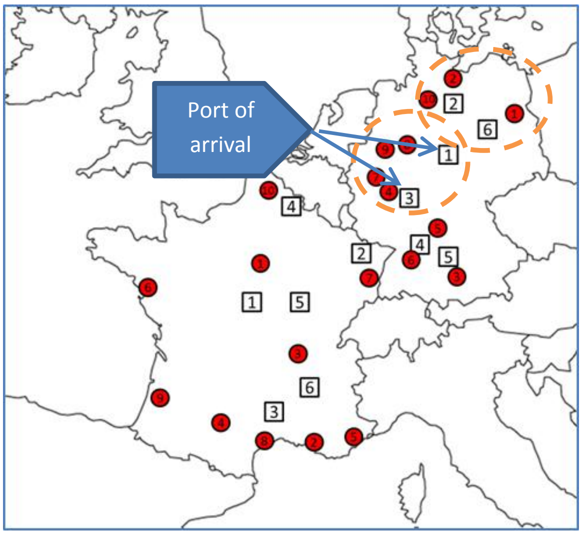


FIGURE 5-32 EXAMPLE OF PLANT LOCATION IN GERMANY

Let us consider now the bottling technology that was selected for France and Germany as shown in Figure 5-33. PET (i.e. plastic bottles) constitutes the dominant choice, which is mainly due to two reasons. First, SC network designs that were evaluated in scenarios 2-4 were restrictive since they had to achieve very low AVUC values in order to be profitable against a fixed price, thus promoting the selection of the cheapest type of bottles, which is PET.

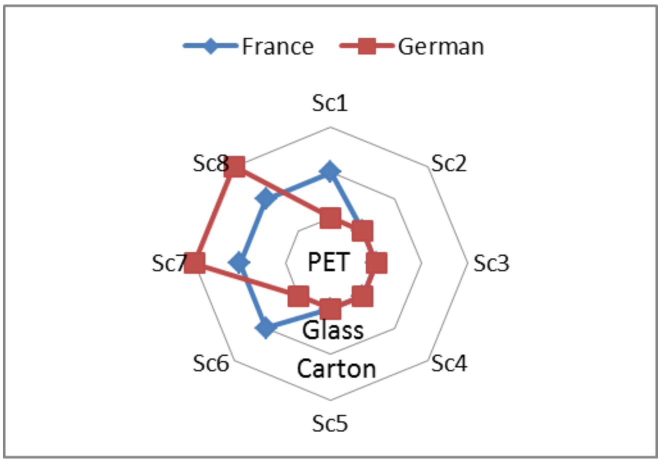


FIGURE 5-33 TYPE OF BOTTLING TECHNOLOGY SELECTED PER SCENARIO IN EACH MARKET REGIONS

Second, scenarios 7 and 8 use an organic eco-label premium that increases *organic* product Sales Price by 25%, making the outcome a slightly less sensitive to the effect of choosing somewhat more expensive bottling technologies (i.e. glass and carton containers). Glass bottles and carton containers became a feasible option within the context of variable sales price. This is reflected in the patterns the AVUC follows shown in Figure 5-34. The pattern is quite similar to that of the bottling technology selection in Figure 5-33.

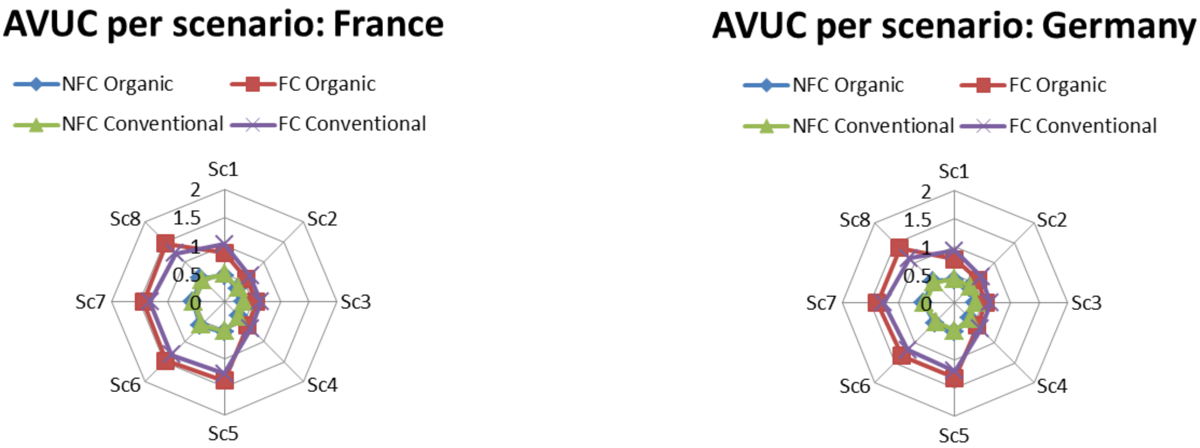


FIGURE 5-34 AVUC VALUES FOR FRANCE AND GERMANY PER TYPE OF PRODUCT

Interestingly, the AVUC values follow the same pattern between market regions (i.e. France and Germany), no matter what the Pricing Policy is. Additionally one sees that the product that use FCOJ raw materials have a much higher cost. This is because of the extra energy needed to process and refrigerate the raw material. In the case study, there is a 70% additional economic and environmental cost added due to refrigerated (below -4°C) transportation used for frozen concentrate, while non-concentrated juice is only chilled. But the model is made under the assumption that there are no additional environmental or economic cost related to process or materials handling. It could be possible to add detail to the SC model that might well produce different outcomes (noting that data driven model precision comes at an economic, complexity and time cost). An example would be to consider the cost of spoilage of product due to shelf life limitations and other material stocking and handling issues fall outside of the scope of the research.

Furthermore, the economic and environmental impact model - targets energy consumption during the pasteurization and concentration process. For concentrated juice much more energy is consumed, and thus drives the cost up. In addition, because transatlantic transport is so inexpensive, the higher processing cost is not offset by the minimization of material during transport. Detailed estimations of materials handling issues where limited due to access to information, this could be overcome for industrial application by using historical data to better reflect the real system. The case study assumes fixed transport cost, energy cost, market demand limits, among other things, that in reality can fluctuate and that certainly affect the behaviour and outcome of the system.

Another important factor that determines the SC network configurations is the demand that is targeted. This demand can be seen from two distinct angles. The first is from a (1) Location-allocation problem perspective, this is to say, 1) defining the capacity or scale of all of the production technologies that need to be installed; 2) defining the location of the bottling plants, which is influenced by the targeted markets, because of distribution costs. This was illustrated previously for the situation described for the German bottling plant location. The second angle the SC network configuration can be seen through is as a (2) long-term planning problem.

The scale of the production capacity will have to match or surpass the demand that is targeted. Each market (city) has a maximum demand or demand upper limit that can be satisfied by allocating production output to be distributed to that market. This allocation of production output is defined by the demand coverage variables that are optimized. The matrix arrangement of radar graphs in Figure 5-35 and Figure 5-36 illustrate the demand coverage as a percentage of the total potential market size (i.e., from the total demand that can be satisfied in a given market city, only a portion is covered and represented as a percentage).

In Figure 5-35, demand coverage for France market region is presented. Several comments can be highlighted: Sc1 (that is formulated to minimize GWP and AVUC from a customer perspective) does not completely cover most markets’ demands (i.e. does not reach near the upper demand limits). This is also true for Sc7 that could partially explain why it does so poorly compared to the other optimization strategies. In contrast, for scenarios 2 to 4 demand is consistently covered near 100%. Scenarios 5 and 6 have mixed coverages. Lastly, scenario 8 performed well relative to the other scenarios and consistently covers most of the market demands (see Sc8 axis in Figure 5-35).

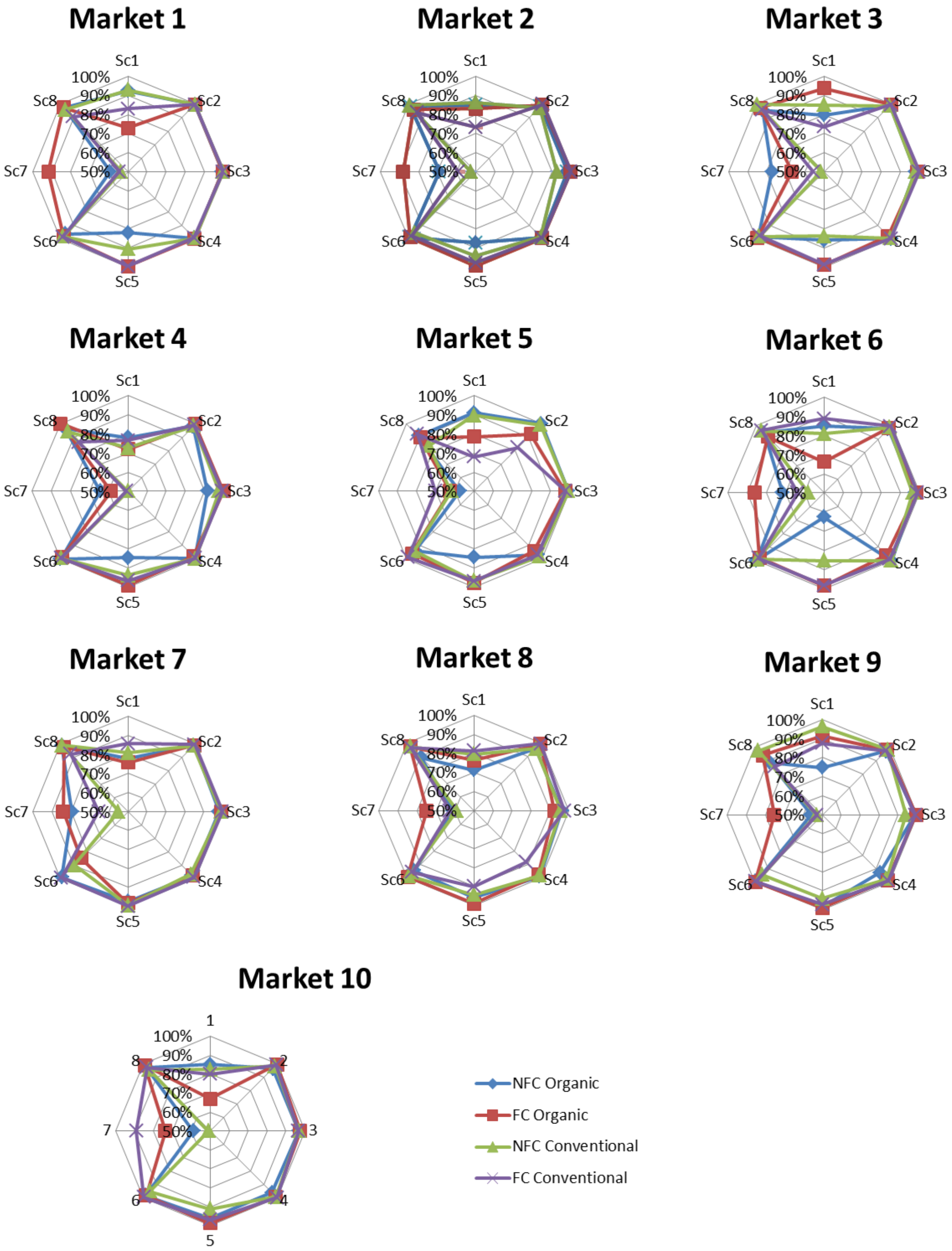


FIGURE 5-35 DEMAND COVERAGE IN PERCENTAGE FOR THE FRANCE MARKET REGION

In the case of the German market presented in Figure 5-36, the results are much more mixed. For example Market 1 (i.e. Berlin) the largest market in the region is not targeted to full capacity for scenarios 1, 3 and 7, while many of the other markets have mixed results. The best performing scenario in terms of NPV this is to say scenario 3 and 8 consistently allocate capacity to fulfil almost

100% for all Markets and products. The poorest performing scenarios, i.e. 5, 6 and 7 have mixed demand coverages in terms of both product type and markets.

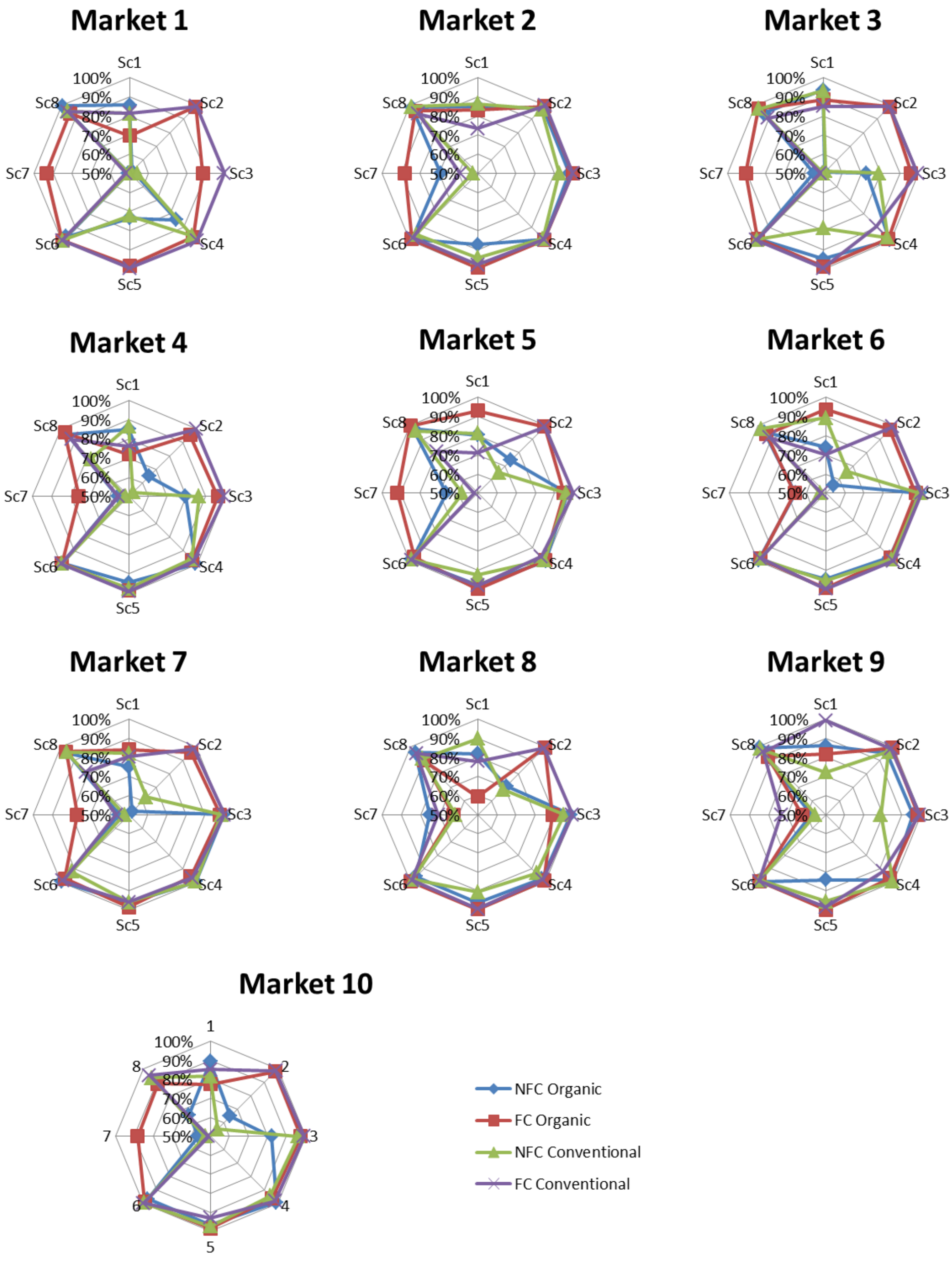


FIGURE 5-36 DEMAND COVERAGE IN PERCENTAGE FOR THE GERMANY MARKET REGION

In addition to these findings, focusing more attention on the environmental issue, Figure 5-37 presents the environmental impact measuring GWP in kg CO_2 eq per L assigned by product type and market region (x-axis). Eight reference values taken from related literature on life cycle assessment of orange juice production are also shown.

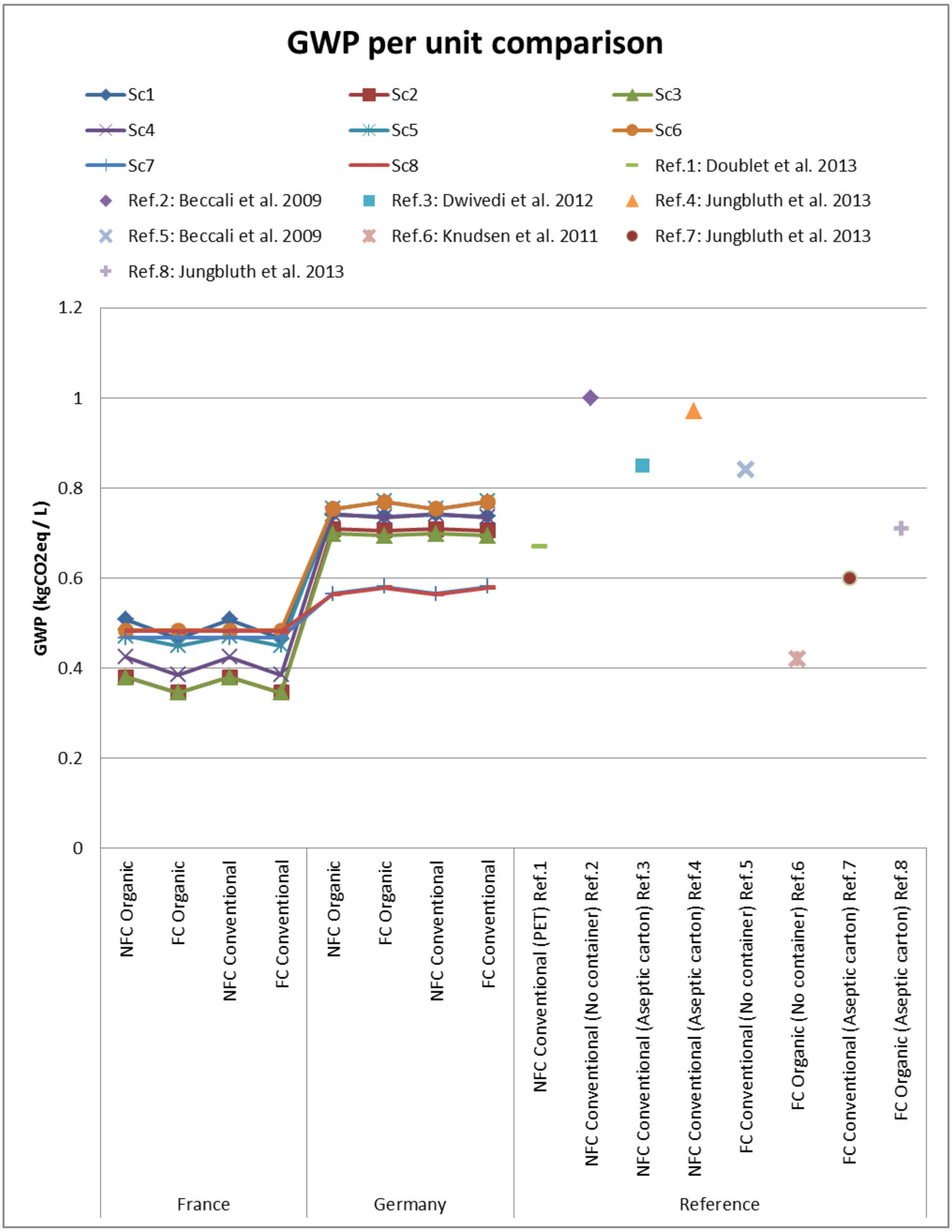


FIGURE 5-37 GWP PER UNIT SUMMARY DEVIDED BY COUNTRY AND PRODUCT TYPE WITH REFERENCE VALUES (DOUBLET ET AL. 2013)

Many observations and conclusions can be drawn by comparing the different values and behavior obtained from the scenarios given the modelling and optimization approach proposed against those provided by the literature. Firstly, comparing the NFC with FC for both Organic and Conventional products one sees that GWP can be higher for NFC that FC. This can be counterintuitive given that less processing is made to NFC orange juice; this behavior is explained through the efficiency lost due to transportation and "last mile" refrigeration (i.e. bottling plant to market) for NFC orange juice. This phenomenon can be clearly seen for most scenarios for the France market, as well as, in general for the reference values.

Secondly, Ref.6 proposed by (Knudsen et al., 2011) exhibits the lowest GWP value since it does not take into account the bottling's impact. Most other reference values are within 0.6 to 1 kgCO_2 eq/L slightly higher than that obtained. The GWP levels obtained with the modelling and optimization approach are explained by two main factors. The first is that the SC is optimized while the reference values are based on case studies focused on measurement not on improvement of performance. Secondly, it must be yet emphasized that the modelling approach does not entail a full LCA for each SC network evaluated. It only takes into account the effects of using agrochemicals, energy and water through the production and transportation processes, and thus the environmental impact is lower than that if a detailed LCA is performed. One main observation is that all product types, no matter the label or processing used on average fall beneath most reference values. In the case of German region it is clear that scenarios 7 and 8, because they use the price premium for *organic* eco-labeled products, have better performing SC network systems in terms of GWP. On average, Sc7 and Sc8 find a trade-off between regions, this is to say, while it is the best performing in the German market region it is a poor performer in the France market region; but for both regions these scenarios insure that GWP performance is as good or better than the reference values excluding Ref.6 that does not consider the bottling process. By developing the model to this level of detail and proposing the Differentiated-Product Optimization Scheme globally environmentally efficient SC networks can be found.

Lastly, comparing the difference between organic and conventionally labeled products, there is not much difference between scenarios within each region. This is contrary to popular belief that *organic* product globally outperform conventionally labeled products. If one where to take suppliers echelon in isolation environmental performance may be improved by using less agrochemicals, but in terms of the global supply chain strategy that is proposed, the agro practice used during raw materials production (i.e. oranges) is less important than that of the other stages (e.g. processing, transportation, bottling, etc.). This can be observed through references 7 and 8 that follow the opposite pattern, this is to say, *organic* product is outperformed by conventionally labeled product. To further illustrate this phenomenon let us compare the LCA results presented in (Doublet et al., 2013) shown in Figure 5-38 with an example taken from Sc3 M-TOPSIS solution for product (of all four types) destined for Market 1 in Germany shown in Figure 5-39.

Figure 5-38 provides a detailed allocation of the sources of GWP emissions throughout the product life cycle. In addition to the classification provided by the author a set of reference clustering through brackets are proposed. Using this arrangement to more closely resemble the level of detail used for in the case study shown in Figure 5-39. While the reference LCA does provide more detail by dealing GWP in terms of more sub process, there is little emphasis on the transportation stages during the products life cycle. The example taken from Sc3 one sees that the steps are more aggregated but emphasis is given to the SC echelons and interfaces. Nonetheless similar distribution of the sources of GWP in the different stages is appreciated. And more importantly, and looking back to the point previously developed in relation to the effect *organic* production has over GWP outcome, one sees that for both LCAs the main source is the bottling process while orange raw material production is far behind.

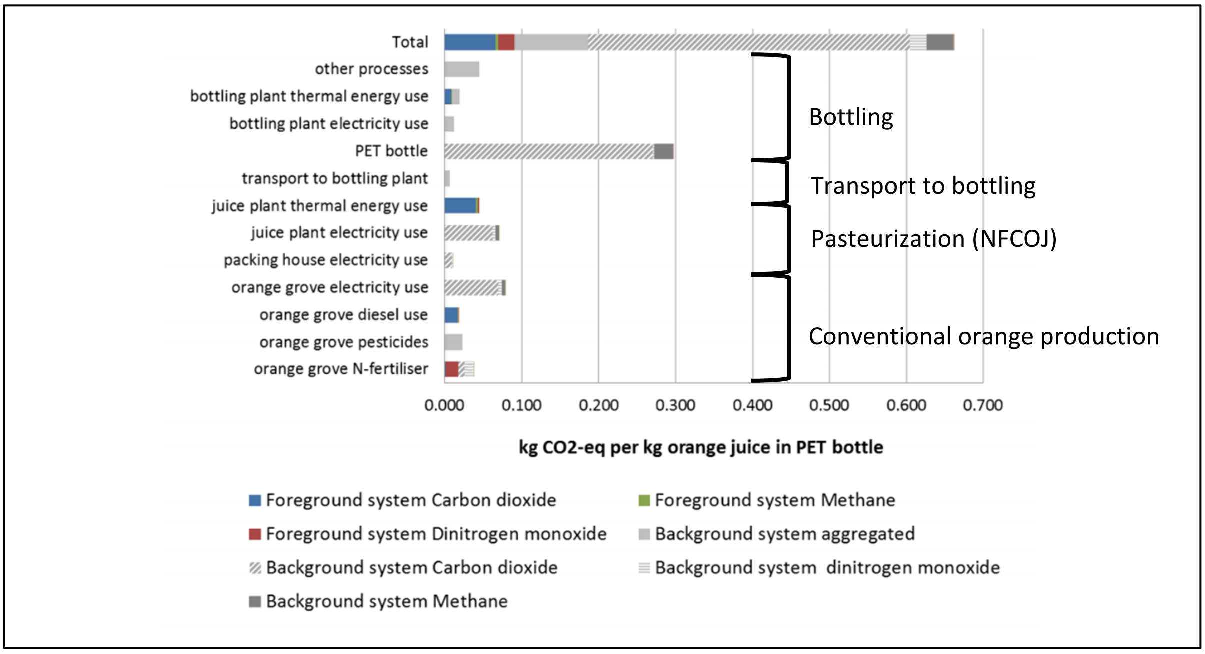


FIGURE 5-38 LCA OUTPUT IN TERMS OF GWP PER KG (~1L) OF ORANGE JUICE IN PET BOTTLE (DOUBLET ET AL. 2013)

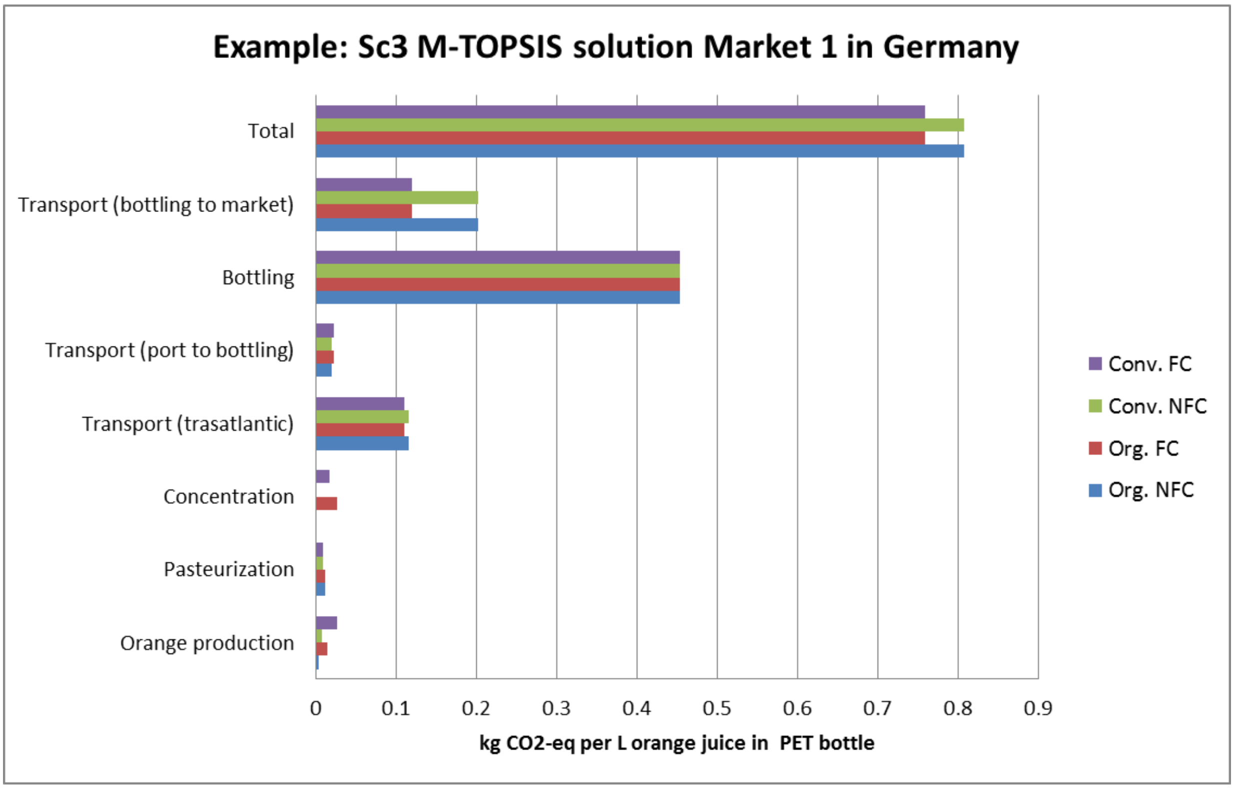


FIGURE 5-39 LCA OUTPUT IN TERMS OF GWP PER L OF ORANGE JUICE IN PET BOTTLE FROM SC3 M-TOPSIS SOLUTION MARKET 1 IN GERMANY

Furthermore one can appreciate the importance of the tranportation stages for the Sc3 example as being the second most important source of GWP emissions. This is in contrast to the results presented in the reference example that indeed uses a more optimistic approach of modelling transportation. This leads us to conclude that while most literature in relation to environmental impact focus on measuring and in evaluating different technique, a more holistic approach provides better insight and a way to take advantage of the scope provided by framing the problem as one of green supply chain network design.

5.6 CONCLUSION

Three optimization schemes to the green supply chain network problem were presented. Each has different advantages and weaknesses. In the first, *Sequential Optimization Scheme*, a base optimization scenario is carried out to obtain the best solution from the customers' perspective. This base scenario is then used to set the Sales Price for each product based on the type (e.g. organic, conventional, FC or NFC) and market that it will be sold and distributed to in subsequent scenarios (i.e. scenarios 2, 3 & 4). By fixing the Sales Price - the scheme proposes solutions that are evaluated during the GA optimization process that are competitive in terms of GWP and AVUC (and thus price). In the subsequent scenarios, different objective functions are used to model the focal company prerogative to be profitable. Using KPIs such as NPV, investment cost and Variable Unit Cost, the optimization process is driven to search for solutions that minimize the investment, operations and transport cost incurred by the focal company during the production and distribution process. By evaluating different objective functions in each scenario, the Pareto front solutions can be iteratively improved in relative terms, providing the best set of alternatives to the decision maker.

In the *Concurrent Optimization Scheme,* different criteria were evaluated simultaneously. The fixed pricing strategy used in the *Sequential Optimization Scheme* was changed to a variable pricing strategy. In this scenario, a 25% price margin cost is added to the Variable Unit Cost of the product to fix the Sales Price (SP). Because no threshold was established for the SP - different solution alternatives were found. Unexpectedly but justifiably the solutions were dominated by those found in the Sequential Optimization Scheme for the reasons presented in the result section.

Lastly, a *Differentiated-Product Optimization* strategy was evaluated. This approach takes into account the premium price that a customer is willing to pay for higher quality *organic* eco-labeled food products. This is particularly sound because the differentiation helps counteract part of the additional cost that may be incurred when producing products under an environmentally conscious SC network design. The optimization search process explores solution spaces that would not otherwise be considered. This approach takes into account the preferences of the consumer by attaching a variable Sales Price based on the AVUC that is minimized. It also takes the focal company objective into consideration through the NPV criteria, while being environmentally conscious through the GWP minimization objective function.

Looking back at the initial objective of the research project – directed at the development of a framework to model and design green supply chain networks for the agrofood industry – one can review the effectiveness of the proposed approach, and ultimately judge its effectiveness in answering this call. The research work provides a conceptual and operational framework to build and utilize GrSCND models in the context of the agrofood industry. In addition, the example and the corresponding scenarios developed provide insight on some of the important issues that have to be considered when applying such a strategy. Indeed, Chapters 4 and 5 act as guidelines to developing and implementing the multi-objective green supply chain network design approach to similar production systems. Through the evaluation of the different optimization schemes presented through the case study, a clear illustration and validation of the effectiveness are shown. While there may be many areas to improve and to derive new research questions, the work here presented provides the basic framework to tackle the problems that where initially established.

Chapter 6 Conclusions and Perspectives

Conclusions

The world is changing rapidly, with population and economic growth driving society towards an unsustainable relationship with the planet. In recent time, advances in technology, like the *green revolution* of the 1940s, allowed societies to prosper and grow. Along with economic growth policies born out of the postwar reconstruction era that promoted repopulation and consumption, society has pushed the limits of growth. This has become more and more apparent as new findings on the effect human activities have on the natural environment and the possible long-term effect they may hold. Food supply chains are an important sector of the growth economy accounting for a large part of the human footprint on earth.

These agro food supply chains are made up by a complex network of suppliers, manufacturers, consumers and the interfaces between these nodes. They provide the food sources essential for societies to thrive. But because of the driving forces that globalization has applied they have been optimized only in economic terms. New approaches to measure environmental performance have been developed and are becoming more and more widely used. In the case of the agro food industry they have led to many new business strategies and public policies. One of the main ones is the use of eco-labels that provide information to the consumer in order to promote the production and consumption of better products. Although eco-labels are used in many industries and products, food products have the special characteristic of the possibility to be classified as *organic* depending on the agricultural practice used.

Organic certification eco-labels allow the producer to market their products with a differentiating attribute that makes them more competitive against normal products and allows the consumer to have more information to base better purchasing decisions.

In addition, recent developments in the field of Green Supply Chain Management has provided new and interesting insights on how supply chain systems can be improved in terms not only of economic, but also of environmental and social criteria. The holistic approach is the essence of the Supply Chain Management paradigm where Environmental Assessment tools such as Life Cycle Assessment can be involved into a synergetic new approach.

The scientific objective of this work was then to propose and develop a systemic framework to improve the performance of the *green* agro food supply chain as a whole. The optimal design of green agro food supply chains was carried out by using Multi-objective Optimization based on Genetic Algorithms and Multicriteria Decision Making concepts.

By taking this metaheuristic approach to the complex problem many elements that would otherwise be left out were included, highlighting the ability to consider multiple antagonistic objectives, from different stakeholders, considering multiple periods, integrating multiple echelons in the chain simultaneously, for multiple products distributed in multiple locations around the globe. Nonlinear relationships and behaviors, as well as, integer variables become manageable through genetic algorithms. Indeed the most important advantage of this approach is that many objectives and criteria, and thus many stakeholders can be satisfied concurrently through the multi-objective approach. Furthermore, many of the limitations that empirical trial-and-error and managerial judgment decision making hold are overcome through the integration of a final multicriteria decision making process. The whole approach allows the decision maker to surpass bias and achieve an objective, feasible and efficient choice.

The case study of the orange juice cluster demonstrated the feasibility of this approach. By using historical and scientific literature data, some general guidelines concerning the implementation of the methodology were highlighted. he environmental impact assessment of the agro food chain was carried out through a single environmental criterion, e.g. GWP, due to the lack of data concerning the quantification of other impacts either partially either totally along the supply chain. The methodological approach is not yet affected by this limitation. Other criteria throughout the different lifecycle stages of the product could be easily integrated into the supply chain design process. By limiting the scope to one environmental criterion, we are aware that important impacts that are not captured by GWP, like Eutrophication and Acidification during the agricultural processes, are missed in the interpretation phase. Yet, the approach based on Partnership for Sustainability presented in Chapter 3 illustrates how more than one environmental criterion can be tackled during the supplier selection process.

This same modelling approach was used in Chapters 4 and 5 in order to frame the Green Supply Chain Design problem in the context of the agro food chain through different scenarios. The main finding from this part of the research lies in three main points. First, the method proves to be not only feasible but efficient at modelling and finding optimal trade-off solutions that would otherwise be impossible to find. Secondly, the different objective functions and pricing strategies that are proposed and studied, provide insight on the importance of choosing the best approach to agro food supply chain problems. Indeed, the main contribution was corroborating that, while organic certification of products in order to add value through eco-labels at the same time as improving environmental performance is useful, the use of more general eco-labeling that reflects the full supply chain could be more suitable and effective. In particular, the case study showed in the final results that the main contributors to one of the main pollution indicators, mainly GWP, come from other stages in the supply chain, e.g. transportation and bottling. By focusing on the agricultural stages of the supply chain, important attention that should be directed at these operations is misrepresented in the current *organic* eco-labeling policy.

The contribution of this work lies in proposing an integrated and holistic approach to greening the agrofood cluster supply chain network design process. Through the case study we provided an illustrative example of its potential use. Furthermore this example allowed us to find insight into the specific case of the orange juice supply chain. The results show that each step in the supply chain holds opportunities to improve environmental performance equal or greater than that of only looking at the agriculture stage of the food supply chain. Because of this, the application and adaptation of this approach to other food products may provide a better design and improvement method for supply chain practitioners. Finally, a wider more inclusive scheme, such as the one proposed in this work can be adopted in mainstream industry and consumers in order to promote better and more effective production systems and greener consumption.

Perspectives

During each stage of this research work different questions arose that fell near the edge of the scope of the work but could not be covered. These questions and observations remain outstanding and could motivate future research:

- **Water impact modelling:** it must be highlighted on the one hand that **water** consumption was included within the modelling scope for both the Green Supplier Selection Problem and the Green Supply Chain Design problem; on the other hand, eutrophication and acidification of water were included as environmental impact criteria in the Green Supplier Selection problem formulation. Yet, these water centric environmental impact criteria were not included in the Green Supply Chain Design problem formulation. Furthermore, other important issues, like irrigation systems, were included in a very limited way within the scope of the case study. This is not a problem for seasonal agro food products and agricultural systems that depend on the natural rain fall. But for other food products that are heavily depend on irrigation systems this issue could require additional attention.

Furthermore the case study limited the scope of the processing step, excluding the initial washing stages of production that are pervasive for most fresh fruit and fruit derived food products. In some cases this can be considered negligible or inexistent, but there are cases where water consumption is very important. Related to this point, another issue is that given that many food production unit operations are in batch form, cleaning of silos, containers, hoppers, feeders, etc. may also require important quantities of **water and cleaning products as well as chemicals**, that consume water and may pollute water runoff. These could also be further detailed in future work depending on the focus and product being studied.

- **Land use:** one very important issue that was considered in the model through the measurement of yields is the **land use**. While it was considered directly in the model formulation, its environmental impact was not quantified nor was included as an explicit optimization objective. Land use and yield are a very important issue given that food security and demographic growth have justified until now the rampant change of land use. Deforestation and erosion of many natural landscapes that should be protected must be also considered. A focus on the value obtained by limiting the changes in use of land could be an important branch of research within the Green Supply Chain domain.

- **Waste** is another issue that fell outside of the scope of this work but is highly related to the objective being considered. W**aste** byproducts are produced in different stages in the product lifecycle. In the first stage a sorting operation is usually necessary for food products, where some residues or non-conforming products are discarded. These waste materials can be treated as solid waste (to be discarded) or could be used by other entities as a raw material. In the developed case study, the potential to consider the biomass from the extraction and concentration processes as a byproduct for the production of animal feed (Lanuzza et al., 2014) or more recently biogas (Wikandari et al., 2015) constitute a potential pathway of improvement for supply chain modelling and for product valorization. This type of reuse of waste materials has been treated in literature in different ways, some of the most popular ones are Industrial Ecology and the **Closed-Loop Supply Chain Logistics**. These approaches could be explored as potential additions or extensions of the method here proposed.

- The consideration of the packaging materials at the end of life stage could be also taken into account in more detail. In the thesis this was treated through the measurement of the environmental impact of each of the bottling technologies that where considered. But there exist within the Supply Chain Management field a subfield called **Reverse Logistics**. It relates to the recovery of materials that can be treated and reused or repurposed. In the case of the food beverage industry bottles are used that can be recovered. Each country has their own policies in place to sort and recover valuable materials and innovative solutions to recycle and recover unavoidable waste are receiving a lot of attention: for instance, in the case of Germany for example, plastic and glass bottles are **recycled** by incentivizing the consumer to sort and bring back the material to places of purchase by paying for the recovery service. Reverse logistics is not new but had been left aside for many years due to the efficiencies gained at producing very cheap packaging materials, but has started to become more important given the renewed awareness of the potential of limiting externalities of food consumption related to packaging. This could be considered in future work where trajectory vectors could be added to the network model to accommodate for reverse logistics. This could be very interesting given that the finding of this thesis and other research papers show that one of the main contributors to the environmental impact of non-alcoholic beverages like orange juice comes from the bottle.

- Additionally the scope of the thesis work was limited to Greening the supply chain by using the Life Cycle Assessment method in order to measure and improve the environmental performance of the supply chain. Recent works have extended it to include the social aspect through the so-called Social Life Cycle Assessment (SLCA). In this approach, the aspect related to labor, social benefit, job creation, community development among other things is also measured and targeted for improvement. In this work, the social element was limited to the collaboration and contract schemes that are proposed in chapter 3 through Partnership for Sustainability. This could be extended in order to evaluate the social benefits of decentralizing suppliers, process plants, de-mechanizing processes in order to produce more jobs for instance in addition to the new social measurements that little by little are starting to be included within this new SLCA paradigm.
- From a methodological point of view, some important perspectives could be incorporated into future research. The inclusion of **uncertainty** into the model framework could be important to overcome many of the random events and fluctuations inherent in agro food supply chains related to the volatility of the weather, global markets, consumer behavior among many other uncertainties. We collaborated in developing some systems related to this during the PhD work that resulted in two publications (Fernandez Lambert et al., 2015,

2014) . But it would be interesting to incorporate uncertainty measurements and variability within the framework presented in the thesis. Connected to this issue is also the possibility of the inclusion of a **dynamical systems** approach where changes that occur in time could be integrated into the framework such as the yield per tree based on the age of the trees, soil erosion, soil nutrient replenishment, and other time dependent phenomena that could provide better descriptions of the system in order to make better decisions.

In summary, the contributions from this research have paved the way to extend the base model and methodology for greening the agro food supply chain and improving the integration of tools to overcome the technical challenges of developing future sustainable production systems.

Bibliography

Abdallah, T., Farhat, A., Diabat, A., Kennedy, S., 2011. Green Supply Chains with Carbon Trading and Environmental Sourcing: Formulation and Life Cycle Assessment. Appl. Math. Model. doi:10.1016/j.apm.2011.11.056

Accorsi, R., Cholette, S., Manzini, R., Pini, C., Penazzi, S., n.d. The land-network problem: ecosystem carbon balance in planning sustainable agro-food supply chains. J. Clean. Prod. doi:10.1016/j.jclepro.2015.06.082

Ahumada, O., Villalobos, J.R., 2009. Application of planning models in the agri-food supply chain: A review. Eur. J. Oper. Res. 196, 1–20.

Aintzane Esturo, 2013. Key environmental challenges Fruit Juice.

Ala-Harja, H., Helo, P., 2014. Green supply chain decisions – Case-based performance analysis from the food industry. Transp. Res. Part E Logist. Transp. Rev. 69, 97–107. doi:10.1016/j.tre.2014.05.015

Albino, V., Dangelico, R.M., Pontrandolfo, P., 2012. Do inter-organizational collaborations enhance a firm's environmental performance? A study of the largest US companies. J. Clean. Prod.

Altiparmak, F., Gen, M., Lin, L., Paksoy, T., 2006. A genetic algorithm approach for multi-objective optimization of supply chain networks. Comput. Ind. Eng., Special Issue on Computational Intelligence and Information Technology: Applications to Industrial Engineering 33rd.ICC&IE - Computational Intelligence & Information 51, 196–215. doi:10.1016/j.cie.2006.07.011

Alves, V.D., Coelhoso, I.M., 2006. Orange juice concentration by osmotic evaporation and membrane distillation: A comparative study. J. Food Eng. 74, 125–133. doi:10.1016/j.jfoodeng.2005.02.019

Amador, J.R., 2011. Procedures for analysis of citrus products: Sixth Edition.

Amin, S.H., Zhang, G., 2012. An integrated model for closed-loop supply chain configuration and supplier selection: Multi-objective approach. Expert Syst. Appl. 39, 6782–6791. doi:10.1016/j.eswa.2011.12.056

Andersson, K., Ohlsson, T., Olsson, P., 1994. Life cycle assessment (LCA) of food products and production systems. Trends Food Sci. Technol. 5, 134–138.

Arkeman, Y., Jong, K.D., 2010. Development of Multiobjective Genetic Algorithms for Agri-Food Supply Chain Design by Considering Global Climate Change [WWW Document]. URL http://repository.ipb.ac.id/handle/123456789/41683 (accessed 10.1.13).

Azadnia, A.H., Saman, M.Z.M., Wong, K.Y., 2014. Sustainable supplier selection and order lot-sizing: an integrated multi-objective decision-making process. Int. J. Prod. Res. 0, 1–26. doi:10.1080/00207543.2014.935827

Azzaro-Pantel, C., Dietz, A., Domenech, S., Pibouleau, L., 2007. Ecodesign of batch processes: optimal design strategies for economic and ecological bioprocesses.

Azzaro-Pantel, C., Ouattara, A., Pibouleau, L., 2013. Ecodesign of Chemical Processes with Multi-Objective Genetic Algorithms, in: Rangaiah, G.P., Bonilla-Petriciolet, A. (Eds.), Multi-Objective Optimization in Chemical Engineering. John Wiley & Sons Ltd, pp. 335–367.

Bai, C., Sarkis, J., 2010. Green supplier development: analytical evaluation using rough set theory. J. Clean. Prod. 18, 1200–1210. doi:10.1016/j.jclepro.2010.01.016

Balda, F.P., Aparicio, B.V., Samson, C.T., 2012. Industrial High Pressure Processing of Foods: Review of Evolution and Emerging Trends. J. Food Sci. Eng. 2, 543–549.

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2010. Life cycle assessment of Italian citrus-based products. Sensitivity analysis and improvement scenarios. J. Environ. Manage. 91, 1415–1428. doi:10.1016/j.jenvman.2010.02.028

Beske, P., Land, A., Seuring, S., 2014. Sustainable supply chain management practices and dynamic capabilities in the food industry: A critical analysis of the literature. Int. J. Prod. Econ., Sustainable Food Supply Chain Management 152, 131–143. doi:10.1016/j.ijpe.2013.12.026

Bloemhof, J.M., Vorst, J.G.A.J. van der, Bastl, M., Allaoui, H., 2015. Sustainability assessment of food chain logistics. Int. J. Logist. Res. Appl. 18, 101–117. doi:10.1080/13675567.2015.1015508

Böge, S., 1995. The well-travelled yogurt pot: lessons for new freight transport policies and regional production. World Transp. Policy Pract. 1, 7–11.

Bomben, J.L., Bruin, S., Thijssen, H.A., Merson, R.L., 1973. Aroma recovery and retention in concentration and drying of foods. Adv. Food Res. 20, 1–111.

Bougherara, D., Combris, P., 2009. Eco-labelled food products: what are consumers paying for? Eur. Rev. Agric. Econ. 36, 321–341. doi:10.1093/erae/jbp023

Bouzembrak, Y., Allaoui, H., Goncalves, G., Bouchriha, H., 2011. A multi-objective green supply chain network design, in: 2011 4th International Conference on Logistics (LOGISTIQUA). Presented at the 2011 4th International Conference on Logistics (LOGISTIQUA), pp. 357–361. doi:10.1109/LOGISTIQUA.2011.5939315

Bowen, F.E., Cousins, P.D., Lamming, R.C., Farukt, A.C., 2001. The Role of Supply Management Capabilities in Green Supply. Prod. Oper. Manag. 10, 174–189. doi:10.1111/j.1937-5956.2001.tb00077.x

Brentrup, F., 2003. Life Cycle assessment to evaluate the environmental impact of arable crop production. Int. J. Life Cycle Assess. 8, 156–156. doi:10.1007/BF02978461

Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. Theoretical concept of a LCA method tailored to crop production. Eur. J. Agron. 20, 247–264. doi:10.1016/S1161-0301(03)00024-8

Brookes, G., 2007. Economic impact assessment of the way in which the EU novel foods regulatory approval procedures affect the EU food sector. Brief. Pap. Confed. Food Drink Ind. Eur. Union CIAA Platf. Ingred. Eur. PIE.

Brown, M.G., Spreen, T.H., Lee, J.-Y., others, 2004. Impacts on US prices of reducing orange juice tariffs in major world markets. J. Food Distrib. Res. 35, 26–33.

Cao, S., Zhang, K., 2011. Optimization of the flow distribution of e-waste reverse logistics network based on NSGA II and TOPSIS, in: 2011 International Conference on E -Business and E -Government (ICEE). Presented at the 2011 International Conference on E -Business and E -Government (ICEE), pp. 1 –5. doi:10.1109/ICEBEG.2011.5881817

Carlsson-Kanyama, A., Ekström, M.P., Shanahan, H., 2003. Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. Ecol. Econ. 44, 293–307.

Cederberg, C., Mattsson, B., 2000. Life cycle assessment of milk production—a comparison of conventional and organic farming. J. Clean. Prod. 8, 49–60.

Cellura, M., Ardente, F., Longo, S., 2012. From the LCA of food products to the environmental assessment of protected crops districts: A case-study in the south of Italy. J. Environ. Manage. 93, 194–208. doi:10.1016/j.jenvman.2011.08.019

Charles-Rodríguez, A.V., Nevárez-Moorillón, G.V., Zhang, Q.H., Ortega-Rivas, E., 2007. Comparison of Thermal Processing and Pulsed Electric Fields Treatment in Pasteurization of Apple Juice. Food Bioprod. Process. 85, 93–97. doi:10.1205/fbp06045

Chopra, S., Meindl, P., 2001. Supply Chain Management: Strategy, Planning, and Operation. Prentice Hall.

Consejo Citrícola Poblano A.C., 2004. Plan rector del sistema producto naranja: Diagnostico para el estado de Puebla.

Correll, D.L., 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27, 261–266.

Corsano, G., Vecchietti, A.R., Montagna, J.M., 2011. Optimal design for sustainable bioethanol supply chain considering detailed plant performance model. Comput. Chem. Eng. 35, 1384–1398. doi:10.1016/j.compchemeng.2011.01.008

Coskun, S., Ozgur, L., Polat, O., Gungor, A., n.d. A Model Proposal for Green Supply Chain Network Design Based On Consumer Segmentation. J. Clean. Prod. doi:10.1016/j.jclepro.2015.02.063

Costa, A., Celano, G., Fichera, S., Trovato, E., 2010. A new efficient encoding/decoding procedure for the design of a supply chain network with genetic algorithms. Comput. Ind. Eng. 59, 986–999. doi:10.1016/j.cie.2010.09.011

Cristina Gimenez, 2006. Logistics integration processes in the food industry. Int. J. Phys. Distrib. Logist. Manag. 36, 231–249. doi:10.1108/09600030610661813

Curti-Díaz, S.A., Diaz-Zorrilla, U., Loredo-Salazar, X., Sandoval Rincon, J.A., Pastrana Aponte, L., Rodriguez Cuevas, M., 1998. Manual de produccion de naranja para Veracruz y Tabasco.

Dalsgaard, H., Abbotts, W., 2003. 8 - Improving energy efficiency, in: Mattsson, B., Sonesson, U. (Eds.), Environmentally-Friendly Food Processing, Woodhead Publishing Series in Food Science, Technology and Nutrition. Woodhead Publishing, pp. 116–129.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002a. A fast and elitist multiobjective genetic algorithm: NSGA-II. Evol. Comput. IEEE Trans. On 6, 182–197.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002b. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Comput. 6, 182 –197. doi:10.1109/4235.996017

de Boer, L., Labro, E., Morlacchi, P., 2001. A review of methods supporting supplier selection. Eur. J. Purch. Supply Manag. 7, 75–89. doi:10.1016/S0969-7012(00)00028-9

Degraeve, Z., Labro, E., Roodhooft, F., 2000. An evaluation of vendor selection models from a total cost of ownership perspective. Eur. J. Oper. Res. 125, 34–58. doi:10.1016/S0377-2217(99)00199-X

De-León Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Pibouleau, L., Senties, O.B., 2013. Assessment of mono and multi-objective optimization to design a hydrogen supply chain. Int. J. Hydrog. Energy 38, 14121–14145. doi:10.1016/j.ijhydene.2013.07.059

Deshpande, S.S., Cheryan, M., Sathe, S.K., Salunkhe, D.K., Luh, B.S., 1984. Freeze concentration of fruit juices. C R C Crit. Rev. Food Sci. Nutr. 20, 173–248. doi:10.1080/10408398409527389

Dietz, A., Azzaro-Pantel, C., Pibouleau, L., Domenech, S., 2006. Multiobjective optimization for multiproduct batch plant design under economic and environmental considerations. Comput. Chem. Eng. 30, 599–613. doi:10.1016/j.compchemeng.2005.10.017

Dietz, A., Pantel, C.A., Pibouleau, L.G., Domenech, S., 2007. Ecodesign of Batch Processes: Optimal Design Strategies for Economic and Ecological Bioprocesses. Int. J. Chem. React. Eng. 5.

Dobbs, T.L., Nguyen, G., Bertramsen, S., Legagneux, B., 2003. Quality and Eco-labeling of Food Products in France and the United States. Econ. Staff Pap. S. D. State Univ.

Doublet, G., Ingólfsdóttir, G.M., Yngvadóttir, E., Landquist, B., Jungbluth, N., Aronsson, A., Ramos, S., Keller, R., Ólafsdóttir, G., 2014. Key Environmental Performance Indicators for a simplified LCA in food supply chains, in: Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014). pp. 8–10.

Doublet, G., Jungbluth, N., Flury, K., Stucki, M., Schori, S., 2013. Life cycle assessment of orange juice. SENSE-Harmonised Environmental Sustainability in the European food and drink chain, Seventh Framework Programme: Project no. 288974. Funded by EC. Deliverable D 2.1 ESU-services Ltd.: Zürich.

Dwivedi, P., Spreen, T., Goodrich-Schneider, R., 2012. Global warming impact of Florida's Not-From-Concentrate (NFC) orange juice. Agric. Syst. 108, 104–111. doi:10.1016/j.agsy.2012.01.006

E.A., M., Amer Eiss, A.H., 2012. Pulsed Electric Fields for Food Processing Technology, in: Amer Eissa, A. (Ed.), Structure and Function of Food Engineering. InTech.

Eaton, C., Shepherd, A.W., 2001. Contract farming - Partnerships for growth.

Ecoinvent Center, 2010. Ecoinvent Life Cycle Inventory Database v2.2.

Eskandarpour, M., Dejax, P., Miemczyk, J., Péton, O., 2015. Sustainable supply chain network design: An optimization-oriented review. Omega 54, 11–32. doi:10.1016/j.omega.2015.01.006

Fernandez Lambert, G., Aguilar Lasserre, A., Azzaro-Pantel, C., Miranda-Ackerman, M.A., Purroy Vázquez, R., del Rosario Pérez Salazar, M., 2015. Behavior patterns related to the agricultural practices in the production of Persian lime (Citrus latifolia tanaka) in the seasonal orchard. Comput. Electron. Agric. 116, 162–172. doi:10.1016/j.compag.2015.06.007

Fernandez Lambert, G.F., Aguilar Lasserre, A.A.A., Miranda-Ackerman, M.A., Sánchez, C.G.M., Rivera, B.O.I., Azzaro-Pantel, C., 2014. An expert system for predicting orchard yield and fruit quality and its impact on the Persian lime supply chain. Eng. Appl. Artif. Intell. 33, 21–30. doi:10.1016/j.engappai.2014.03.013

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. doi:10.1016/j.jenvman.2009.06.018

Fonseca, C.M., Fleming, P.J., 1993. Genetic Algorithms for Multiobjective Optimization: Formulation, Discussion and Generalization, in: Forrest, S. (Ed.), Fifth International Conference on Genetic Algorithms. Morgan Kauffman Publishers, San Mateo, California, pp. 416–423.

García-cascales, M.S., Lamata, M.T., 2012. On rank reversal and TOPSIS method. Math. Comput. Model. 56, 123–132. doi:10.1016/j.mcm.2011.12.022

Garcia, D.J., You, F., 2015. Supply chain design and optimization: Challenges and opportunities. Comput. Chem. Eng. doi:10.1016/j.compchemeng.2015.03.015

Gen, M., Cheng, R., Gen, M., Cheng, R., 1999. Genetic Algorithms and Engineering Optimization. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Gen, M., Kumar, A., Ryul Kim, J., 2005. Recent network design techniques using evolutionary algorithms. Int. J. Prod. Econ. 98, 251–261. doi:10.1016/j.ijpe.2004.05.026

Goedkoop, M., De Schryver, A., Oele, M., 2008. Introduction to LCA with SimaPro 7. PRé Consult. Rep. 4.

Gomez, A., 2008. Optimisation technico-économique multiobjectif de systèmes de conversion d’énergie: cogénération électricité-hydrogène à partir d’un réacteur nucléaire de IVème génération. Université de Toulouse - Institut National Polytechnique de Toulouse.

Gomez, A., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., Latgé, C., Haubensack, D., 2010a. Multiobjective genetic algorithm strategies for electricity production from generation IV nuclear technology. Energy Convers. Manag. 51, 859–871.

Gomez, A., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., Latgé, C., Haubensack, D., 2010b. Multiobjective genetic algorithm strategies for electricity production from generation IV nuclear technology. Energy Convers. Manag. 51, 859–871. doi:10.1016/j.enconman.2009.11.022

Gómez Cruz, M.A., Schwentesius Rindermann, R., Universidad Autónoma Chapingo. Centro de Investigaciones Económicas, S. y T. de la A. y de la A.M., 1997. La agroindustria de naranja en México. CIESTAAM, México.

Govindan, K., Soleimani, H., Kannan, D., 2015. Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. Eur. J. Oper. Res. 240, 603–626. doi:10.1016/j.ejor.2014.07.012

Grunert, K.G., Hieke, S., Wills, J., 2014. Sustainability labels on food products: Consumer motivation, understanding and use. Food Policy 44, 177–189. doi:10.1016/j.foodpol.2013.12.001

Guillén-Gosálbez, G., Grossmann, I.E., 2009. Optimal design and planning of sustainable chemical supply chains under uncertainty. AIChE J. 55, 99–121. doi:10.1002/aic.11662

Gunasekaran, A., Kobu, B., 2007. Performance measures and metrics in logistics and supply chain management: a review of recent literature (1995–2004) for research and applications. Int. J. Prod. Res. 45, 2819–2840. doi:10.1080/00207540600806513

Gunasekaran, A., Patel, C., McGaughey, R.E., 2004. A framework for supply chain performance measurement. Int. J. Prod. Econ., Supply Chain Management for the 21st Century Organizational Competitiveness 87, 333–347. doi:10.1016/j.ijpe.2003.08.003

Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., 2011. Life Cycle Assessment: Past, Present, and Future. Environ. Sci. Technol. 45, 90–96.

Heinz, D.I.V., Buckow, D.R., 2010. Food preservation by high pressure. J. Für Verbraucherschutz Leb. 5, 73–81. doi:10.1007/s00003-009-0311-x

Heinz, V., Alvarez, I., Angersbach, A., Knorr, D., 2001. Preservation of liquid foods by high intensity pulsed electric fields—basic concepts for process design. Trends Food Sci. Technol. 12, 103–111. doi:10.1016/S0924-2244(01)00064-4

Heinz, V., Toepfl, S., Knorr, D., 2003. Impact of temperature on lethality and energy efficiency of apple juice pasteurization by pulsed electric fields treatment. Innov. Food Sci. Emerg. Technol. 4, 167–175. doi:10.1016/S1466-8564(03)00017-1

Hernando Saiz, A., Tarrago Mingo, S., Purroy Balda, F., Tonello Samson, C., n.d. Advances in design for successful commercial high pressure food processing. Food Aust. 60, 154–156.

Hicks, D.T., Pivarnik, L.F., McDermott, R., Richard, N., Hoover, D.G., Kniel, K.E., 2009. Consumer Awareness and Willingness to Pay for High-Pressure Processing of Ready-to-Eat Food. J. Food Sci. Educ. 8, 32–38. doi:10.1111/j.1541-4329.2009.00069.x

Hodgins, A. m., Mittal, G. s., Griffiths, M. w., 2002. Pasteurization of Fresh Orange Juice Using Low-Energy Pulsed Electrical Field. J. Food Sci. 67, 2294–2299. doi:10.1111/j.1365-2621.2002.tb09543.x

Horn, J., Nafpliotis, N., Goldberg, D.E., 1994. A niched Pareto genetic algorithm for multiobjective optimization, in: Proceedings of the First IEEE Conference on Evolutionary Computation. IEEE World Congress on Computational Intelligence. IEEE, Orlando, Fl, pp. 82–87. doi:10.1109/ICEC.1994.350037

Ho, S., Mittal, G.S., 2000. High Voltage Pulsed Electrical Field for Liquid Food Pasteurization. Food Rev. Int. 16, 395–434. doi:10.1081/FRI-100102317

Hugo, A., Pistikopoulos, E., 2004. Environmentally conscious process planning under uncertainty, in: Sixth International Conference on Foundations of Computeraided Process Design. Edited by CA. Floudas, R. Agrawal, Princeton, CACHE Corporation.

Hugo, A., Pistikopoulos, E.N., 2005. Environmentally conscious long-range planning and design of supply chain networks. J. Clean. Prod., Recent advances in industrial process optimisation Recent advances in industrial process optimisation 13, 1471–1491. doi:10.1016/j.jclepro.2005.04.011

Hugos, M.H., 2003. Essentials of Supply Chain Management. John Wiley & Sons.

Huijbregts, M.J., Seppälä, J., 2001. Life Cycle Impact assessment of pollutants causing aquatic eutrophication. Int. J. Life Cycle Assess. 6, 339–343. doi:10.1007/BF02978864

Humphreys, P.., Wong, Y.., Chan, F.T.., 2003. Integrating environmental criteria into the supplier selection process. J. Mater. Process. Technol. 138, 349–356. doi:10.1016/S0924-0136(03)00097-9

Hwang, C.L., Yoon, K., 1981. Multiple Attribute Decision Making: Methods and Applications. Springer, Berlin.

International Standard Organization, 2000. ISO 14044. Environmental management-life cycle assessment- requirements and guidelines.

International Standard Organization, 1997. ISO 14040. Environmental management-life cycle assessment—principles and framework.

Janssen, M., Hamm, U., 2012. Product labelling in the market for organic food: Consumer preferences and willingness-to-pay for different organic certification logos. Food Qual. Prefer. 25, 9–22. doi:10.1016/j.foodqual.2011.12.004

Jesus, D.F., Leite, M.F., Silva, L.F.M., Modesta, R.D., Matta, V.M., Cabral, L.M.C., 2007. Orange (Citrus sinensis) juice concentration by reverse osmosis. J. Food Eng. 81, 287–291. doi:10.1016/j.jfoodeng.2006.06.014

Jolliet, O., Saadé, M., Crettaz, P., 2010a. Analyse du cycle de vie : comprendre et réaliser un écobilan. Presses polytechniques et universitaires romandes, Lausanne.

Jolliet, O., Saadé, M., Crettaz, P., 2010b. Analyse du Cycle de Vie: Comprendre et réaliser un écobilan, 2nd ed. Presses polytechniques et universitaires romandes, Lausanne.

Knudsen, M.T., Almeida, G.F. de, Langer, V., Abreu, L.S. de, Halberg, N., 2011. Environmental assessment of organic juice imported to Denmark: a case study on oranges (Citrus sinensis) from Brazil. Org. Agric. 1, 167–185. doi:10.1007/s13165-011-0014-3

Lai, Y.-J., Liu, T.-Y., Hwang, C.-L., 1994. TOPSIS for MODM. Eur. J. Oper. Res., Facility Location Models for Distribution Planning 76, 486–500. doi:10.1016/0377-2217(94)90282-8

Landquist, B., Ingólfsdóttir, G.M., Yngvadóttir, E., Jungbluth, N., Doublet, G., Esturo, A., Ramos, S., Ólafsdóttir, G., 2013. Set of environmental performance indicators for the food and drink chain SENSE-Harmonised Environmental Sustainability in the European food and drink chain, Seventh Framework Programme: Project no. 288974. Funded EC Deliv. D 2.

Lanuzza, F., Mondello, F., Tripodo, M.M., 2014. Studies About the Utilization of Citrus Wastes in View of Environment Protection, in: Salomone, R., Saija, G. (Eds.), Pathways to Environmental Sustainability. Springer International Publishing, pp. 147–156.

Lee, A.H., Kang, H.-Y., Hsu, C.-F., Hung, H.-C., 2009. A green supplier selection model for high-tech industry. Expert Syst. Appl. 36, 7917–7927.

Lee, P.Y., Lusk, K., Mirosa, M., Oey, I., 2015. Effect of information on Chinese consumers' perceptions and purchase intention for beverages processed by High Pressure Processing, Pulsed-Electric Field and Heat Treatment. Food Qual. Prefer. 40, Part A, 16–23. doi:10.1016/j.foodqual.2014.08.006

Leppelt, T., Foerstl, K., Reuter, C., Hartmann, E., 2013. Sustainability management beyond organizational boundaries–sustainable supplier relationship management in the chemical industry. J. Clean. Prod., Sustainability management beyond corporate boundaries 56, 94–102. doi:10.1016/j.jclepro.2011.10.011

Levitan, L., Merwin, I., Kovach, J., 1995. Assessing the relative environmental impacts of agricultural pesticides: the quest for a holistic method. Agric. Ecosyst. Environ. 55, 153–168.

Lin, S.-S., Juang, Y.-S., 2008. Selecting green suppliers with analytic hierarchy process for biotechnology industry. J. Oper. Supply Chain Manag. 1, 115–129.

Loureiro, M.L., Mccluskey, J.J., Mittelhammer, R.C., Loureiro, M.L., Mccluskey, J.J., Mittelhammer, R.C., 2002. Will Consumers Pay a Premium for Eco-labeled Apples?, Will Consumers Pay a Premium for Eco-labeled Apples? J. Consum. Aff. J. Consum. Aff. 36, 36, 203, 203–219, 219. doi:10.1111/j.1745-6606.2002.tb00430.x, 10.1111/j.1745-6606.2002.tb00430.x

Lu, L.Y.Y., Wu, C.H., Kuo, T.-C., 2007. Environmental principles applicable to green supplier evaluation by using multi-objective decision analysis. Int. J. Prod. Res. 45, 4317–4331. doi:10.1080/00207540701472694

Manuilova, A., Suebsiri, J., Wilson, M., 2009. Should Life Cycle Assessment be part of the Environmental Impact Assessment? Case study: EIA of CO2 Capture and Storage in Canada. Energy Procedia, Greenhouse Gas Control Technologies 9Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), 16–20 November 2008, Washington DC, USA 1, 4511–4518. doi:10.1016/j.egypro.2009.02.269

Markovic, Z., 2010. Modification of TOPSIS method for solving of multicriteria tasks. Yugosl. J. Oper. Res. 20, 117–143.

Marsden, T., Murdoch, J., Morgan, K., 1999. Sustainable agriculture, food supply chains and regional development: editorial introduction. Int. Plan. Stud. 4, 295–301.

MATHIAS, M.C., CECCHI, J.C., 2009. INDUSTRIA DE GAS NATURAL EN BRASIL: PASADO, PRESENTE Y FUTURO.

McKinnon, A., Piecyk, M., 2010. Measuring and managing CO2 emissions of European chemical transport. Heriot-Watt Univ. Edinb.

Meisterling, K., Samaras, C., Schweizer, V., 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. J. Clean. Prod. 17, 222–230.

Melo, M.T., Nickel, S., Saldanha-da-Gama, F., 2009. Facility location and supply chain management – A review. Eur. J. Oper. Res. 196, 401–412. doi:10.1016/j.ejor.2008.05.007

Mentzer, J.T., DeWitt, W., Keebler, J.S., Min, S., Nix, N.W., Smith, C.D., Zacharia, Z.G., 2001. Defining Supply Chain Management. J. Bus. Logist. 22, 1–25. doi:10.1002/j.2158-1592.2001.tb00001.x

Milà i Canals, L., Burnip, G.M., Cowell, S.J., 2006. Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): Case study in New Zealand. Agric. Ecosyst. Environ. 114, 226–238. doi:10.1016/j.agee.2005.10.023

Minot, N., 1986. Contract farming and its effect on small farmers in less developed countries. Michigan State University, Department of Agricultural, Food, and Resource Economics.

Miranda-Ackerman, M.A., Azzaro-Pantel, C., Montastruc, L., Aguilar Lasserre, A., 2015. A multi-objective green supply chain network design optimization approach for global food systems under product mix consideration of eco-labeled. Presented at the International Congress AgriFood Supply Chain and Green Logistics, Porto Carras, Greece.

Miranda-Ackerman, M.A., Azzaro-Pantel, C., Montastruc, L., Domenech, S., 2013a. Multiobjective Optimization of a Green Supply Chain: Application to the Agro-Food Industry. Presented at the 9th European Congress of Chemical Engineering (ECCE-9), The Hague, The Netherlands.

Miranda-Ackerman, M.A., Azzaro-Pantel, C., Montastruc, L., Domenech, S., Lasserre, A.A.A., 2013b. Optimal design of a green supply chain: application to the agro-food industry supplier selection problem, in: Coll. Récents Progrès En Génie Des Procédés, N° 104 Les Sciences Du Génie Des Procédés Pour Une Industrie Durable XIVe Congrès SFGP 2013 8 Au 10 Octobre 2013, Lyon. Société Française de Génie des Procédés.

Miranda-Ackerman, M.A., Fernández-Lambert, G., Azzaro-Pantel, C., Aguilar-Lasserre, A.A., 2014. A Multi-Objective Modelling and Optimization Framework for Operations Management of a Fresh Fruit Supply Chain: A Case Study on a Mexican Lime Company, in: Valadi, J., Siarry, P. (Eds.), Applications of Metaheuristics in Process Engineering. Springer International Publishing, pp. 373–394.

Miyawaki, O., Liu, L., Shirai, Y., Sakashita, S., Kagitani, K., 2005. Tubular ice system for scale-up of progressive freeze-concentration. J. Food Eng. 69, 107–113. doi:10.1016/j.jfoodeng.2004.07.016

Mújica-Paz, H., Valdez-Fragoso, A., Samson, C.T., Welti-Chanes, J., Torres, J.A., 2011. High-pressure processing technologies for the pasteurization and sterilization of foods. Food Bioprocess Technol. 4, 969–985.

Neves, M.F., Trombin, V.G., Lopes, F.F., Kalaki, R., Milan, P., 2011. Breakdown of the price of orange juice on the retail market, in: The Orange Juice Business. Wageningen Academic Publishers, pp. 97–113.

Nyaga, G.N., Whipple, J.M., Lynch, D.F., 2010. Examining supply chain relationships: Do buyer and supplier perspectives on collaborative relationships differ? J. Oper. Manag. 28, 101–114. doi:10.1016/j.jom.2009.07.005

Oakdene Hollins Research and Consulting, 2011. EU Ecolabel for food and feed products (Feasibility study No. ENV.C.1/ETU/2010/0025). DG Environment, European Commission.

Oelofse, M., Høgh-Jensen, H., Abreu, L.S., Almeida, G.F., Hui, Q.Y., Sultan, T., de Neergaard, A., 2010. Certified organic agriculture in China and Brazil: Market accessibility and outcomes following adoption. Ecol. Econ. 69, 1785–1793. doi:10.1016/j.ecolecon.2010.04.016

Opricovic, S., Tzeng, G.-H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. Eur. J. Oper. Res. 156, 445–455. doi:10.1016/S0377-2217(03)00020-1

Ouattara, A., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., Baudet, P., Yao, B., 2012. Economic and environmental strategies for process design. Comput. Chem. Eng. 36, 174–188. doi:10.1016/j.compchemeng.2011.09.016

Pereira, R.N., Vicente, A.A., 2010. Environmental impact of novel thermal and non-thermal technologies in food processing. Food Res. Int., Climate Change and Food Science 43, 1936–1943. doi:10.1016/j.foodres.2009.09.013

Perez-Gallardo, J.R., Azzaro-Pantel, C., Astier, S., Domenech, S., Aguilar-Lasserre, A., 2014. Ecodesign of photovoltaic grid-connected systems. Renew. Energy 64, 82–97.

Peters, M.S., 2003. Plant design and economics for chemical engineers, 5th ed. ed, McGraw-Hill chemical engineering series. McGraw-Hill, New York.

Pinter, U., Pšunder, I., 2013. Evaluating construction project success with use of the M-TOPSIS method. J. Civ. Eng. Manag. 19, 16–23. doi:10.3846/13923730.2012.734849

Qiang, Q. (Patrick), 2015. The closed-loop supply chain network with competition and design for remanufactureability. J. Clean. Prod., Decision-support models and tools for helping to make real progress to more sustainable societies 105, 348–356. doi:10.1016/j.jclepro.2014.07.005

Ramudhin, A., Chaabane, A., Kharoune, M., Paquet, M., 2008. Carbon Market Sensitive Green Supply Chain Network Design, in: Industrial Engineering and Engineering Management, 2008. IEEM 2008. IEEE International Conference on. pp. 1093 –1097. doi:10.1109/IEEM.2008.4738039

Rao, P., Holt, D., 2005. Do green supply chains lead to competitiveness and economic performance? Int. J. Oper. Prod. Manag. 25, 898–916.

Rehber, E., 2000. Vertical Coordination In The Agro-Food Industry And Contract Farming: A Comparative Study Of Turkey And The Usa (Food Marketing Policy Center Research Reports No. 052). University of Connecticut, Department of Agricultural and Resource Economics, Charles J. Zwick Center for Food and Resource Policy.

Ren, L., Zhang, Y., Wang, Y., Sun, Z., 2010. Comparative Analysis of a Novel M-TOPSIS Method and TOPSIS. Appl. Math. Res. EXpress. doi:10.1093/amrx/abm005

Ren, L., Zhang, Y., Wang, Y., Sun, Z., 2007. Comparative Analysis of a Novel M-TOPSIS Method and TOPSIS. Appl. Math. Res. EXpress 2007, 1–10. doi:10.1093/amrx/abm005

Ren, L., Zhang, Y., Wang, Y., Sun, Z., 2007. Comparative Analysis of a NovelM-TOPSISMethod and TOPSIS. Appl. Math. Res. EXpress Vol. 2007, 10 pages. doi:doi:10.1093/amrx/abm005

ReVelle, C.S., Eiselt, H.A., 2005. Location analysis: A synthesis and survey. Eur. J. Oper. Res. 165, 1–19. doi:10.1016/j.ejor.2003.11.032

Richard, L., Kohls, J.N.U., 1998. Marketing of agricultural products. New Jersey: Prentice Hall, Upper Saddle River.

Rogers, D.S., Tibben-Lembke, R.S., 1998. Going backwards: reverse logistics practices and trends. Univ. Nev. Reno Cent. Logist. Manag. Reverse Logist. Exec. Counc.

Roheim, C.A., Asche, F., Santos, J.I., 2011. The Elusive Price Premium for Ecolabelled Products: Evidence from Seafood in the UK Market. J. Agric. Econ. 62, 655–668. doi:10.1111/j.1477-9552.2011.00299.x

Rousseau, S., Vranken, L., 2013. Green market expansion by reducing information asymmetries: Evidence for labeled organic food products. Food Policy 40, 31–43. doi:10.1016/j.foodpol.2013.01.006

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90, 1–10.

Ryder, R., Fearne, A., 2003. Procurement best practice in the food industry: supplier clustering as a source of strategic competitive advantage. Supply Chain Manag. Int. J. 8, 12–16. doi:10.1108/13598540310463314

Sadler, B., 1996. Strategic environmental assessment: Status, challenges and future directions. Ministry of Housing, Spatial Planing and the Environment.

Samira, C., Habiba, B., 2013. Controllers Tuning through Multi-objective Non-Dominated Sorting Genetic Algorithms. World J. Control Sci. Eng. 1, 15–24.

Sampedro, F., McAloon, A., Yee, W., Fan, X., Zhang, H.Q., Geveke, D.J., 2013. Cost analysis of commercial pasteurization of orange juice by pulsed electric fields. Innov. Food Sci. Emerg. Technol. 17, 72–78. doi:10.1016/j.ifset.2012.10.002

Santoyo-Castelazo, E., Gujba, H., Azapagic, A., 2011. Life cycle assessment of electricity generation in Mexico. Energy 36, 1488–1499. doi:10.1016/j.energy.2011.01.018

Saravacos, G., Maroulis, Z., 2007. Food Plant Economics, Food Science and Technology. CRC Press.

Schade, W., Doll, C., Maibach, M., Sieber, N., Lilico, A., Conti, M., Crespo, F., Carvalho, D., 2006. Analysis of the contribution of transport policies to the competitiveness of the EU economy and comparison with the United States (COMPETE). Final Rep. Eur. Comm. Proj. Co-Ordination Fraunhofer-Inst. Syst. Innov. Res. ISI Karlsr. Ger.

Schaffer, J.D., 1985. Multiple Objective Optimization with Vector Evaluated Genetic Algorithms, in: 1st International Conference on Genetic Algorithms. Erlbaum Associates Inc., NJ, USA, pp. 93–100.

Secretaría de Energía, Mexico, 2012. Prospectiva del Mercado de Gas Natural 2012-2026 : Mexico. Secretaría de Energía de Mexico, Mexico.

Seuring, S., Muller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. J. Clean. Prod. 16, 1699–1710.

Sha, D.Y., Che, Z.H., 2005. Supply chain network design: partner selection and production/distribution planning using a systematic model. J. Oper. Res. Soc. 57, 52–62. doi:10.1057/palgrave.jors.2601949

Singhal, P., Ahonen, S., Rice, G., Stutz, M., Terho, M., van der Wel, H., 2004. Key Environmental Performance Indicators (KEPIs): A new approach to environmental assessment, in: Electronics Goes Green. pp. 6–8.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ., Reactive nitrogen in agroecosystems: Integration with greenhouse gas interactions 133, 247–266. doi:10.1016/j.agee.2009.04.021

Spalding, R.F., Exner, M.E., 1993. Occurrence of nitrate in groundwater—a review. J. Environ. Qual. 22, 392–402.

Spitzley, D.V., Keoleian, G.A., McDaniel, J.S., 1997. Life cycle design of milk and juice packaging. US Environmental Protection Agency, National Risk Management Research Laboratory.

Srinivas, N., Deb, K., 1994. Muiltiobjective Optimization Using Nondominated Sorting in Genetic Algorithms. Evol. Comput. 2, 221–248.

Srivastava, S.K., 2007. Green supply-chain management: a state-of-the-art literature review. Int. J. Manag. Rev. 9, 53–80.

Tate, W.L., Ellram, L.M., Dooley, K.J., 2012. Environmental purchasing and supplier management (EPSM): Theory and practice. J. Purch. Supply Manag. 18, 173–188. doi:10.1016/j.pursup.2012.07.001

Toepfl, S., Mathys, A., Heinz, V., Knorr, D., 2006. Review: Potential of High Hydrostatic Pressure and Pulsed Electric Fields for Energy Efficient and Environmentally Friendly Food Processing. Food Rev. Int. 22, 405–423. doi:10.1080/87559120600865164

Tukker, A., Jansen, B., 2006. Environmental impacts of products. J. Ind. Ecol. 10, 159–182.

Upham, P., Dendler, L., Bleda, M., 2011. Carbon labelling of grocery products: public perceptions and potential emissions reductions. J. Clean. Prod. 19, 348–355. doi:10.1016/j.jclepro.2010.05.014

Vachon, S., Klassen, R.D., 2006. Extending green practices across the supply chain: The impact of upstream and downstream integration. Int. J. Oper. Prod. Manag. 26, 795–821. doi:10.1108/01443570610672248

Van der Werf, H.M., Petit, J., 2002. Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agric. Ecosyst. Environ. 93, 131–145.

van Hoof, B., Lyon, T.P., 2012. Cleaner Production in Small Firms taking part in Mexico’ s Sustainable Supplier Program. J. Clean. Prod.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate Change and Food Systems. Annu. Rev. Environ. Resour. 37, 195–222. doi:10.1146/annurev-environ-020411-130608

Viets, F.G., Lunin, J., 1975. The environmental impact of fertilizers. C R C Crit. Rev. Environ. Control 5, 423–453. doi:10.1080/10643387509381630

Walton, S.V., Handfield, R.B., Melnyk, S.A., 1998. The Green Supply Chain: Integrating Suppliers into Environmental Management Processes. Int. J. Purch. Mater. Manag. 34, 2–11. doi:10.1111/j.1745-493X.1998.tb00042.x

Ware, N.R., Singh, S.P., Banwet, D.K., 2012. Supplier selection problem: A state-of-the-art review. Manag. Sci. Lett. 2, 1465–1490. doi:10.5267/j.msl.2012.05.007

Wauchope, R.D., 1978. The pesticide content of surface water draining from agricultural fields—a review. J. Environ. Qual. 7, 459–472.

Wikandari, R., Nguyen, H., Millati, R., Niklasson, C., Taherzadeh, M.J., 2015. Improvement of Biogas Production from Orange Peel Waste by Leaching of Limonene. BioMed Res. Int. 2015, e494182. doi:10.1155/2015/494182

Yeh, W.-C., Chuang, M.-C., 2011. Using multi-objective genetic algorithm for partner selection in green supply chain problems. Expert Syst. Appl. 38, 4244–4253. doi:10.1016/j.eswa.2010.09.091

Yue, D., You, F., Snyder, S.W., 2014. Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges. Comput. Chem. Eng., Selected papers from ESCAPE-23 (European Symposium on Computer Aided Process Engineering - 23), 9-12 June 2013, Lappeenranta, Finland 66, 36–56. doi:10.1016/j.compchemeng.2013.11.016

Yuk, H.G., Sampedro, F., Fan, X., Geveke, D.J., 2014. Nonthermal Processing of Orange Juice Using a Pilot-Plant Scale Supercritical Carbon Dioxide System with a Gas–Liquid Metal Contactor. J. Food Process. Preserv. 38, 630–638. doi:10.1111/jfpp.12013

Zhu, Q., Sarkis, J., 2004. Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. J. Oper. Manag. 22, 265–289.

Zitzler, E., Thiele, L., 1999. Multiobjective evolutionary algorithms: a comparative case study and the strength Pareto approach. IEEE Trans. Evol. Comput. 3, 257–271. doi:10.1109/4235.797969

Zsidisin, G.A., Siferd, S.P., 2001. Environmental purchasing: a framework for theory development. Eur. J. Purch. Supply Manag. 7, 61–73. doi:10.1016/S0969-7012(00)00007-1

Annex A

For the case study Upper and Lower Demand limits were projected based on population demographics taken from Worldpopulationreview.com database website (extracted December 2014). Using the population per city an estimation of the minimum production target for each market and type of product is calculated. The Lower demand limit value is taken directly from the tables B.1 and B.2 for France and Germany respectively; for the Upper limits, Lower limits are multiplied by 2 to represent a 4% maximum market share penetration of new production capacity.

Market size (L of juice to produce and sell) per city was estimated by targeting a 1% share of all population with an average consumption rate of 12.762L per year per person for France, and an 11.67L per year per person for Germany .

For each type of product (NFC Organic, FC Organic, NFC Conventional and FC Conventional) market share as a percentage of market size is shown in the titles row. These market shares model consumer preference partially based on data from European Fruit Juice Association 2012 Liquid Fruit Market Report.

APPENDIX A TABLE 1 DEMAND LOWER LIMITS FOR MARKETS IN FRANCE REGION

			Market size	NFC Org.	FC Org.	NFC Conv.	FC Conv.
Market	City	Population	(2% share pop. *12.76L/yr)	18% share market	19% share market	31% share market	32% share market
1	Paris	2138551	545843	97988	103974	166845	177036
2	Marseille	794811	202867	36418	38643	62009	65797
3	Lyon	472317	120554	21642	22963	36849	39100
4	Toulouse	433055	110533	19843	21055	33786	35850
5	Nice	33862	8643	1552	1646	2642	2803
6	Nantes	277269	70770	12704	13480	21632	22953
7	Strasbourg	274845	70151	12593	13363	21443	22753
8	Montpellier	248252	63364	11375	12070	19368	20551
9	Bordeaux	231844	59176	10623	11272	18088	19193
10	Lille	228328	58278	10462	11101	17814	18902

APPENDIX A TABLE 2 DEMAND LOWER LIMITS FOR MARKETS IN GERMANY REGION

Market	City	Population	Market size (2% share pop. *11.67L/yr)	NFC Org. 1% share market	FC Org. 8% share market	NFC Conv. 12% share market	FC Conv. 79% share market
1	Berlin	3426354	799693	9669	64302	94866	630856
2	Hamburg	1739117	405901	4908	32638	48151	320204
3	Munich	1260391	294169	3557	23654	34896	232062
4	Cologne	963395	224851	2719	18080	26674	177379
5	Frankfurt am Main	650000	151707	1834	12199	17997	119677
6	Stuttgart	593085	138423	1674	11130	16421	109198
7	Dusseldorf	589793	137655	1664	11069	16330	108592
8	Dortmund	588462	137344	1661	11044	16293	108347
9	Essen	573057	133749	1617	10755	15866	105511
10	Bremen	546501	127551	1542	10256	15131	100621

The input data of the SC are exhibited in the Tables B.3-B.8. In Table B.3 presents the distance in km for the boat trajectories from the port of departure in either Mexico or Brazil towards the port of arrival in France and the Netherlands (Netherlands port is widely used for orange juice reception destined for Germany).

APPENDIX A TABLE 3 TRANSPORT DISTANCE FROM PORT OF DEPARTURE TO PORT OF ARRIVAL

Port of Departure→ ↓Port of Arrival	Mexico (Veracruz)	Brazil (Santos)
Nantes(FR)	10623km	11629km
Rotterdam(NL)	11492km	12497km

Source: Extracted from sea transport web page Ports.com retrieved 06/2013

- http://ports.com/sea-route/port-of-veracruz,mexico/port-of-rotterdam,netherlands/
- http://ports.com/sea-route/port-of-veracruz,mexico/port-of-nantes,france/
- http://ports.com/sea-route/port-of-santos,brazil/port-of-nantes,france/
- http://ports.com/sea-route/port-of-santos,brazil/port-of-rotterdam,netherlands/

Table B.4 Are the standard environmental burden and monetary cost for each kg of product carried one kilometer (kgkm). These values are used to estimate the total environmental impact and cost for trajectories based on the quantity of product being transported and the distances between nodes.

APPENDIX A TABLE 4 STANDARD TRANSPORT ENVIRONMENTAL IMPACT AND COST PER TRANSPORTATION MODE

	Environmetal impact ($kgCO_2eq/kgkm$) (SimaPro Eco-Invent data base)	Cost (\$/kgkm)
Sea	8.00E-06	7.6923E-06(Brown et al., 2004)
Land	6.20E-05	1.92E-04(Schade et al., 2006)

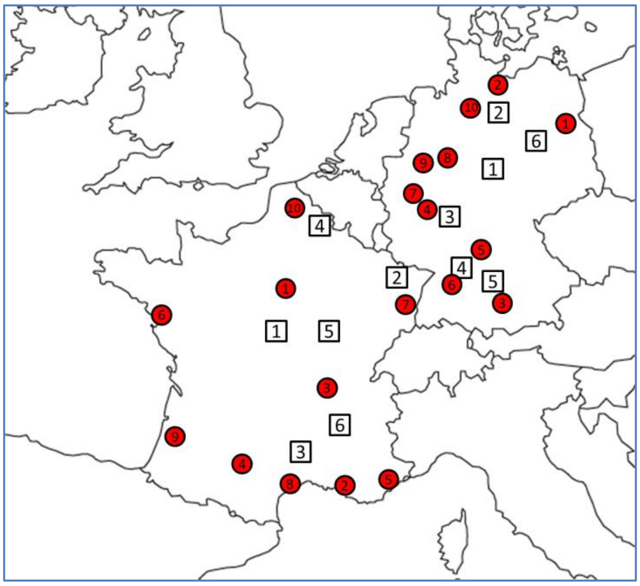
Using Table 5 estimations on the standard cost and environmental impact are presented in Table B.5 for each kg of product transported from the port of arrival of each country to the different bottling plant locations.

APPENDIX A TABLE 5 STANDARD DISTANCES, COST AND ENVIRONMENTAL IMPACT FROM PORT OF ARRIVAL TO BOTTLING PLANTS

Arrival Nantes	Distance (km)	$\Theta_{r'\to b}$ Cost (\$/kg)	$\psi_{r'\to b}$ EI (kg CO_2 eq/kg) (McKinnon and Piecyk, 2010)	Arrival Rotterdam	Distance (km)	$\theta_{r'\to b}$ Cost (\$/kg)	$\psi_{r'\to b}$ EI (kg CO_2 eq/kg) (McKinnon and Piecyk, 2010)
Saint-Martin-d'Abbat	369	0.07077	0.022878	Dassel	441	0.08458	0.027342
Sarre-Union	793	0.15209	0.049166	Bad Fallingbostel	452	0.08669	0.028024
St. Alban Auriolles	764	0.14653	0.047368	Bröl	305	0.05849	0.01891
Quesnoy	599	0.11488	0.037138	Nieder-Olm	441	0.08458	0.027342
Nuits	659	0.12639	0.040858	Waibstadt	528	0.10127	0.032736
Drôme	835	0.16015	0.05177	Calvörde	529	0.10146	0.032798

Table 6 for France region and Table 7 for Germany distances from the different bottling plant locations (columns) to the different markets cities (rows) in France region (see Figure B.1). The distances are in km and are used in conjunction with Table B.4 to estimate the cost and environmental impact from each bottling plant to each market location. It is important to note that for NFC type of juice a 70% markup is

added to the cost and environmental impact given that chilled transport must be used with an added energy and handling charge.



APPENDIX A FIGURE 1 MAP OF LOCATION OF MARKETS (RED CIRCLES) AND BOTTLING PLANT SITES (WHITE SQUARES)

APPENDIX A TABLE 6 TABLE B.6 DISTANCES FROM BOTTLING PLANT LOCATIONS TO MARKET CITIES: FRANCE REGION

Principal markets	Saint-Martin-d'Abbat (FR)	Sarre-Union(FR)	St. Alban Auriolles(FR)	Le Quesnoy(FR)	Nuits(FR)	Drôme(FR)
Paris	163	418	662	225	324	615
Marseille	741	821	198	935	480	233
Lyon	432	512	199	626	170	156
Toulouse	556	989	378	894	647	459
Nice	898	864	355	1092	636	390
Nantes	369	793	764	599	659	835
Strasbourg	550	80	691	485	349	647
Montpellier	626	810	142	924	469	210
Bodeaux	503	1018	618	805	646	686
Lille	377	481	886	68	525	831

APPENDIX A TABLE 7 DISTANCES FROM BOTTLING PLANT LOCATIONS TO MARKET CITIES: GERMANY REGION

Market-city	Dassel (DE)	Bad Fallingbostel (DE)	Bröl (DE)	Nieder-Olm (DE)	Waibstadt (DE)	Calvörde (DE)
Berlin	355	348	622	614	644	207
Hamburg	266	94	454	537	612	195
Munich	558	685	549	451	346	561
Cologne	267	341	42	198	289	413
Frankfurt	281	405	166	52	126	405
Stuttgart	439	566	348	205	137	566
Dusseldorf	253	328	80	246	327	400
Dortmund	186	261	123	268	340	333
Essen	38	300	101	258	348	368
Bremen	234	74	344	486	561	230

Annex B

Scenario 1 M-TOPSIS solution

APPENDIX B TABLE 1 LOCATION AND TECHNOLOGY SELECTION

Orchard/Processing Plant location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle Technology France	Bottle Technology Germany
Mexico	HHP	R. Osmosis	Saint-Martin-d'Abbat (FR)	Bröl (DE)	Aseptic carton	PET bottle

APPENDIX B TABLE 2 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0
Agro practice	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1
Land area	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

APPENDIX B TABLE 3 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France				Germany			
Market City	Label	Process	Production output	Market City	Label	Process	Production output
Paris	Organic	NFC	104984	Berlin	Organic	NFC	10020
		FC	145909			FC	65199
	Conventional	NFC	174091		Conventional	NFC	97618
		FC	207074			FC	632868
Marseille	Organic	NFC	38786	Hamburg	Organic	NFC	4918
		FC	44587			FC	34106
	Conventional	NFC	70305		Conventional	NFC	50043
		FC	67821			FC	322363
Lyon	Organic	NFC	21934	Munich	Organic	NFC	3641

		FC	23424
	Conventional	NFC	38046
		FC	40222
Toulouse	Organic	NFC	20925
		FC	22062
	Conventional	NFC	36093
		FC	37445
Nice	Organic	NFC	1605
		FC	1713
	Conventional	NFC	2649
		FC	2807
Nantes	Eco	NFC	13004
		FC	13880
	Conventional	NFC	22499
		FC	24396
Strasbourg	Eco	NFC	12916
		FC	13523
	Conventional	NFC	22136
		FC	24280
Montpellier	Organic	NFC	11774
		FC	12250
	Conventional	NFC	20317
		FC	20682
Bordeaux	Organic	NFC	10723
		FC	11578
	Conventional	NFC	18836
		FC	19741
Lille	Organic	NFC	10611
		FC	11282
	Conventional	NFC	19222
		FC	19733

		FC	24358
	Conventional	NFC	36876
		FC	233815
Cologne	Organic	NFC	2754
		FC	18312
	Conventional	NFC	27813
		FC	178557
Frankfurt	Organic	NFC	1858
		FC	12393
	Conventional	NFC	18300
		FC	120553
Stuttgart	Eco	NFC	1686
		FC	12549
	Conventional	NFC	17809
		FC	110523
Dusseldorf	Organic	NFC	1738
		FC	11579
	Conventional	NFC	16723
		FC	109172
Dortmund	Organic	NFC	1718
		FC	11668
	Conventional	NFC	16976
		FC	111381
Essen	Organic	NFC	1661
		FC	11055
	Conventional	NFC	16235
		FC	107364
Bremen	Organic	NFC	1587
		FC	10474
	Conventional	NFC	15463
		FC	101992

Scenario 2 M-TOPSIS solution

APPENDIX B TABLE 4 LOCATION AND TECHNOLOGY SELECTION

Orchard & Plant Processing location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle Technology France	Bottle Technology Germany
Mexico	PEF	R. Osmosis	Saint-Martin-d'Abbat (FR)	Bröl (DE)	PET bottle	PET bottle

APPENDIX B TABLE 5 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	1	1	1
Agro practice	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	2	1	1
Land area	50	81	50	50	50	51	50	50	50	50	50	50	50	50	50	50	50	50	50	50

APPENDIX B TABLE 6 TABLE C.2.3 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France				Germany			
Market City	Label	Process	Production output	Market City	Label	Process	Production output
Paris	Organic	NFC	188481	Berlin	Organic	NFC	12877
		FC	109584			FC	119397
	Conventional	NFC	259870		Conventional	NFC	101020
		FC	181070			FC	1261296
Marseille	Organic	NFC	44202	Hamburg	Organic	NFC	5820
		FC	47953			FC	61273
	Conventional	NFC	76709		Conventional	NFC	53152
		FC	69261			FC	639933
Lyon	Organic	NFC	25416	Munich	Organic	NFC	6626
		FC	30723			FC	44722
	Conventional	NFC	42844		Conventional	NFC	44424
		FC	49369			FC	463755
Toulouse	Organic	NFC	32324	Cologne	Organic	NFC	4855

		FC	23910
	Conventional	NFC	50887
		FC	40357
Nice	Organic	NFC	3040
		FC	2310
	Conventional	NFC	4616
		FC	3144
Nantes	Organic	NFC	20887
		FC	13788
	Conventional	NFC	36244
		FC	30719
Strasbourg	Organic	NFC	21970
		FC	21215
	Conventional	NFC	26096
		FC	29164
Montpellier	Organic	NFC	20206
		FC	16163
	Conventional	NFC	22513
		FC	27846
Bordeaux	Organic	NFC	12087
		FC	14180
	Conventional	NFC	28312
		FC	23924
Lille	Organic	NFC	13262
		FC	14609
	Conventional	NFC	24802
		FC	24857

		FC	33759
	Conventional	NFC	31176
		FC	354157
Frankfurt	Organic	NFC	3553
		FC	23861
	Conventional	NFC	20327
		FC	238835
Stuttgart	Organic	NFC	2826
		FC	20240
	Conventional	NFC	20166
		FC	218375
Dusseldorf	Organic	NFC	2208
		FC	20135
	Conventional	NFC	20799
		FC	216730
Dortmund	Organic	NFC	2188
		FC	18996
	Conventional	NFC	21190
		FC	216354
Essen	Organic	NFC	2599
		FC	20580
	Conventional	NFC	22854
		FC	210886
Bremen	Organic	NFC	2625
		FC	12207
	Conventional	NFC	16864
		FC	200636

Scenario 3 M-TOPSIS solution

APPENDIX B TABLE 7LOCATION AND TECHNOLOGY SELECTION

Orchard/Processing Plant location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle Technology France	Bottle Technology Germany
Mexico	PEF	R. Osmosis	Saint-Martin-d'Abbat (FR)	Bröl (DE)	PET bottle	PET bottle

APPENDIX B TABLE 8 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	1	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Agro practice	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1
Land area	69	50	71	50	74	96	66	91	80	93	84	71	100	90	94	70	58	55	63	100

APPENDIX B TABLE 9 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France				Germany			
Market City	Label	Process	Production output	Market City	Label	Process	Production output
Paris	Organic	NFC	190005	Berlin	Organic	NFC	12716
		FC	105950			FC	124063
	Conventional	NFC	332988		Conventional	NFC	106155
		FC	204393			FC	1261550
Marseille	Organic	NFC	50833	Hamburg	Organic	NFC	8787
		FC	43095			FC	64068
	Conventional	NFC	116817		Conventional	NFC	63115
		FC	78694			FC	638996
Lyon	Organic	NFC	37463	Munich	Organic	NFC	6601
		FC	26489			FC	45899
	Conventional	NFC	55221		Conventional	NFC	57274
		FC	53673			FC	463285

Toulouse	Organic	NFC	32824
		FC	29040
	Conventional	NFC	56251
		FC	40975
Nice	Organic	NFC	2746
		FC	2925
	Conventional	NFC	5121
		FC	5356
Nantes	Organic	NFC	21061
		FC	19044
	Conventional	NFC	40529
		FC	34490
Strasbourg	Organic	NFC	23048
		FC	19349
	Conventional	NFC	36279
		FC	35610
Montpellier	Organic	NFC	21392
		FC	18493
	Conventional	NFC	36616
		FC	22951
Bordeaux	Organic	NFC	19906
		FC	16987
	Conventional	NFC	32829
		FC	30997
Lille	Organic	NFC	19143
		FC	15831
	Conventional	NFC	32825
		FC	27641

Cologne	Organic	NFC	4897
		FC	33169
	Conventional	NFC	30048
		FC	354118
Frankfurt	Organic	NFC	3258
		FC	23641
	Conventional	NFC	35049
		FC	238132
Stuttgart	Organic	NFC	2074
		FC	21215
	Conventional	NFC	22501
		FC	217432
Dusseldorf	Organic	NFC	2871
		FC	21748
	Conventional	NFC	29501
		FC	216236
Dortmund	Organic	NFC	2361
		FC	17200
	Conventional	NFC	26211
		FC	215788
Essen	Organic	NFC	2980
		FC	20496
	Conventional	NFC	27731
		FC	209831
Bremen	Organic	NFC	2563
		FC	19977
	Conventional	NFC	24056
		FC	200568

Scenario 4 M-TOPSIS solution

APPENDIX B TABLE 10 LOCATION AND TECHNOLOGY SELECTION

Orchard/Processing Plant location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle Technology France	Bottle Technology Germany
Mexico	PEF	R. Osmosis	Saint-Martin-d'Abbat (FR)	Bröl (DE)	PET bottle	PET bottle

APPENDIX B TABLE 11 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0	1	0	1
Agro practice	1	1	1	2	2	1	1	1	1	1	4	1	1	4	1	2	4	1	2	1
Land area	98	100	100	100	100	100	97	100	99	100	100	98	97	100	97	86	99	97	100	100

APPENDIX B TABLE 12 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France

Market City	Label	Process	Production output
Paris	Organic	NFC	193391
		FC	203406
	Conventional	NFC	332416
		FC	353971
Marseille	Organic	NFC	72569
		FC	75789
	Conventional	NFC	122901
		FC	126686
Lyon	Organic	NFC	43187
		FC	44334
	Conventional	NFC	73128
		FC	77944
Toulouse	Organic	NFC	39354
		FC	41237
	Conventional	NFC	64407

Germany

Market City	Label	Process	Production output
Berlin	Organic	NFC	19059
		FC	125881
	Conventional	NFC	180781
		FC	1249994
Hamburg	Organic	NFC	9782
		FC	63402
	Conventional	NFC	91291
		FC	637629
Munich	Organic	NFC	7072
		FC	47012
	Conventional	NFC	69053
		FC	463524
Cologne	Organic	NFC	5346
		FC	35338
	Conventional	NFC	52926

		FC	69391			FC	342450
Nice	Organic	NFC	2827	Frankfurt	Organic	NFC	3472
		FC	3169			FC	24136
	Conventional	NFC	5198		Conventional	NFC	35916
		FC	5480			FC	234355
Nantes	Organic	NFC	25122	Stuttgart	Organic	NFC	3347
		FC	26545			FC	21453
	Conventional	NFC	41605		Conventional	NFC	31827
		FC	44340			FC	216852
Strasbourg	Organic	NFC	25048	Dusseldorf	Organic	NFC	3285
		FC	25514			FC	22048
	Conventional	NFC	42420		Conventional	NFC	31906
		FC	45423			FC	215943
Montpellier	Organic	NFC	21763	Dortmund	Organic	NFC	3289
		FC	23492			FC	20821
	Conventional	NFC	38578		Conventional	NFC	32016
		FC	40911			FC	214308
Bordeaux	Organic	NFC	21119	Essen	Organic	NFC	3190
		FC	21442			FC	21424
	Conventional	NFC	36103		Conventional	NFC	31545
		FC	37259			FC	207746
Lille	Organic	NFC	20219	Bremen	Organic	NFC	3084
		FC	21760			FC	19266
	Conventional	NFC	35601		Conventional	NFC	25567
		FC	37229			FC	200519

Scenario 5 M-TOPSIS solution

APPENDIX B TABLE 13 LOCATION AND TECHNOLOGY SELECTION

Orchard/Processing Plant location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle Technology France	Bottle Technology Germany
Mexico	PEF	R. Osmosis	Saint-Martin-d'Abbat (FR)	Bröl (DE)	PET bottle	PET bottle

APPENDIX B TABLE 14 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1
Agro practice	4	4	4	4	2	4	4	1	4	2	4	4	1	4	1	4	4	4	2	1
Land area	100	100	100	100	100	100	100	96	100	80	100	100	100	100	100	100	100	100	100	100

APPENDIX B TABLE 15 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France				Germany			
Market City	Label	Process	Production output	Market City	Label	Process	Production output
Paris	Organic	NFC	195972	Berlin	Organic	NFC	19338
		FC	207941			FC	128517
	Conventional	NFC	333687		Conventional	NFC	189682
		FC	354067			FC	1261001
Marseille	Organic	NFC	72836	Hamburg	Organic	NFC	9814
		FC	77284			FC	65259
	Conventional	NFC	124007		Conventional	NFC	96291
		FC	131590			FC	640276
Lyon	Organic	NFC	43281	Munich	Organic	NFC	7113
		FC	45926			FC	47264
	Conventional	NFC	73698		Conventional	NFC	69789
		FC	78196			FC	464022
Toulouse	Organic	NFC	39677	Cologne	Organic	NFC	5437
		FC	42106			FC	36159
	Conventional	NFC	67570		Conventional	NFC	53346
		FC	71699			FC	354535
Nice	Organic	NFC	3103	Frankfurt	Organic	NFC	3668
		FC	3292			FC	24395
	Conventiona	NFC	5283		Conventiona	NFC	35993

	l	FC	5606		l	FC	239302
Nantes	Organic	NFC	25408	Stuttgart	Organic	NFC	3347
		FC	26960			FC	22260
	Conventional	NFC	43261		Conventional	NFC	32841
		FC	45906			FC	218382
Strasbourg	Organic	NFC	25186	Dusseldorf	Organic	NFC	3328
		FC	26725			FC	22137
	Conventional	NFC	42885		Conventional	NFC	32659
		FC	45505			FC	217093
Montpellier	Organic	NFC	22749	Dortmund	Organic	NFC	3321
		FC	24114			FC	22087
	Conventional	NFC	38733		Conventional	NFC	32584
		FC	41102			FC	216681
Bordeaux	Organic	NFC	21239	Essen	Organic	NFC	3234
		FC	22543			FC	21509
	Conventional	NFC	36175		Conventional	NFC	31729
		FC	38385			FC	211016
Lille	Organic	NFC	20923	Bremen	Organic	NFC	3084
		FC	22202			FC	20512
	Conventional	NFC	35627		Conventional	NFC	30261
		FC	37797			FC	201238

Scenario 6 M-TOPSIS solution

APPENDIX B TABLE 16 LOCATION AND TECHNOLOGY SELECTION

Orchard & Plant Processing location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle Technology France	Bottle Technology Germany
Mexico	PEF	R. Osmosis	Saint-Martin-d'Abbat (FR)	Bröl (DE)	PET bottle	PET bottle

APPENDIX B TABLE 17 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	1	1	1	0	0	0	0	1	0	0	0	0	1	1	0	1	1	0	0	0
Agro practice	4	2	1	4	4	4	4	2	4	4	4	4	4	1	4	2	4	4	4	4
Land area	100	100	100	100	96	99	99	100	99	98	100	100	97	99	89	100	100	100	100	93

APPENDIX B TABLE 18 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France				Germany			
Market City	Label	Process	Production output	Market City	Label	Process	Production output
Paris	Organic	NFC	190005	Berlin	Organic	NFC	12716
		FC	105950			FC	124063
	Conventional	NFC	332988		Conventional	NFC	106155
		FC	204393			FC	1261550
Marseille	Organic	NFC	50833	Hamburg	Organic	NFC	8787
		FC	43095			FC	64068
	Conventional	NFC	116817		Conventional	NFC	63115
		FC	78694			FC	638996
Lyon	Organic	NFC	37463	Munich	Organic	NFC	6601
		FC	26489			FC	45899
	Conventional	NFC	55221		Conventional	NFC	57274
		FC	53673			FC	463285
Toulouse	Organic	NFC	32824	Cologne	Organic	NFC	4897
		FC	29040			FC	33169
	Conventional	NFC	56251		Conventional	NFC	30048
		FC	40975			FC	354118
Nice	Organic	NFC	2746	Frankfurt	Organic	NFC	3258
		FC	2925			FC	23641
	Conventional	NFC	5121		Conventional	NFC	35049
		FC	5356			FC	238132
Nantes	Organic	NFC	21061	Stuttgart	Organic	NFC	2074
		FC	19044			FC	21215

	Conventional	NFC	40529		Conventional	NFC	22501
		FC	34490			FC	217432
Strasbourg	Organic	NFC	23048	Dusseldorf	Organic	NFC	2871
		FC	19349			FC	21748
	Conventional	NFC	36279		Conventional	NFC	29501
		FC	35610			FC	216236
Montpellier	Organic	NFC	21392	Dortmund	Organic	NFC	2361
		FC	18493			FC	17200
	Conventional	NFC	36616		Conventional	NFC	26211
		FC	22951			FC	215788
Bordeaux	Organic	NFC	19906	Essen	Organic	NFC	2980
		FC	16987			FC	20496
	Conventional	NFC	32829		Conventional	NFC	27731
		FC	30997			FC	209831
Lille	Organic	NFC	19143	Bremen	Organic	NFC	2563
		FC	15831			FC	19977
	Conventional	NFC	32825		Conventional	NFC	24056
		FC	27641			FC	200568

Scenario 7 M-TOPSIS solution

APPENDIX B TABLE 19 LOCATION AND TECHNOLOGY SELECTION

Orchard & Processing plant location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle technology France	Bottle technology Germany
Brazil	PEF	Multieffects	Drôme(FR)	Calvörde (DE)	Glass bottle	Aseptic carton

APPENDIX B TABLE 20 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0
Agro practice	4	1	4	4	4	1	4	4	4	4	4	1	4	4	4	4	4	1	4	4
Land area	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

APPENDIX B TABLE 21 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France			
Market City	Label	Process	Production output
Paris	Organic	NFC	194181
		FC	137605
	Conventional	NFC	333471
		FC	353877
Marseille	Organic	NFC	72544
		FC	72007
	Conventional	NFC	123917
		FC	131077
Lyon	Organic	NFC	43184
		FC	43773
	Conventional	NFC	73698
		FC	78036
Toulouse	Organic	NFC	39461
		FC	42043
	Conventional	NFC	67452
		FC	71646
Nice	Organic	NFC	3102
		FC	3280
	Conventional	NFC	5261
		FC	5581
Nantes	Organic	NFC	25331
		FC	26947
	Conventional	NFC	43234
		FC	45887
Strasbourg	Organic	NFC	25129
		FC	26469
	Conventional	NFC	42842
		FC	45489

Germany			
Market City	Label	Process	Production output
Berlin	Organic	NFC	19307
		FC	128505
	Conventional	NFC	189692
		FC	1261144
Hamburg	Organic	NFC	9811
		FC	64891
	Conventional	NFC	96103
		FC	639346
Munich	Organic	NFC	7100
		FC	46841
	Conventional	NFC	69526
		FC	463299
Cologne	Organic	NFC	5435
		FC	36051
	Conventional	NFC	53294
		FC	354546
Frankfurt	Organic	NFC	3664
		FC	24281
	Conventional	NFC	35961
		FC	238805
Stuttgart	Organic	NFC	3347
		FC	21806
	Conventional	NFC	32834
		FC	218279
Dusseldorf	Organic	NFC	3328
		FC	22137
	Conventional	NFC	32444
		FC	217114

Montpellier	Organic	NFC	22716	Dortmund	Organic	NFC	3321
		FC	24096			FC	21910
	Conventional	NFC	38675		Conventional	NFC	32508
		FC	41091			FC	216203
Bordeaux	Organic	NFC	21238	Essen	Organic	NFC	3234
		FC	22459			FC	21449
	Conventional	NFC	36037		Conventional	NFC	31609
		FC	38224			FC	210844
Lille	Organic	NFC	20572	Bremen	Organic	NFC	3084
		FC	22015			FC	20395
	Conventional	NFC	35538		Conventional	NFC	30097
		FC	37748			FC	201054

Scenario 7 M-TOPSIS solution

APPENDIX B TABLE 22 LOCATION AND TECHNOLOGY SELECTION

Orchard & Processing Plant location	Pasteurization technology	Concentration technology	Bottling location France	Bottling location Germany	Bottle Technology France	Bottle Technology Germany
Brazil	PEF	Multieffects	Saint-Martin-d'Abbat (FR)	Nieder-Olm (DE)	PET bottle	PET bottle

APPENDIX B TABLE 23 SUPPLIER SELECTION AND AGRO PRACTICE

Supplier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Selection	1	0	1	1	0	1	1	0	0	0	0	1	1	0	1	1	0	0	0	1
Agro practice	1	4	4	1	4	4	2	4	4	4	4	2	1	4	2	1	4	4	4	3
Land area	100	97	100	100	100	100	100	98	100	97	99	100	100	100	100	100	100	99	100	98

APPENDIX B TABLE 24 PRODUCTION CAPACITY ALLOCATION PER PROCESS TYPE, LABEL AND MARKET

France				Germany			
Market City	Label	Process	Production output	Market City	Label	Process	Production output
Paris	Organic	NFC	189235	Berlin	Organic	NFC	18615

		FC	205380
	Conventional	NFC	332256
		FC	335065
Marseille	Organic	NFC	70098
		FC	74062
	Conventional	NFC	122181
		FC	130349
Lyon	Organic	NFC	42026
		FC	44306
	Conventional	NFC	69575
		FC	76535
Toulouse	Organic	NFC	38918
		FC	41540
	Conventional	NFC	60779
		FC	69566
Nice	Organic	NFC	2910
		FC	3116
	Conventional	NFC	4903
		FC	4868
Nantes	Organic	NFC	25256
		FC	26288
	Conventional	NFC	41955
		FC	44458
Strasbourg	Organic	NFC	22677
		FC	25975
	Conventional	NFC	41251
		FC	43475
Montpellier	Organic	NFC	21138
		FC	24036
	Conventional	NFC	37846
		FC	40874
Bordeaux	Organic	NFC	18682

		FC	126264
	Conventional	NFC	187679
		FC	1260982
Hamburg	Organic	NFC	9223
		FC	62608
	Conventional	NFC	78379
		FC	613831
Munich	Organic	NFC	6364
		FC	45982
	Conventional	NFC	66205
		FC	456292
Cologne	Organic	NFC	4542
		FC	34069
	Conventional	NFC	52293
		FC	333412
Frankfurt	Organic	NFC	3389
		FC	24235
	Conventional	NFC	34188
		FC	238648
Stuttgart	Organic	NFC	3292
		FC	20896
	Conventional	NFC	31395
		FC	201018
Dusseldorf	Organic	NFC	2647
		FC	20729
	Conventional	NFC	31868
		FC	203739
Dortmund	Organic	NFC	3129
		FC	21699
	Conventional	NFC	31291
		FC	208825
Essen	Organic	NFC	3166

		FC	20839
	Conventional	NFC	35411
		FC	36567
Lille	Organic	NFC	19595
		FC	21653
	Conventional	NFC	31980
		FC	35835

		FC	20917
	Conventional	NFC	27261
		FC	207169
Bremen	Organic	NFC	2938
		FC	20051
	Conventional	NFC	28898
		FC	196755

List of Figures

List of Tables