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Supply chain design with product life cycle considerations

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To my parents, to my brothers,
To my husband,
To my daughter,
To my in-laws,
To all those who believe in the richness of learning

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Abstract

Our research addresses the problem of designing a multi-level supply chain, while taking into consideration the product life cycle. By product life cycle, we mean the succession of the four marketing stages that a product goes through since its introduction to the market and until it will be removed from. All products have a life cycle. Generally this life cycle can be classified into four discrete stages: introduction, growth, maturity and decline.

Depending on the product life cycle phases, and based on a thorough analysis of the different supply chain potential actors, this study aims to establish mathematical models to design an efficient supply chain network.

Three main models have been developed in this thesis.

The first proposed model aims to design a product-driven supply chain with a minimal total cost, taking into consideration the evaluation of the different potential actors effectiveness, according to several criteria (cost, quality, innovation, quality service, timely delivery ...).

A second model was developed to design of a sustainable supply chain network, taking into account the product life cycle. In this model, three different objectives were simultaneously considered, namely, an economic objective, an environmental objective and a social objective.

In the two previous models, we have assumed that the product has a classical life cycle. However, in the reality this is not always the case. Indeed, some products have very atypical life cycles, whose curves are very different from the classical one.

To tackle this problem, in the third part of this thesis, we propose a stochastic model to design a robust supply chain network, taking into account the different product life cycle scenarios.

Résumé

Notre travail de recherche traite la problématique de la conception d'une chaîne logistique multi-niveaux tout en tenant compte du cycle de vie du produit. Par cycle de vie du produit, nous entendons la succession des quatre phases de commercialisation que traverse généralement un produit à travers le temps, à savoir : l'introduction, la croissance, la maturité et le déclin. L'objectif est de mette en place un modèle mathématique qui soit fondé sur une analyse approfondie des différents acteurs de la chaîne, selon la phase du cycle de vie du produit.

Trois principaux modèles ont été développés dans cette thèse. Chacun fait l'objet d'un chapitre à part entière.

Le premier modèle développé vise à concevoir une chaîne logistique de coût minimum, tout en prenant en considération l'efficacité des différents acteurs potentiels calculée selon plusieurs critères (coût, qualité, innovation, qualité du service, délais de livraisons, …), ainsi que sa variation au cours du cycle de vie du produit.

Un deuxième modèle a été mis en place pour la conception d'une chaîne logistique durable, tout en prenant en considération le cycle de vie du produit. Dans ce modèle, trois objectifs différents ont été pris en compte à la fois, à savoir, un objectif économique, un objectif environnemental et un objectif social.

Dans les deux premiers modèles, nous avons supposé que le produit aura un cycle de vie classique. Cependant, dans la réalité, ceci n'est pas toujours le cas. En effet, quelques produits connaissent des cycles de vie très atypiques et donc très éloignés de la courbe d'un cycle de vie théorique.

Pour ce faire, un troisième modèle stochastique a été proposé pour la conception d'une chaîne logistique robuste, tenant compte des différents scénarios du cycle de vie du produit.

CHAPTER 1

Introduction

1.1 Motivation

Globalization has increased the complexity of supply chains with the involvement of more stakeholders, facilities, and technologies. Therefore, many new challenges and complexities have emerged in the field of supply chain management.

Indeed, global competition has imposed a tremendous pressure on product and service providers to transform and improve their operations and practices. Companies are responding to this pressure by reengineering and streamlining their operations to better serve their customers. More specifically, firms are involved in improving the performance of their supply chains through various strategic and operational tools. One of the strategies utilized by companies is to concentrate on their core competencies in the chain value and outsource of the other functions. Actually, firms are indulged in strategic organizational networks such as network organizations, virtual corporations, and value-added partnerships. However, the success of supply chain networks depends ,to a large extent, on how effectively they are designed and operated.

These supply chain networks are considered as a solution to effectively meet the customer's requirements such as low costs, a high product variety, high quality, and short lead times

(Busby and Fan, 1993; Byrne, 1993; Goldman, 1994; Iacocca Institute, 1991; Johnston and Lawrence, 1988; Snow et al., 1992).

Referring to marketing the literature, we note that this performance is directly related to the life cycle of the product. Indeed, the product life cycle could direct the supply chain to the appropriate market strategy.

Similarly, it should be noted that the consumer's requirements are closely linked to the product life cycle and their relative importance differs from one stage to another; for instance, availability and technology are needed at the ‘‘introduction’’ phase, and cost, quality and speed are needed at the ‘‘maturity’’ phase.

Facing this problem, the whole company should carefully manage the product life cycle, and the supply chain actors’ mechanism should also be matched up concurrently.

Nokia, the Finnish mobile phone manufacturer for example, manufactures the early series of its products in Finland at a product launch, and once established, will hand a volume production to contract manufacturers who are located in the Baltic and in China, and at the end of the life span (in some cases) even taking the production back in-house as they become close to withdrawing the product from the market.

The main concept that we focus on ,in this thesis, is the consideration of the product life cycle in the supply chain network design.

1.2 Research axes and contributions

This introductory Chapter is followed by the theoretical background and the state of art in Chapter 2, which is a review of the Supply Chain Network Design approaches and resolution methods. Among other things, we recall the different decision levels in the Supply Chain (strategic, tactical and operational level), the supply chain network structure (single/multiple layer(s), single/multiple product(s), single/multiple period(s), single/multiple objective (s), single/multiple modality, deterministic/stochastic parameters) and existing deterministic SCND models and SCND models under uncertainty.

For an effective supply chain, the assessment of actors and the selection process are essential for improving the performance of a focal company and its supply chains. An investigation is made, in chapter 3, to develop a selection procedure of supply chain actors by considering different selection criteria and different product life cycle phases.

An attempt is made to ensure that the evaluation results satisfy the current product competition strategies, and also improve the effectiveness and efficiency of the entire supply chain. The resolution procedure is made up of two phases. In the first phase, a multi-criteria decision making problem is proposed for the supply chain actors' evaluation.

A combination between the Analytical Hierarchical Process (AHP) and the Fuzzy Linguistic Quantifier Guided Order-Weighted Aggregation (FLQG-OWA) operator is used to satisfy the enterprise product development strategy based on different phases of the product life cycle. The second phase looks for the optimal supply chain design to satisfy the customer's demands and economic criteria using a mixed integer linear programming model.

As supply chains have grown tremendously in recent years, focusing only on the economic performance to optimize the costs or returns of the investments (ROIs), became not sufficient to sustain the development of supply chain operations. Indeed, the impact of different activities that are involved in supply chains, such as the process of manufacturing, warehousing, distributing etc. on the environment and social life of city residents cannot be ignored.

Correspondingly, the concepts of green supply chain management and sustainable supply chain management have emerged to emphasize the importance of implementing environmental and social concerns simultaneously with economical factors in supply chain planning.

In chapter 4 of this thesis, we study the problem of designing sustainable supply chain networks. However, few studies endeavor to optimize economic returns, environmental concerns, and the social performance, all together for supply chains. The challenging issues are how to achieve a certain balance among the business goals, social concerns, and the environmental impacts of different activities in supply chains. This chapter focuses on the problem of designing sustainable supply chain networks and taking into consideration the triple bottom lines of maximizing economic returns, minimizing environmental impacts, and maximizing the social performance for the supply chains. We use the Weighted Goal Programming (WGP) approach seeking to reach the three set goals.

Up to this level of the thesis, we have only considered the classical product life cycle curve.

However, numerous marketing-oriented articles have discussed the product life cycle theory, and they all reached an agreement on the fact that there may be different scenarios of life cycle curves, that could be different from the classical ones.

Indeed, the classical PLC shape that we have used in the previous chapters, has been only one of 12 types of PLC patterns discovered by the investigators.

Theoretically, product sales follow a bell curve, and the product life cycle should begin with the introductory stage, then growth, maturity and finally the decline stage.

Although this scenario remains the most classical, in reality, products could have been very atypical life cycle curves and so, very far from the theoretical life cycle curve.

As uncertainty is one of the characteristics of the product-driven supply chain networks, the strategic phase has to take uncertain information into account.

Certainly, the supply chain structure must be very robust to deal with the unpredictable market demand, the uncompromising levels of competition, and the different product life cycle patterns.

In chapter 5 of the thesis, we present a based stochastic programming method that seeks a solution which is appropriately balanced among some alternative product life cycle scenarios, as identified by field experts. We apply the stochastic models to a representative real case study. The interpretation of the results is meant to grant more insight to decision-making under the uncertainty of the supply chain design.

Finally, chapter 6 concludes the research findings and the activities undertaken throughout the thesis.

CHAPTER 2

Supply chain design with product life cycle considerations:
Theoretical background and state of the art

2.1 Introduction

This chapter is devoted to introduce general supply chain design problems and more specifically the particular supply chain design problem with product life cycle considerations. We present the basic concepts that are necessary to understand the different issues and concepts discussed in this thesis.

We first present the concept of the supply chain, the different supply chain decision levels, and some supply chain strategies.

Then, we are particularly interested in the supply chain design problem with product life cycle considerations. We introduce the different product types, define the product life cycle concept, and present some supply chain design strategies as proposed in the literature dealing with linking the supply chain design to the product life cycle, according to the product type.

After, a non-exhaustive review of various supply chain design problems proposed in the literature was illustrated, as well as the different resolution methods proposed to solve them.

Finally, we present the few studies in the literature that consider the product life cycle in the supply chain design network problem.

2.2 Theoretical background

The past decade has witnessed an increasing recognition of the importance of the supply chain management. In industry, the rapid growth of supply chain software companies testifies to the significance that businesses place on the efficient management of their supply chains. Research in this area has become a key focus of the operations of the management academic community in recent years.

The current research on supply chain management has covered conceptual issues and managerial themes (Cox and Lamming, 1997), frameworks for strategy implementation (Harland, 1996), social aspects of supply chain management (Price, 1996), coordinated management of the supply chain (Thomas and Griffin, 1996), the application of inter-organizational information systems in the supply chain (Holland, 1995), design and analysis of supply chain models (Beamon, 1998), etc.

But what exactly is supply chain and supply chain management?

Numerous definitions of a supply chain exist in the literature.

According to Beamon (1998), a supply chain is ‘‘an integrated process wherein a number of various business entities; namely suppliers, manufacturers, distributors, and retailers; work together in an effort to: (1) acquire raw materials, (2) convert these raw materials into specified final products, and (3) deliver these final products to retailers’’ .This chain is traditionally characterized by the flow of materials and information both within and between business entities.

Mentzer et al. (2001) defined the supply chain as a set of organizations directly linked by one or more upstream and downstream flows of products, services, finances, and information from a source to a customer.

Another definition is given by Simchi-Levi et al. (2003), who state that supply chains are flexible, dynamic and complex networks of organizations.

A customer focused definition is given by Hines (2004) "Supply chain strategies require a total systems's view of the linkages in the chain that work together efficiently to create customer satisfaction at the end point of delivery to the consumer. As a consequence, costs must be lowered throughout the chain by driving out unnecessary costs and focusing attention on adding value. Throughout efficiency must be increased, bottlenecks removed and performance measurement must focus on total systems efficiency and equitable reward distribution to those in the supply chain adding value. The supply chain system must be responsive to customer requirements".

According to the Council of Supply Chain Management Professionals , supply chain management encompasses the planning and management of all activities involved in sourcing, procurement, conversion, and logistics' management. It also includes the crucial components of coordination and collaboration with channel partners, who can be suppliers, intermediaries, third-party service providers, and customers. In essence, supply chain management integrates both supply and demand management within and across companies.

This definition leads to several observations. First, supply chain management takes into consideration every facility that has an impact on cost and plays a role in making the product conform to the customer's requirements: from supplier and manufacturing facilities , through warehouses and distribution centers to retailers and stores. Indeed, in some supply chain analyses, it is necessary to account for the suppliers’ suppliers and the customers’ customers because they have an impact on the supply chain performance.

Second, the objective of supply chain management is to be efficient and cost-effective across the entire system; total system wide costs, from transportation and distribution to inventories of raw materials, work in process, and finished goods, are to be minimized. Thus, the emphasis is not on simply minimizing transportation cost or reducing inventories but, rather, on taking a system's approach to supply chain management. Finally, because supply chain management revolves around an efficient integration of suppliers, manufacturers, warehouses, and stores, it encompasses the firm’s activities at many levels, from the strategic level through the tactical to the operational one.

2.2.1 *Supply chain decision levels*

Supply chain management decisions are often said to belong to one of three levels; the strategic, the tactical, or the operational level.

At the strategic level, company management makes high level strategic supply chain decisions that are relevant to the whole organization. The decisions that are made with regards to the supply chain should reflect the overall corporate strategy that the organization is following.

The strategic supply chain processes that management has to decide upon whether or not it will cover the breadth of the supply chain. These processes include product development, customers, manufacturing, sellers and logistics.

Tactical supply chain decisions focus on adopting measures that will produce cost benefits for a company. Tactical decisions are made within the constraints of the overarching strategic supply chain decisions made by the company management.

Operational supply chain decisions can be made hundreds of times each day in a company. These are the decisions that are made at business locations that affect how products are developed, sold, moved and manufactured. Operational decisions are made with an awareness of the strategic and tactical decisions that have been adopted within a company. These higher level decisions are made to create a framework within the company's supply chain and to operate the best competitive advantage. The day to day operational supply chain decisions ensure that the products efficiently move along the supply chain achieving as such the maximum cost benefit.

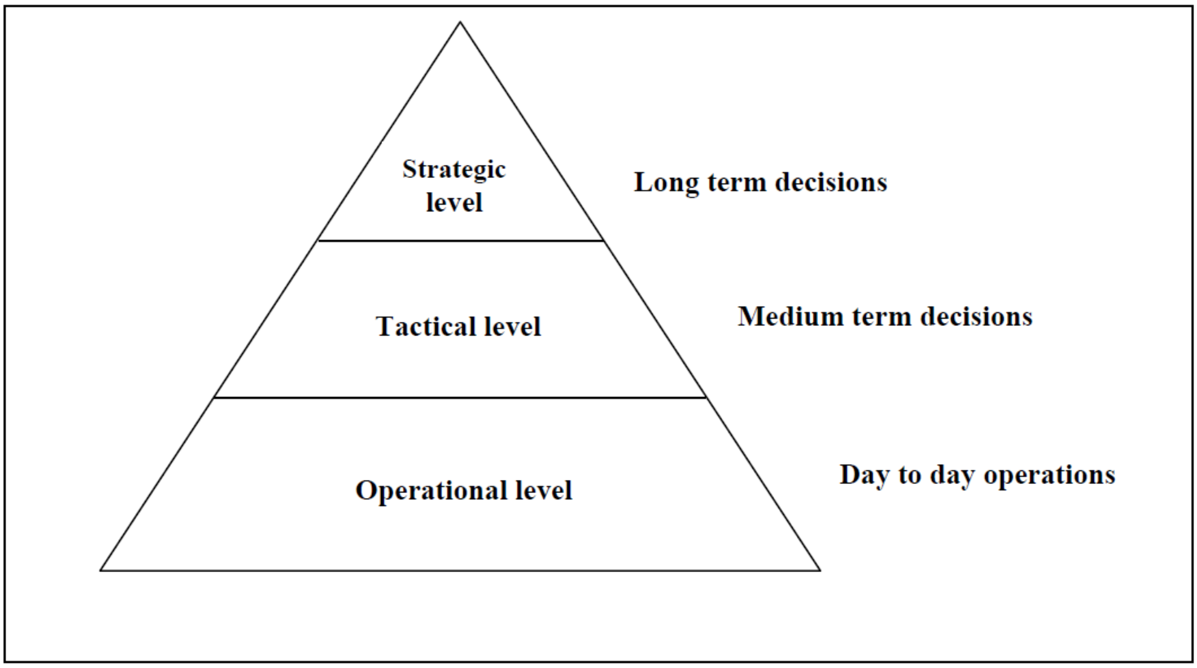


Figure 2.1:Supply chain decision levels

The effective supply chain design calls for robust analytical models and design tools. Previous works in this area are mostly operation research oriented without taking into account the manufacturing aspects.

In the last decade, researchers began to realize that the decision and integration effort in supply chain design should be driven by the manufactured product, specifically, product characteristics and product life cycle.

This problem has two main aspects: the importance of the product life cycle in the supply chain strategy, and the decision support models for the supply chain network design. Consequently, we review the relevant the literature pertaining to these two themes.

2.2.2 *The product types, product life cycle and supply chain strategies*

a. The product types

Generally, products can be categorized into three types, namely, functional, innovative, and hybrid (Huang et al., 2002).

Functional products’ demand can be forecast quite accurately and their market share remains fairly constant. They enjoy the life cycle with a superficial design modification leading to different product types.

Innovative products are new products developed by organizations to capture a wider share of the market. They are significantly different from the available product types and are more adapted to the customer requirements (mass customization). They, at times, represent a breakthrough at the level of product design. Innovative products are the result of customers' designs, which indicate their ever-changing requirements.

Hybrid products can consist of either (a) different combinations of functional components, or (b) a mixture of functional and innovative components.

b. The product life cycle

All products have a life cycle, typically depicted as a curve of unit sales for a product category over time (Wiersema, 1982), which can be classified into four discrete stages: introduction, growth, maturity and decline.

When the product is introduced, sales will be low until customers become aware of the product and its benefits. The distribution is selective and scattered as the firm starts the implementation of the distribution plan. During the introductory stage, the firm is likely to incur additional costs associated with the initial distribution of the product. These higher costs coupled with a low sales' volume usually make the introduction stage a period of negative profits.

After, sales' volume grows as the customers become more aware of the product and its benefits and additional market segments are targeted. An improvement of the product quality may be considered. The distribution becomes more intensive and trade discounts are minimal if wholesalers show a strong interest in the product. The growth stage is a period of a rapid revenue growth.

The maturity stage is the most profitable. Into this stage, sales' volume continues to increase, but at a slower rate. New distribution channels are selected in order to avoid losing shelf space. The primary goal during the maturity stage is to maintain market share and extend the product life cycle.

After the period of maturity, eventual sales come to decline as the market becomes saturated, the product becomes technologically obsolete, or customers' tastes change. In this decline stage, distribution becomes more selective and channels that are no longer profitable are phased out.

Table 2.1 summarizes the different business characteristics over the product life cycle.

If a curve is drawn showing the product sales volume, over a fixed time horizon H, it may take one of many different shapes, the most classical among them is shown in figure 2.2.

Table 2.1: the different business characteristics over the product life cycle

Stage	Introduction	Growth	Maturity	Decline
Market growth rate	Slight	Very large	Moderate to nil	Negative
Technological change in product design	Very great	Great	Moderate to slight	slight
Key business opportunity	Capturing market leadership	Capturing market share	Capturing market volume	Capturing market legacy demand
Key business risk	Investing in a wrong technology/product	Failing to manage ramp up	Price ware/price erosion	Obsolete stocks

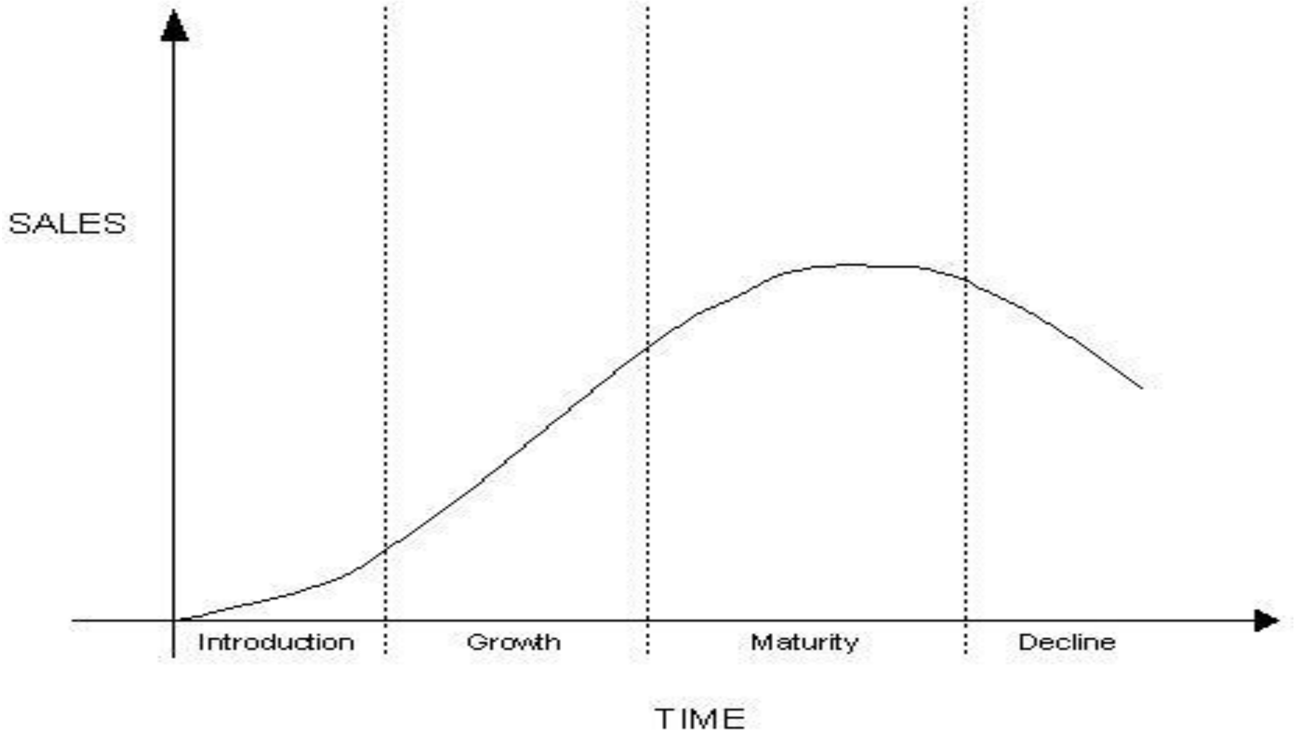


Figure 2.2:Marketable product life cycle

2.2.3 *The supply chain strategies*

Typically, the chain can be classified into three categories: lean supply chain, agile supply chain, and hybrid supply chain.

A lean supply chain resorts to a continuous improvement to focus on the elimination of waste or non-value added steps in the supply chain. It is supported by the reduction of setup times to allow the economic production of small quantities; thereby achieving a cost reduction, flexibility and internal responsiveness.

An agile supply chain basically focuses on responding to unpredictable market changes and capitalizing on them. It tries to achieve a faster delivery and lead time flexibility. It deploys new technologies and methods, utilizes information systems/technologies and data interchange facilities, puts more emphasis on organization issues and people (knowledge and empowered employees), integrates the whole businesses' process, enhances innovations all over the company, and forms virtual companies and a production based on customer designed orders.

Along with the lean and agile supply chain, the existence of an intermediate chain known as the hybrid supply chain was proposed (Huang et al., 2002). It generally involves ‘‘assemble to order’’ products whose demand can be quite accurately forecast. The chain helps achieve a mass customization by postponing product differentiation until a final assembly. Both lean and agile techniques may be utilized for a component production. The company– market interface has to be agile to understand and satisfy customers' requirements by being responsive, adaptable and innovative.

Based on Wang et al. (2004), table 2.2 provides a comparison of different types of supply chains.

Table 2.2: the different types of supply chains

Category	Lean supply chain	Agile supply chain	Hybrid supply chain
Purpose	Focus on cost reduction and flexibility for already available products. Primarily aims at cost cutting, flexibility and incremental improvements in products.	Aims to produce in any volume and deliver to a wide variety of market niches simultaneously. Provides customized products at short lead times (responsiveness) by reducing the cost of variation.	Employ lean production methods manufacturing. Interfaces with the market to understand customer requirements.
Length of product life cycle	Standard products have relatively long life cycle times (>2 years).	Innovative products have short life cycle times (3 months–1 year).	Involved the production of ‘‘assemble to order’’ products, which stay in the maturity phase of the life cycle for a long time.
Demand patterns	Demand can be accurately forecasted and average margin of forecasting error tends to be low, roughly 10%	Demand are unpredictable with forecasting errors exceeding 50%.	The average product demand can be accurately forecasted. Component level forecasting may involve larger errors.

Approach to choosing suppliers	Supplier attributes involve low cost and high quality.	Supplier attributes involve speed, flexibility, and quality.	Supplier attributes involve low cost and high quality, along with the capability for speed and flexibility, as and when required.
Production planning	Works on confirmed orders and reliable forecasts.	Has the ability to respond quickly to varying customer needs (mass customization).	Works on confirmed orders and reliable forecasts with some ability to achieve some produce variety.
Product design strategy	Maximize performance and minimize cost.	Design products to meet individual customer needs.	Use modular design in order to postpone product differentiation for as long as possible.
Approach to manufacturing	Advocates lean manufacturing techniques.	Advocates agile manufacturing techniques, which is an extension of lean manufacturing.	Employs lean and agile manufacturing techniques
Manufacturing focus	Maintain high average utilization rate.	Deploy excess buffer capacity to ensure that raw material/ components are available to manufacture the innovative products according to market requirements.	Combination of lean and agile supply chain depending on components

Inventory strategy	Generates high turns and minimizes inventory throughout the chain.	Make in response to customer demand.	Postpone product differentiation and minimize functional components inventory.
Lead time focus	Shorten lead-time as long as it does not increase cost.	Invest aggressively in ways to reduce lead times.	Similar to the lean supply chain at component level (shorten lead-time but not at the expense of cost). At product level, to accommodate customer requirements.
Human resources	Empowered individuals working in teams in their functional departments.	Involves decentralized decision making. Empowered individuals working in cross-functional teams, which may be across company borders too.	Empowered individuals working in teams in their functional departments.

Table 2.3: the supply chain classification based on product type and product life cycle

Product life cycle	Product type		
	Functional	Innovative	Hybrid
Introduction	Lean Supply chain	Agile Supply chain	Hybrid Supply chain
Growth	Lean Supply chain	Agile Supply chain	Hybrid Supply chain
Maturity	Lean Supply chain	Hybrid/Lean Supply chain	Hybrid Supply chain
Decline	Lean Supply chain	Hybrid/Lean Supply chain	Hybrid Supply chain

The discussions in marketing and logistic the literature universally conclude that the product life cycle stages have a great impact on the appropriate supply chain design. Consequently, depending on the product life cycle stage, a firm should select its effective supply chain partners and dynamically match the supply chain strategies to satisfy the product requirements across multiple criteria and to maximize competitiveness over time. Indeed, the competitive criteria generally differ depending on the product type and the product life cycle phase. Based on Wang et al. (2004), table 2.3 summarizes the supply chain classification based on product type and product life cycle.

The consideration of the product life cycle in the design of the supply chain has started to receive more interest in the last decade. However, there are still gaps to fill. Indeed, it should be noted that all existing papers dealing with this subject in the literature, focus only on one level, namely the suppliers.

In the following, we classify the research on supply chain design with product life cycle consideration into four major categories and list representative publications in table 2.4. From this table, we can remark that, in the literature, many papers have only suggested marketing strategies to link the supply chain design with the product life cycle.

Also, only few researchers have treated the problem as an optimization problem, while these decision-making processes should be guided by a comprehensive set of performance metrics.

Another main point to notice is that, even the few papers that have dealt with the problem as an optimization one, have taken into consideration only a single supply chain level and only a single product life cycle period.

2.3 State of the art

2.3.1 The decision support models for the supply chain network design

The literature about the supply chain design is very rich in mathematical models addressing different issues referring to this problem, but despite the success in resolving these supply chain design problems, the existing models and resolution procedures are more often confined to a single period, and are not designed to handle the design of a multi-level supply chain taking into account the different phases of a product life cycle.

Dolgui et al. (2005) presented a set of modelling techniques taking into account the enterprise integration problem, the knowledge management in the SME networks, and the human resources in business process engineering. They considered all the stages of product life cycle in an integrated approach, from the product/process design to the customer delivering.

Thomas et al. (2008) proposed a special procedure based on mathematical programming modelling to obtain a stable Master Production Schedules (MPS) on the basis of a stable and robust Sales and Operations Planning (SOP).

Dolgui and Proth (2012) considered how modern production and operations management techniques can respond to the pressures of the competitive global marketplace. It presents a comprehensive analysis of concepts and models related to outsourcing, dynamic pricing, inventory management, RFID, and flexible and re-configurable manufacturing systems, as well as real-time assignment and scheduling processes.

2.3.2 The multi-period supply chain design

Arntzen et al. (1995) developed a model for a global multi-period supply chain system, incorporating a bill of material constraints. The model contains several inter- national features such as duty relief and drawback. The authors reported the solutions of several real life cases by employing non- traditional solution methods, such as elastic constraints, row factorization, cascaded problem solution, and constraint-branching enumeration.

Hinojosa et al. (2000) addressed the use of a mixed integer programming for solving a multi-period two- echelon multi-commodity capacitated location problem. They proposed a lagrangean relaxation to solve the problem, together with a heuristic procedure that constructs feasible solutions of the original problem from the solutions at the lower bounds obtained by the relaxed problems.

Canel et al. (2001) developed an algorithm to solve the capacitated, multi-commodity, dynamic, and multi-stage facility location problem. Their algorithm consisted of two parts: in the first part, a branch and bound procedure is used to generate several candidate solutions for each period, and then a dynamic programming is used to find an optimal sequence of configurations over the multi-period planning horizon.

Yildirim et al. (2005) studied a dynamic planning and sourcing problem with service level constraints. Specifically, the manufacturer must decide how much to produce, where to produce, when to produce, how much inventory to carry, etc., in order to fulfill random customer demands in each period. They formulated the problem as a multi-period stochastic programming problem, where service level constraints appear in the form of chance constraints (Birge and Louveaux, 1997).

2.3.3 The multi-criteria supply chain design

The manufacturing strategy the literature suggests five categories of competitive priorities: cost, quality, delivery, flexibility, and innovation (Hayes & Wheelwright, 1979). Strategic sourcing recognizes that suppliers have a strategic role and that an effective configuration of the supply base and development of the appropriate buyer– supplier relationships can provide access to resources for achieving competitive priorities (Carr & Pearson, 1999; Narasimhan & Das, 1999; Krause, Scannell, & Calantone, 2000). Consequently, the evaluation and selection of the suppliers according to the buyer's changing priorities is important in the strategic sourcing.

The product life cycle offers a framework to plan and examine the sourcing strategy of a firm (Birou et al., 1998; Rink & Dodge, 1980). The product life cycle of both the procured products and end products, manufactured by a firm, would affect the sourcing context and should, therefore, be considered in the analysis. Based on the empirical research, Rink and Fox (1999) developed a PLC-oriented procurement framework which suggests that the sourcing strategy for the components that strongly influence sales of end products should be governed by the competitive priorities of the end products. Their study suggests that a buying firm's relative priority for cost increases from introduction to maturity stage as the end product becomes increasingly standard.

When the product life cycle of procured components is strongly linked to that of the end products (Tibben-Lembke, 2002), it follows that the relative importance of cost for the procured components also increases over time as they become increasingly standardized.

Consequently, the buyer emphasizes the cost toward the later stages of a component's product life cycle (Reed, 2002).

In some real-life situations, decision makers may not possess a precise or sufficient level of knowledge of the problem, or are unable to discriminate explicitly the degree to which a criterion is more important than another or one alternative is better than other. In such cases, it is very suitable to express the decision maker's preference values with the use of a linguistic variable rather than exact numerical values (Bordogna et al.1997; Kacprzyk, 1986; Zadeh, 1975).

Many techniques were used to tackle the multi-criteria decision making problems using linguistic terms. Among these methods, we can cite the Analytical Hierarchical Process (AHP).

This method provides a framework to cope with multiple criteria situations, involving intuitive, rational, qualitative, and quantitative aspects (Khurrum et al.(2002)).

Ghodsypour and O'Brien (1998) solved a supplier selection problem using a hybrid approach involving AHP and linear programming.

Wang, et al. (2004) applied the AHP method to choose a strategy from the agile/lean supply chain. Further, they used the Pre-emptive Goal Programming (PGP) to obtain the optimal order quantity from the suppliers. Tuzkaya et al. (2008) included qualitative and quantitative criteria (benefits, opportunities, costs and risks), to assess and select undesirable facility locations. Further, Kumar et al. (2008) solved a supplier selection problem using AHP and a fuzzy linear programming. Ku et al. (2010) and Lee et al. (2006b) used fuzzy AHP and fuzzy goal for the supplier selection. In their model, the fuzzy AHP was first applied to calculate the weights of the criteria. These weights were subsequently used in a fuzzy goal programming to select the supplier.

Furthermore, many aggregation operators have been developed to aggregate a linguistic preference information during the aggregation phase, such as the linguistic Ordered Weighted Averaging operators OWA.

Chang et al. (2006) proposed a fuzzy multiple attribute decision making method based on the fuzzy linguistic quantifier. They attempted to ensure that the evaluation results satisfy the current product competition strategies, and improve the effectiveness and efficiency of the entire supply chain. They applied the fuzzy concept to both the ordinal and cardinal pieces of information, and used the Fuzzy Linguistic Quantifier Guided Order-Weighted Aggregation (FLQG-OWA) operator to satisfy the enterprise product development strategy based on different phases of the product life cycle.

This operator allows the aggregation of different amounts and numbers of sets into a single final evaluation value, in accordance to the distinct fuzzy linguistics. The fuzzy quantifier acts as a medium for aggregating the evaluation values among different attributes, which represented the outcome of evaluation for each supply chain actor by decision makers.

Wang et al. (2009) presented a further research that is deeper into the concept introduced in Chang et al. (2006), using a multi-granularity linguistic variable and numerical ration scale to represent the overall supply performance. They resolved the measurement complexity by unifying the derived information, and constructed a fuzzy preference to adjust the consistent direction and transform information into a fuzzy relationship. Finally, the fuzzy linguistic quantifier guided ordered weighted aggregation (FLQG-OWA) operator with a maximal entropy was computed and aggregated with all indicators to meet the current policy of the focal company.

Besbes et al. (2012) presented a multi-phase mathematical programming approach for effective supply chain design with product life cycle considerations. The methodology proposed develops and applies a combination of multi-criteria decision making models, based on aggregation concepts, and linear and integer programming methods.

Singh and Benyoucef (2013) presented a fuzzy TOPSIS and soft consensus based group decision making methodology to solve the multi-criteria decision making problems in supply chain coordination, i.e., selection problems. The methodology is proposed to improve the coordination in decentralized supply chains, i.e., supply chains that comprise several independent, legally separated entities with their own decision authorities.

Lajili et al. (2013) considered the multi-criteria inventory classification problem. They proposed a new classification algorithm referred to as Constructive Order Classification Algorithm (COCA). This algorithm is based on some simple priority rules and aims to standardize the classification and provide relative stability in the classification through a consensus process.

2.3.4 The multi-objective supply chain design

In spite of the complexity and economic importance of the supply chain actors' selection, relatively less attention has been paid, in the literature, to the application of mathematical programming methods for the actors' selection and the supply chain network design.

The initial research in this area mainly dealt with single-objective and single-product supplier selection problems, and subsequent studies increasingly focused on multi-criteria, multi-objective, multi-product cases.

Several studies have applied the multi-objective programming MOP approach for supplier-selection problems (e.g., Akinc, 1993; Weber & Ellram, 1993; Weber, Current, & Desai, 2000). These models allow the allocation of orders to suppliers who satisfy the minimum performance criteria across multiple dimensions, that are; delivery, quality, and other factors.

Roghanian et al. (2007) considered a probabilistic bi-level linear multi-objective programming problem and its application in enterprise-wide supply chain planning problem, where market demand and warehouse capacity are random variables.

Alcada-Almeida et al. (2009) proposed a multi-objective programming approach to identify locations and capacities of hazardous material incineration facilities and balance the social, economic, and environmental impacts.

Benyoucef and Xie (2011) addressed the design of supply chain networks including both network configuration and related operational decisions such as order splitting, transportation allocation and inventory control. The goal is to achieve the best compromise between cost and customer service level. They proposed an optimisation methodology that combines a multi-objective genetic algorithm (MOGA) and simulation to optimise not only the structure of the network but also its operation strategies and related control parameters. They also developed a flexible simulation framework to enable the automatic simulation of the supply chain network with all possible configurations and all possible control strategies.

2.3.5 The green supply chain design

Green supply chains, or environmentally conscious supply chains, involve the design and implementation of supply chains that incur minimal environmental impact (Sarkis, 2006).

Environmental awareness and legislation have successfully pushed companies to aim at manufacturing greener products that would have less impact on the environment through all the stages of their manufacturing and distribution (Azzone and Noci,1996). Reducing the supply chain’s emissions has become a necessary obligation, and the trade-offs in the supply chain are no longer just about cost, service and quality, but cost, service, quality and carbon, (Butner et al. 2008).

Ramudhin et al. (2008) introduced a Mixed Integer Linear Program (MILP) formulation of the green supply chain design network problem. Their model focuses on the impact of transportation, subcontracting, and production activities on the design of a green supply chain. Wang et al. (2011) proposed a multi-objective optimization model that captures the trade-off between the total cost and the environmental influence.

Abdallah et al. (2012) developed a MILP for the carbon-sensitive supply chain that minimizes the emissions throughout the supply chain by taking into consideration the green procurement. Elhedhli and Merrick (2012) developed a green supply chain design model that incorporates the cost of carbon emissions into the objective function. The goal of the model is to simultaneously minimize the logistics' costs and the environmental CO2 emissions cost by strategically locating warehouses within the distribution network.

Jaegler and Burlat (2012) focused on CO2 emissions along supply chains, from freight energy use to inventories storage. Their purpose was to compare levels of CO2 emitted for differing configurations of different scenarios.

Chaabane et al. (2012) presented a mixed-integer linear programming based framework for a sustainable supply chain design with Life Cycle Assessment (LCA) considerations. The LCA is a theory that is very different from the PLC. The LCA is the process that evaluates the environmental impacts associated with a product, process or activity. It identifies and quantifies the energy and materials used and the waste released into the environment, and evaluates and implements the possible opportunities for environmental improvements. The assessment covers the entire life cycle of the product, process or activity, including extracting and processing raw materials, manufacturing, transportation and distribution, reuse and maintenance, recycling and final disposal. Besbes et al. (2013) presented a two-phase mathematical programming approach for effective supply chain design with a total cost minimization, while considering environmental aspects throughout the product life cycle.

2.3.6 The Stochastic supply chain design

The most recent comprehensive review for supply chain design demonstrated that a great part of the literature deals with deterministic models when compared to stochastic ones (approximately 82% against 18%) (Melo et al., 2009). Uncertainty is one of the most important but also the most challenging problems in the practical analysis of the supply chain design performance. However, the the literature in the background of the supply chain design under uncertainty is still scarce. Because of the difficulty in solving the stochastic supply chain design problems, research on more complex multi-echelon models, under uncertainty, began to appear in the literature only in the past decade.

Within the supply chain design models under demand, uncertainty has received a significant attention in the literature.

Aghezzaf (2005) discussed the multi-period strategic capacity planning and warehouse location problem for supply chains serving markets with uncertain and unpredictable demands. Klibi et al. (2010) discussed the supply chain network design problem under uncertainty, and presented a criteria review of the optimization models proposed in the literature. Wang et al. (2011) developed a genetic algorithm with an efficient greedy heuristics to solve a facility location and task allocation problem of a two-echelon supply chain against stochastic demand. Chen (2012) proposed a two- stage optimization model by using a real option approach for a dynamic supply chain under stochastic demands.

Some articles include several stochastic components simultaneously with the market demand.

Azaron et al. (2008) developed a multi-objective stochastic programming approach for supply chain design under uncertainty. They considered that demands, supplies, processing, transportation, shortage and capacity expansion costs are all uncertain parameters.

Bidhandi and Yusuff (2011) proposed an integrated model for solving supply chain network design problems under uncertainty. The stochastic supply chain network design model was provided as a two-stage stochastic program. The main uncertain parameters were the operational costs, the customer's demand and the capacity of the facilities.

2.4 *State of the art interpretation*

Based on the current the literature review, it should be noted that we only have a small number of scientific researches dealing with the coordination of the supply chain network design and the product life cycle, and even less multi-level and multi-period optimization problems in this field. To our knowledge, there is no quantitative study in the literature considering the multi-level, multi-period supply chain network design with a product life cycle consideration. Researches in the framework of this thesis are positioned in this context.

Table 2.4: Summary of research in supply chain design with product life cycle considerations

	Marketing strategies		Optimization		Level		Period	
Authors	Identification	Analysis	Mono-objective	Multi-objective	Single	Multiple	Single	Multiple
Hayes and Wheelwright (1979)	✓							
Rink and Swan (1979)	✓							
Porter (1980)	✓							
Hill (1985)	✓							
Cavinato (1987)	✓							
Kotler (1994)	✓							
Fisher (1997)	✓							

Pagh and Cooper (1998)	✓							
Mason-Jones et al. (2000)	✓							
Christopher and Towil (2002)	✓							
Aitken et al. (2003)	✓							
Wang et al. (2004)	✓	✓		✓	✓		✓	
Chang et al. (2006)	✓	✓			✓		✓	
Narasimhan and talluri (2006)				✓	✓		✓	
Wang et al. (2009)	✓	✓			✓		✓	
Amini and Li (2011)			✓		✓		✓	
Mahapatra et al. (2012)	✓	✓			✓		✓	

2.5 Conclusion

In the first part of this chapter, we introduced the basic concepts needed to a comprehensive supply chain network design with product life cycle considerations. We began by presenting the problem of supply chain network design and its different components. Then, we were interested in a particular problem that is the supply chain network design with a product life cycle consideration.

Some tools, which may be needed for the resolution of these problems, are presented, as the identification of the product type, the product life cycle phases, and the different marketing strategies proposed to link the supply chain design to the product life cycle according to the product type.

The purpose of the second part was to make a general review of what exists in the literature related to the supply chain network design with a product life cycle consideration. We presented a review of the most relevant and recent studies dealing with this problem. We also listed some particular supply chain design problems, as well as the proposed methods to solve them.

The following chapters are devoted to mathematical formulations and methods developed for solving problems of supply chain network design with a product life cycle consideration addressed in this thesis.

CHAPTER 3

A multi-criteria multi-period supply chain design with product life cycle considerations

3.1 Introduction

In this chapter, we focus on designing a multi-period supply chain network which takes into account the different phases the product goes through during its life cycle. This multi-period supply chain network is considered as a solution for effectively meeting the market requirements such as low cost, high product variety, high quality, high service level and short lead times. The efficiency of the supply chain actors is then measured through these criteria emanating from a fixed objective and a same overall goal. To achieve our purposes, a two-phased method will be proposed. The first phase presents a multi-attribute decision making problem for measuring the supply chain potential actors' efficiencies. The second phase, however, presents a mono-objective model based on MIP.

The application model and insights will be detailed through numerical illustrations.

This chapter is organized as follows: the problem statement is defined in section 2.

In section 3, we discuss our proposed solution methodology. In section 4 and 5, we present the first and second resolution phases respectively. In section 6, we present the real case and the experimental study. Section 7 presents some limitations of the model and proposes the corresponding solutions. Finally, section 8 contains some concluding remarks.

3.2 Problem statement

We consider the case of a focal company, which will launch a new product in the market. The problem involves designing a multi-level and multi-period supply chain network taking into consideration all the product life cycle stages the product will go through.

The proposed multi-level and multi-period supply chain network design problem can be described as follows:

From the sets of potential suppliers, producers and distributors, the needed and effective supply chain actors at each product life cycle stage have to be selected, and the optimal supply chain network will then be designed by defining the different flows circulating between the pre-determined actors, on the base of minimizing the supply chain's total cost.

A graphical network representation is given by figure 3.1 to illustrate the considered supply chain network.

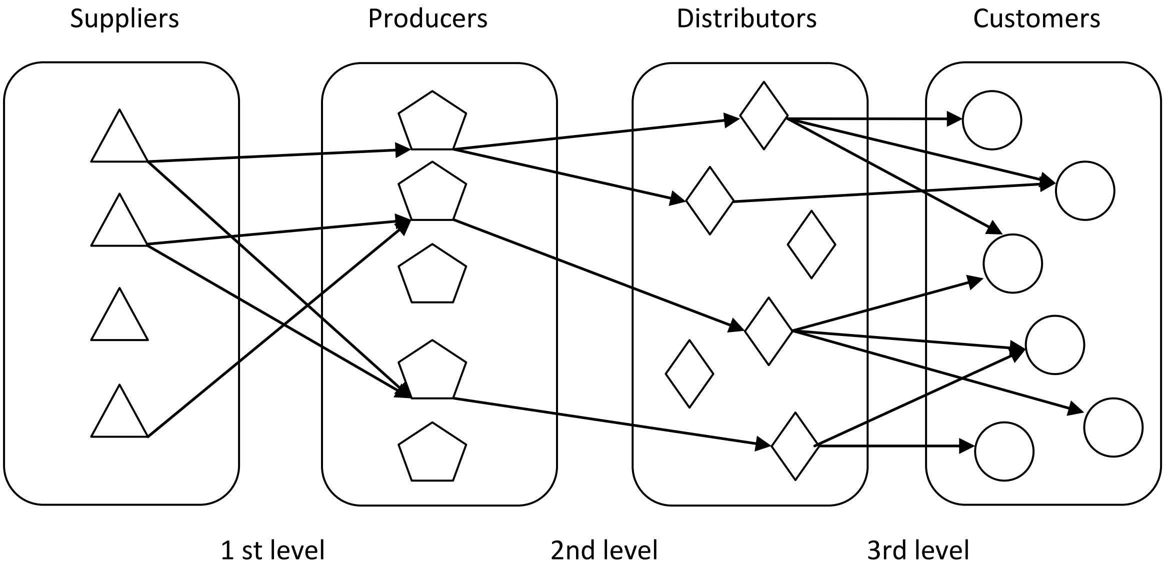


Figure 3.1:A simple network of three-stages in supply chain network.

To reduce that complexity, a set of assumptions has been introduced:

1. From a strategic perspective, all the business and decision-making processes are planned centrally by the focal considered company, which dominates the supply chain and owns all decision-making powers with regard to planning for all the subsidiaries.

2. The set of potential suppliers, producers, distributors, as well as the customer zone locations are considered as already pre-established data of the model. The same is true for the supplier's, producer's and distributor's capacities.

4. Variable and fixed costs are stated for all elements of the business process. Fixed costs are related to each product life cycle stage, and are generated for each opening, closing and operating of a facility.

5. The production of one unit of a product requires one unit of the producer capacity. The similar assumption is considered for both suppliers and distributors.

The verbal formulation of the supply chain network design problem can be set as follows:

Objective function: Minimize sum over the product life cycle stages of the supply chain total cost

Where the supply chain total cost can be divided into two essential elements, namely the fixed and the variable costs = Sum of (fixed costs of opening, closing and operating facilities)

+ Sum of (raw materials purchasing costs + production costs + distribution costs)

Subject to:

1. Suppliers’ capacity limits,
2. Production capacity limits of the plants,
3. Distributors’ capacity limits,
4. Market total demand satisfaction,
5. Flow conservation constraints,

6. Bounds on decisions variables

We will suppose that the transportation costs related to the first and second levels are included into the raw materials purchasing costs and into the production costs respectively.

However, it is noteworthy that this model, as it has been exploited, is substantially characterized by the flow of materials and information both within and between business entities. It only considers global settings and especially a single criterion, namely the cost.

This approach has proven a certain limit in the efficiency of the supply chain, and then a further research can be conducted taking into account a number of additional specific and important criteria. The selection of these criteria has to be closely related to the product life cycle and its different phases, and should be detailed for each potential actor, depending on the specification of the project and under the control of the decision maker.

Generally, traditional techniques in operations' research mainly deal with quantitative measures, while vagueness and uncertainty, which are described by qualitative measures, exist everywhere within the supply chain. A technique that can deal with both quantitative and qualitative measures is needed to better tackle this issue.

This study primarily deals with the selection and design of an appropriate supply chain configuration to achieve an optimal performance, which is measured using a subjective set of criteria.

3.3 *The resolution methodology*

In this chapter, we develop a rigorous modeling and an analytical framework for multi-criteria , multi-level and multi-period supply chain network design.

The essential contribution of this approach is that it incorporates the efficiencies of the individual supply chain processes, developed from a multi-criteria analysis, and capacity constraints into the decision making process. More specifically, the methodology develops and applies a combination of a multi-criteria efficiency model and mathematical programming methods.

These performance criteria; as well as their importance along the different product life cycle stages; are adopted as subjective criteria for evaluating the focal company's performance. It should be noted that the solution's methodology is generic and does not depend on the metrics used. In other words, the same methodology can be used if a company decides to either remove or add criteria, and inversely.

The developed methodology is based on a two- phase method. The first phase deals with the evaluation of the potential actors' performances using multi-criteria decision making methods, including a combination of the AHP and the OWA aggregation models, where both quantitative and qualitative factors are integrated. In order to minimize the total cost of the supply chain network design, the second phase involves the application of a mathematical programming model, which optimally selects candidates for the supply chain network design, and identifies the optimal routing decisions for all entities in the network by integrating the efficiencies identified in the first phase, demand, capacity requirements, and flow conservation constraints. Figure 3.2 shows the two-phase resolution methodology.

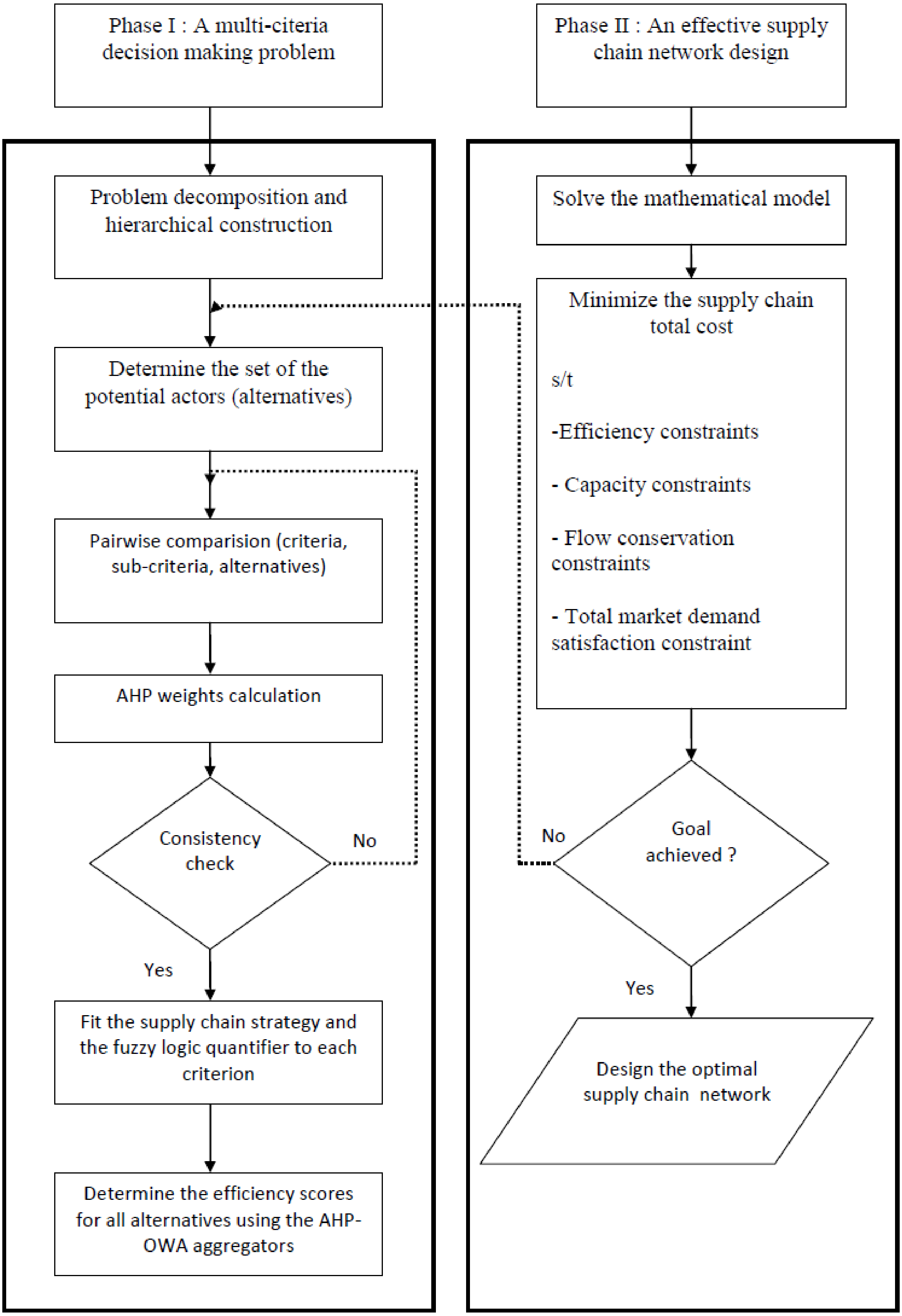


Figure 3.2:The resolution methodology

3.4 Phase 1: a multi-criteria decision making model for potential actors' efficiency evaluation

All multi-criteria analysis approaches require the exercise of judgment. They make the alternatives and their contribution to the different criteria explicit, and differ, however, in how combining the data. Formal multi-criteria analysis' techniques usually provide an explicit relative weighting system for the different criteria. The main role of these techniques is to deal with the difficulties that human decision-makers have shown to deal with large amounts of complex pieces of information in a consistent way.

A key feature of a multi-criteria analysis is its emphasis on the judgment of the decision making team, in establishing objectives and criteria, estimating relative importance weights and, to some extent, in judging the contribution of each alternative to each performance criterion. The subjectivity that pervades this can be a matter of concern. Its foundation, in principle, is the decision makers' own choices of objectives, criteria, weights and assessments of achieving the objectives and therefore the overall goal.

These techniques are mainly used to identify a single most preferred alternative, to rank alternatives, to short-list a limited number of alternatives for a subsequent detailed appraisal, or simply to distinguish acceptable and unacceptable possibilities.

Among the many advantages of the multi-criteria analysis techniques:

- the choice of objectives and criteria that any decision making group may make is open to analysis and change if they are felt to be inappropriate,

- Scores and weights, when used, are also explicit and are developed according to established techniques. They can also be cross-referenced to other sources of information on relative values, and amended if necessary,

- weights and performance measurements are further sub-contracted for the optimization phase, and need not necessarily be anew in the hands of the decision maker himself.

- These techniques can provide an important mean of communication, with the decision maker and sometimes, later, between him and the decision making team.

As it is clear from a growing the literature, there are many multi-criteria analysis techniques and their number is still rising.

To cope with the multi-criteria decision making problem, a combination of two multi-criteria operators is used namely the Analytical Hierarchy Process (AHP) and the Ordered Weighted Averaging (OWA).

The AHP provides a comprehensive methodology for the solution of the multi-criteria decision problems, which makes a considerable use of comparison to help in the aggregation of lower order concepts in the formulation of higher order concepts.

The extension of the AHP by the OWA was introduced by Yager and Kelman (1999). More specifically, this extension which generalizes the aggregation process used in the AHP, allows more flexibility in the formulation of higher order concepts, and provides the AHP an even greater facility for modeling human decision making. The OWA operator allows modeling situations where the number of sub-criteria needed to satisfy a higher order concept can be expressed in terms of linguistic quantifiers. This extension should provide a generic decision making tool that will be able to more powerfully model human reasoning.

This multi criteria decision making problem is solved separately for each of the three business process types at each product life cycle stage, and the solutions identify the efficiency scores; corresponding to the potential suppliers, manufacturers, and distributors ; to be utilized in the supply chain network design model.

3.4.1 The Analytical hierarchy Process (AHP)

The AHP was introduced by Saaty(1980) as a tool for modeling human decision making. AHP is a decision-making tool that can help describe the general decision operation by decomposing a complex problem into a multi-level hierarchical structure of objectives, criteria, sub-criteria and alternatives (Saaty, 1990).

The AHP procedure is employed for ranking a set of alternatives or for the selection of the best in a set of alternatives. This procedure is not only a numerical method for the ranking or selection of alternatives, but it also provides a complete method for analyzing and solving complex decision-making problems by structuring them into a hierarchical framework that provides an exhaustive list of all the sub-criteria, criteria, and objectives that are involved.

The ranking is done with respect to an overall goal, which is broken down into a set of criteria, which also in their turn, are broken down, each into a set of sub-criteria.

The AHP procedure involves three major steps: (i) developing the AHP hierarchy, (ii) a pairwise comparison of elements of the hierarchical structure, (iii) determination of component weights, and (iv) constructing an overall priority rating.

a. *The AHP hierarchy*

This step is probably the most significant step in the process, though it contains no numerical information. At this level, the decision maker provides his whole knowledge of the decision process by breaking it down into a hierarchical structure, for which the top level is the ultimate goal of the decision at hand. This hierarchy consists generally of going from the most general objective to the most specific one, and where the last level contains the alternatives.

In the context of this chapter, a typical five-level hierarchy of goal, objective, criteria, sub-criteria and alternatives has been considered (Figure 3.3).

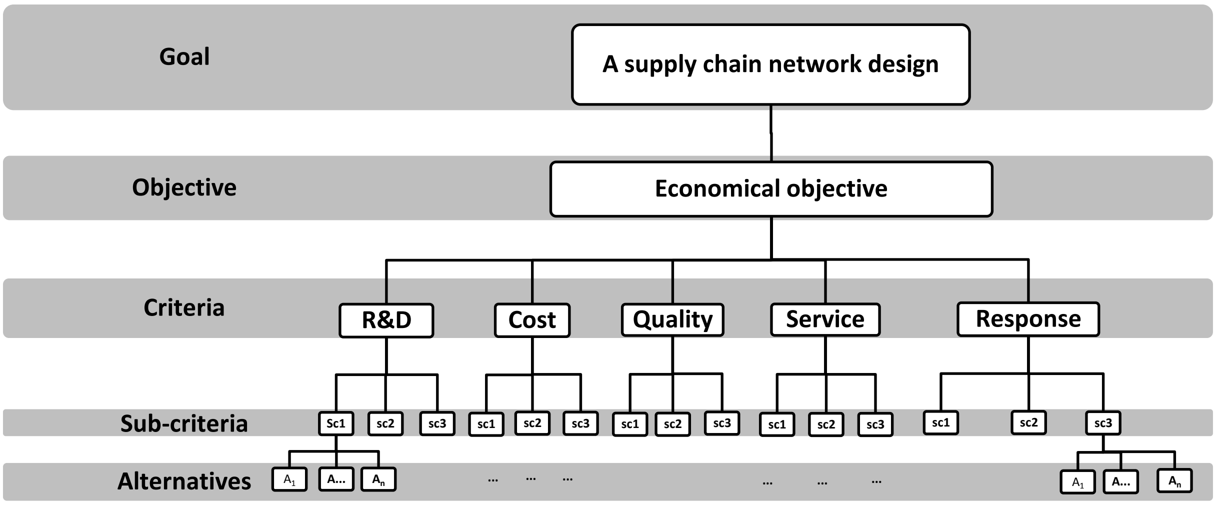


Figure 3.3:Hierarchical structure of the decision problem

The set of s alternatives is denoted here by A_l , for l=1, 2, .., s. The alternatives are to be evaluated with respect to a set of p objectives O_i , for i=1, 2,.., p. The objectives are measured in terms of the underlying criteria, and the same for criteria which are measured in terms of the underlying sub-criteria. Thus, there are a set of q criteria C_j for j=1,2..,q associated with the p objectives, and a set of r sub-criteria B_k for k=1,2..,r associated with the q criteria. The performance of the alternatives A_l with respect to the sub-criterion B_k is described by a set of standardized values: $X = [x_{kl}]_{r\times s}$

b. *The pairwise comparison*

In this step, the decision maker provides the input data which are the essence of the different sub-criteria, criteria, and objectives.

The pairwise comparison is the basic measurement mode employed in the AHP procedure. The procedure greatly reduces the conceptual complexity of a problem since only two components are considered at any given time. The different targets are given through the pairwise comparisons of the elements emanating from a node of the hierarchy in regard to the parent node. The pair-wise comparison method is made on a semantic scale with values from 1 to 9 to rate the relative preferences for two elements of the hierarchy (table 3.1).

All these pair-wise comparisons are stored in matrices. The pair-wise comparison matrix for the objective level has the following form: $M = [e_{ii'}]_{p \times p}$ where $e_{ii'}$ is the pairwise comparison rating for the objective j and objective i’. This matrix M is reciprocal, that is $e_{ii'} = {e_{i'i}}^{-1}$, and all its diagonal elements are unity, that is $e_{ii'} = 1$, for i= i'. The same principles apply to the criteria and sub-criteria levels as well. At the criteria level, a pair-wise comparison matrix is obtained for each of the objectives by comparing the associated criteria; thus, $M_i = \left[e_{ijj'}\right]_{q \times q}$ for i=1,2,…,p, where $e_{ijj'}$ is the pairwise comparison rating for an attribute j and attribute j’ is associated with the objective i.

Table 3.1:Scales for pairwise compatisons, adapted from Saaty(1980)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

c. *The component weights*

Once the pair-wise comparison matrix is obtained, each element can be assigned a relative role by computing the vectors of weights $w_i = \left[w_1, w_2, \dots, w_p\right]$ for the objectives, $w_{ij} = \left[w_{i1}, w_{i2}, \dots, w_{iq}\right]$ for the criteria associated with the i-th objective, and $w_{ijk} = \left[w_{ij1}, w_{ij2}, \dots, w_{ijr}\right]$ for the sub-criteria associated with the j-th criterion associated with the ith objective.

The weights have the following properties:

$w_i \in [0,1]$,$\sum_{i=1}^{p} w_i = 1$;

$w_{ij} \in [0,1]$,$\sum_{j=1}^{q} w_{ij} = 1$; for all i=1, 2... p

and $w_{ijk} \in [0,1]$,$\sum_{k=1}^{r} w_{ijk} = 1$, for all j=1, 2,..,q, for all i=1, 2... p.

These relative weights are given by the eigenvalue method applied to the different matrices obtained in step 2 (Saaty, 1977) . This method consists of finding ,for each matrix, the biggest eigenvalue and the normalized and associated eigenvector, the elements sum to one. The eigenvector then gives the relative weights of each of the children. This normalized eigenvector can be composed of an iterative process. Firstly, the matrix $\widehat{M}$ is computed by normalizing the columns of M:

$\widehat{M} = [e^*_{ii'}]_{p \times p}$,

where

$e^*_{ii'} = \frac{e_{ii'}}{\sum_{i=1}^{p} e_{ii'}}$ for all i'=1,2,…,p.

Then $\widehat{M}$ is computed and normalized in $\widehat{M}_2$, next $\widehat{M}_3, \dots, \widehat{M}_n$ are computed until the columns of the obtained matrix are all identical, or close. This column then gives the vector of w:

$w_i = \hat{e}^*_{ni\,i'}$ for all i =1,2,…,p.

The criteria weights w_{ij} are calculated in an analagous way; thus:

$e^*_{ij\,j'} = \frac{e_{ij\,j'}}{\sum_{j=1}^{q} e_{ij\,j'}}$ for all j'=1,2,…,q; for all i =1,2,…,p

Then the criteria weights are given by:

$w_{ij} = \hat{e}^*_{ij\,j'}$ for all j=1,2,…,q, for all i =1,2,…,p

And similarly, we calculate the sub-criteria weights w_{ijk} :

$e^*_{ijk\,k'} = \frac{e_{ijkk'}}{\sum_{k=1}^{r} e_{ijkk'}}$ for all k'=1,2,…,r, for all j=1,2,…,q, for all i =1,2,…,p

The sub-criteria weights are then given by:

$w_{ijk} = \hat{e}^*_{ijkk'}$ for all k=1,2,…,r, for all j=1,2,…,q, for all i =1,2,…,p

As the pair-wise comparisons are based on human judgments, a degree of imperfection or inconsistency cannot be avoided. Therefore, it is valuable to have a measure of inconsistency associated with the pair-wise comparison matrix M.

In order to measure the degree of consistency, we can calculate the consistency index (CI) as:

$CI = \frac{\Delta_{max} - p}{p-1}$

where Δ_{max} is the biggest eigenvalue that can be obtained once we have its associated eigenvector, and p is the number of columns of matrix M. At this point, the consistency ratio (CR) can be calculated as follows: $CR = \frac{CI}{RI}$

where RI is the random index, it presents the consistency index of a randomly generated pair-wise comparison matrix. It can be shown that RI depends on the number of elements being compared (Table 3.2). If the consistency ratio CR is less than 0.1, then it is acceptable and it indicates a reasonable level of consistency in the pair-wise comparison; otherwise the values of the ratio are indicative of inconsistent judgments. In such cases, one should reconsider and revise the original values in the pair-wise comparison to have new and more consistent matrices.

Table 3.2:Random inconsistency indices (RI), adapted from Saaty(1980)

Number of criteria	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

d. The overall priority rating

This step can then be completed by computing the overall score of each alternative with respect to the most general objective. This is done through an iterative process of local calculations involving a weighted sum at each level of the hierarchy.

For the hierarchical structure predefined in section a (figure 3.3), the overall evaluation score, $E_l$of the l-th alternative is calculated as follows:

$$E_l = \sum_{i=1}^{p} \sum_{j=1}^{q} \sum_{k=1}^{l} w_i * w_{ij} * w_{ijk} * x_{kl}$$

This process is repeated for each alternative and then the alternative with the highest overall score is selected as the best one.

While the AHP has proven to be very useful, however, it has been shown by Yager and Kelman (1999) that it can be improved by the inclusion of some techniques for modeling linguistic quantifiers used in the fuzzy set theory. The main idea was to modify the basic aggregation process used in the AHP.

The used techniques, based on the Ordered Weighted Averaging (OWA) operator, allow for a more general modeling of the process used to combine information in these hierarchies.

The extension of the AHP with these techniques provided a generic decision making tool that is able to more powerfully model human reasoning.

3.4.2 The Ordered Weighted Averaging (OWA) operators

In the multi-criteria decision making process, aggregation functions are used to obtain the overall evaluation of the alternatives with respect to the different objectives, criteria and sub-criteria considered. Generally, the construction of these aggregation functions must reflect a number of considerations. Referring to Yager and Kelma, (1999), the two most important ones are:

- The first consideration is the relationship between the criteria and the sub-criteria respectively; as perceived by the decision maker. At this level, there are some relevant questions to ask: “Does he desire all criteria and sub-criteria respectively to be satisfied?”, “Will he be happy if most of them are satisfied?”, “Is there some proportion of criteria and sub-criteria respectively; whose satisfaction is required for an acceptable solution?”

To answer these different questions, Yager (1988) suggested an approach allowing for a parameterization of the agenda the decision maker can use to aggregate the relevant criteria, and sub-criteria respectively. This parameterization allows to go from the extreme of requiring “all criteria” to be satisfied, to the other extreme of requiring “at least one criterion” to be satisfied, and includes the case of taking the average of the criteria scores.

- The second consideration is the relative importance or the weights of the criteria. This allows the decision maker to emphasize such or such criterion relatively to the other ones, so that its impact on the overall aggregative process will be higher.

These two concepts, though are totally different, are included in a same aggregation operator, the OWA operator.

a. *The OWA operators: definition and properties*

OWA operators are a generalization of the original decision-making process suggested by Bellman and Zadeh (1970), and were introduced by Yager (1988) as a tool for decision-making in a fuzzy environment, where the criteria were fuzzy subsets over the space of decision alternatives, and each alternative satisfies a single criterion with a degree of satisfaction lying in the unit interval [0, 1]. This degree of satisfaction can also be interpreted as a membership degree, putting the problem in a fuzzy environment.

Based on Yager (1993), an aggregation operator F:

$$F: I^n \rightarrow I \ \ , where\ I \in [0,1]$$

is called an ordered weighted averaging (OWA) operator of dimension n if it has associated with it a weighting vector W :

$$W = \begin{bmatrix} W_1 \\ \vdots \\ W_n \end{bmatrix}$$

Such that:

(1) $W_i \in [0,1]$

(2) $\sum_{i=1}^{n} W_i = 1$

and

(3) $F(c_1, c_2, \ldots, c_n) = \sum_{j=1}^{n} d_j W_j$

Where b_j is the j-th largest element of the $\{c_1, c_2, \ldots, c_n\}$. The weights W_j are not associated with a particular argument a_i but with the ordered position of the arguments d_j.

Example:

Assume:

$W = \begin{bmatrix} 0.4 \\ 0.3 \\ 0.2 \\ 0.1 \end{bmatrix}$, then

$f(0.7, 1, 0.3, 0.6)$ =(1)(0.4)+(0.7)(0.3)+(0.6)(0.2)+(0.3)(0.1)=0.76 .

Yager (1988) showed that the OWA have the following properties:

- Commutativity: the indexing of the arguments is irrelevant.
- Monotonicity: if $\forall\ i \ \ c_i \geq c'_i$ then $F(c_1, c_2, \ldots, c_n) \geq \ F(c'_1, c'_2, \ldots, c'_n)$.
- Idempotency: $F(c, c, \ldots, c) = c$

These properties imply that the OWA operator is a mean operator (Dubois and Prade, 1985), and it can be shown that $\forall\, c_1, c_2, \dots, a_n \quad Max_i[c_i] \geq\ F(c_1, c_2, \dots, c_n) \geq Min_i[c_i]$.

Min, Max, and the Mean are also special cases of the OWA aggregation as they can be obtained with specific weighting vectors:

- If $W_1 = 1$ and $W_j = 0$ for $j \neq 1$, then $F(c_1, c_2, \dots, c_n) = Max_i[c_i]$
- If $W_n = 1$ and $W_i = 0$ for $i \neq n$, then $F(c_1, c_2, \dots, c_n) = Min_i[c_i]$
- If $W_i = {}^{1}\!/_{n}\ \forall\, i$ then $F(c_1, c_2, \dots, c_n) = \frac{1}{n}\sum_{i=1}^{n} c_i$

b. *Fuzzy logic quantifier-guided OWA combination*

Fuzzy linguistic quantifiers were introduced by Zadeh (1983). In accordance to Yager and Kelman(1999), there are two general classes of linguistic quantifiers: absolute and relative quantifiers. Absolute quantifiers can be used to represent linguistic terms such 'as about 5' or 'more than 3'.However, the relative quantifiers are closely related to imprecise proportions. They can be represented as fuzzy subsets over the unit interval, with proportional fuzzy statements such as 'few', 'half', 'many', etc.

In the framework of this thesis, we will only consider the class of the relative quantifiers known as the regular increasing monotone (RIM) quantifiers.

According to Zadeh (1983), if a fuzzy subset corresponding to a relative linguistic quantifier is denoted Q, then for any value *r* in the unit interval, the membership grade Q(*r*) corresponds to the compatibility of the value *r* with the concept which Q is representing.

A general form of a linguistically quantified statement is:

Q of *Y* are *P*

where *Q* is the linguistic quantifier (e.g., all, at least one, most), *Y* is a class of objects (e.g., the important criteria, the objectives) and P is some property (e.g., satisfied).

When we have $C_1, \dots, C_n$ criteria represented as fuzzy subsets over the set of alternatives A, then the relationship between the criteria can be perceived by the decision maker as:

‘Q criteria are satisfied by an acceptable solution’

A natural question in the definition of the fuzzy linguistic OWA operator is how to obtain the associated weighting vector. Yager (1988) suggested an interesting way to compute the weights of OWA operator using fuzzy logic quantifiers, which are given by the following expression:

$$W_i = Q\left(\frac{i}{n}\right) - Q\left(\frac{i-1}{n}\right) \ , \ i = 1, \dots, n$$

The non-decreasing relative quantifier, Q, is defined by Zadeh(1983) as:

$$Q(r) = \begin{cases} 0 & if \quad r < \alpha \\ \dfrac{r-\alpha}{\beta-\alpha} & if \quad \alpha \le r \le \beta \\ 1 & if \quad r > \beta \end{cases}$$

with $\alpha, \beta, r \in [0, 1]$ and Q(r) indicating the degree to which the proportion r is compatible with the meaning of the quantifier it represents.

Possible graphic representations of some non-decreasing relative quantifiers are shown in figure 3.4, where the parameters (α ; β) are (0.3; 0.8), (0; 0.5) and (0.5; 1), respectively.

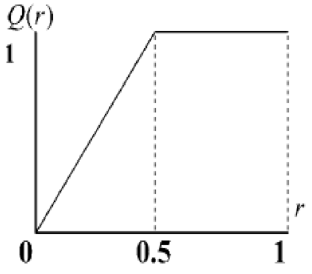
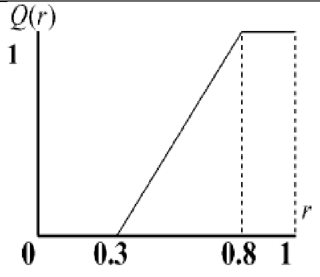
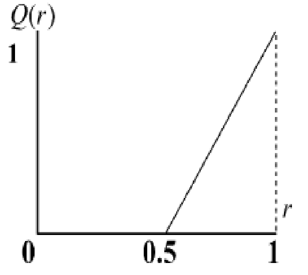
Quantifier: At least half	Quantifier: Most	Quantifier: As many as possible
 	 	

Figure 3.4:Monotonically non-decreasing fuzzy linguistic quantifier (Herrera et al., 2000)

For each alternative A, the overall satisfaction *S(A)* is:

$$e(A) = F(C_1(A), C_2(A), C_3(A), \dots, C_n(A)\ )$$

where F is an OWA aggregation using the weighting previously determined, and $C_i(A)$ is the satisfaction of alternative A to criteria C_i .

Some special cases are interesting to note:

- If Q = 'All' , $Q(1) = 1, and\ Q(r) = 0\ \ if\ r \neq 1$, thus $W_n\ = 1\ and\ W_i\ = 0\ if\ i \neq n$ which means that

$$e(A) = Min_i[C_i(A)]$$

- If Q = 'At least one', $Q(0) = 0, and\ Q(r) = 1\ \ if\ r \neq 0$,thus $W_1\ = 1\ and\ W_i\ = 0\ if\ i \neq 1$ which means that

$$e(A) = Max_i[C_i(A)]$$

- If Q is such that $Q(r) = r$, thus $W_i\ = \frac{1}{n}$ which means that

$$e(A) = \frac{1}{n}\sum\nolimits_i C_i(A)$$

which is the average of the satisfactions.

Hence we see that using the operator in combination with the concept of the linguistic quantifiers provides a useful methodology for formulating multi-criteria formulation functions.

c. *Inclusion of the importances in OWA operators*

Yager(1996) suggested a method to evaluate the decision function for the situation where each of the criteria has an associated importance, and the overall aggregation function is of the form:

'Q of the **important** *criteria are satisfied by an acceptable solution'*

Assuming that $(C_1, \dots, C_n)$ represent the different criteria, V_i are the importances of each criterion, and that $a \in A$ is an alternative.

The first step consists on reordering the $C_i(a)$ such that b_j is the j-th largest of the $(C_1(a), \dots, C_n(a))$. u_i then, denote the importance associated with the criterion that has the j-th largest satisfaction.

Subsequently, the weighting vector is calculated as follows:

$$w_j = Q\left(\frac{\sum_{k=1}^{j} u_k}{\sum_{k=1}^{n} u_k}\right) - Q\left(\frac{\sum_{k=1}^{j-1} u_k}{\sum_{k=1}^{n} u_k}\right)$$

Finally, the decision aggregator is :

$$e(a) = \sum_{j=1}^{n} b_j w_j$$

3.4.3 *The AHP-OWA operator*

Yager and Kelman (1999) proposed an extension of the AHP using the OWA. However, these two procedures do not operate at the same level. The AHP is a global tool for creating a hierarchical model of the decision problem, analyzing the whole process and evaluating each alternative. The evaluation process in the AHP uses a simple weighted linear combination to calculate the local score of each alternative. The OWA operators, alternatively, provide a general framework for making a series of local aggregations used in the AHP.

As OWA are local tools, they were included in the AHP to compute the local scores of the alternatives, without interfering with the global analysis process.

Once achieving the two first steps of the AHP, which are formation of the hierarchical structure and calculating the relative weights of the elements (objectives criteria, and sub-criteria) of the hierarchy by conducting pair-wise comparisons, the fuzzy linguistic quantifier guided by OWA procedures take then the lead for the rest of the analysis. The procedure at this stage involves three main steps (Malczewski, 2006b): (i) specifying the linguistic quantifier Q, (ii) generating a set of ordered weights associated with Q, and (iii) computing the overall evaluation for each alternative at each level of the hierarchy by means of the OWA combination function.

As the criterion weights given by the AHP have the property $\sum_{i=1}^{n} Ww_i = 1$, therefore $\sum_{k=1}^{n} u_k = 1$, and the weighting vector and the decision aggregator are then of the form:

$$w_j = Q\left(\sum_{k=1}^{j} u_k\right) - Q\left(\sum_{k=1}^{j-1} u_k\right)$$

$$e(a) = \sum_{j=1}^{n} b_j w_j$$

3.5 Phase II: The supply chain network design

At each product life cycle stage; and taking into account the efficiency scores that already have been calculated in the previous phase, the capacity and the demand satisfaction constraints; the supply chain network design framework needs to identify the effective supply chain actors as well as the deployment plans.

The proposed model allows identifying, at each product life cycle stage, the optimal routing of material from the selected suppliers to manufacturers to warehouses by minimizing the supply chain total cost.

Notations

To formulate the problem, the following parameters are used:

$CF_{i,t}$	Fixed cost to operate the supplier i at stage t
$CF_{j,t}$	Fixed cost to operate the producer j at stage t
$CF_{k,t}$	Fixed cost to operate the distributor k at stage t

$CO_{i,t}$	Fixed cost of opening the supplier i at stage t
$CO_{j,t}$	Fixed cost of opening the producer j at stage t
$CO_{k,t}$	Fixed cost of opening the distributor k at stage t
$CC_{i,t}$	Fixed cost of closing the supplier i at stage t
$CC_{j,t}$	Fixed cost of closing the producer j at stage t
$CC_{k,t}$	Fixed cost of closing the distributor k at stage t
$c_{i,j,t}$	Unit production and transportation cost from supplier i to producer j , at stage t
$c_{j,k,t}$	Unit production and transportation cost from producer j to distributor k, at stage t
$c_{k,z,t}$	Unit production and transportation cost from distributor k to customer zone z, at stage t
$e_{i,t}$	Mean efficiency score of the supplier i, at stage t
$e_{j,t}$	Mean efficiency score of the producer j, at stage t
$e_{k,t}$	Mean efficiency score of the distributor k, at stage t
$Eexp_{I,t}$	The minimum expected group efficiency average set forth by the decision maker for the suppliers at stage t
$Eexp_{J,t}$	The minimum expected group efficiency average set forth by the decision maker for the producers at stage t
$Eexp_{K,t}$	The minimum expected group efficiency average set forth by the decision maker for the distributors at stage t
$cap_{i,t}$	Capacity limit of the supplier i , at stage t
$cap_{j,t}$	Capacity limit of the producer j, at stage t
$cap_{k,t}$	Capacity limit of the distributor k at stage t
$D_{z,t}$	Minimum downstream demand of the customer zone z, at stage t

Decision variables:

$X_{i,t}$	=1 if the supplier i is selected at stage t, 0 otherwise
$Y_{j,t}$	=1 if the producer j is selected at stage t, 0 otherwise
$Z_{k,t}$	=1 if the distributor k is selected at stage t,

	0 otherwise
$Q_{i,j,t}$	Quantity shipped from supplier i to producer j, at stage t, in Ton
$Q_{j,k,t}$	Quantity shipped from producer j to distributor k, at stage t, in Ton
$Q_{k,z,t}$	Quantity shipped from distributor k to customer zone z, at stage t, in Ton

$i = 1, \dots, m,$

$j = 1, \dots, n,$

$k = 1, \dots, p,$

$z = 1, \dots, q$

3.5.1 *The mathematical model*

The effective multi-period supply chain network design problem, can be formulated as follows:

$$\begin{aligned}
\min f = \ & \sum_{t} \Bigg[\Bigg[\sum_{i=1}^{m} CF_{i,t} * X_{i,t} + \sum_{j=1}^{n} CF_{j,t} * Y_{j,t} + \sum_{k=1}^{p} CF_{k,t} * Z_{k,t} \Bigg] \\
& + \Bigg[\sum_{i \in I} CO_{i,t} * X_{i,t} * \left(1 - X_{i,t-1}\right) \\
& + \sum_{j \in J} CO_{j,t} * Y_{j,t} * \left(1 - Y_{j,t-1}\right) + \sum_{k \in K} CO_{k,t} * Z_{k,t} * \left(1 - Z_{k,t-1}\right) \Bigg] \\
& + \Bigg[\sum_{i \in I} CC_{i,t} * X_{i,t} * \left(1 - X_{i,t+1}\right) \\
& + \sum_{j \in J} CC_{j,t} * Y_{j,t} * \left(1 - Y_{j,t+1}\right) + \sum_{k \in K} CC_{k,t} * Z_{k,t} * \left(1 - Z_{k,t+1}\right) \Bigg] \\
& + \Bigg[\sum_{i=1}^{m} \sum_{j=1}^{n} c_{i,j,t} * Q_{i,j,t} + \sum_{j=1}^{n} \sum_{k=1}^{p} c_{j,k,t} * Q_{j,k,t} \\
& + \sum_{k=1}^{p} \sum_{z=1}^{q} c_{k,z,t} * Q_{k,z,t} \ \Bigg] \Bigg] \qquad (1)
\end{aligned}$$

s.t

Efficiency constraints:

$e_{i,t} X_{i,t} \geq Eexp_{I,t} \, X_{i,t} \quad \forall \, i, t$ (2)

$$e_{j,t} Y_{j,t} \geq \; Eexp_{J,t} \, Y_{j,t} \;\; \forall \, j, t \tag{3}$$

$$e_{k,t} Z_{k,t} \geq Eexp_{K,t} \, Z_{k,t} \quad \forall \, k, t \tag{4}$$

Capacity limits constraints:

$$\sum_{j=1}^{n} Q_{i,j,t} \leq cap_{i,t} * X_{i,t} \quad \forall \, i \, , t \tag{5}$$

$$\sum_{k=1}^{p} Q_{j,k,t} \leq cap_{j,t} * Y_{j,t} \quad \forall j \, , t \tag{6}$$

$$\sum_{z=1}^{q} Q_{k,z,t} \leq cap_{k,t} * Z_{k,t} \quad \forall k \, , t \tag{7}$$

Flow conservation constraints

$$\sum_{i=1}^{m} Q_{i,j,t} - \sum_{k=1}^{p} Q_{j,k,t} = 0 \quad \forall \, j \, , t \tag{8}$$

$$\sum_{j=1}^{n} Q_{j,k,t} - \sum_{z=1}^{q} Q_{k,z,t} = 0 \quad \forall \, k \, , t \tag{9}$$

Total market demand satisfaction constraint:

$$\sum_{k=1}^{p} Q_{k,z,t} \geq \; D_{z,t} \quad \forall \, z, t \tag{10}$$

Non-negativity constraints

$$Q_{i,j,t} \; \geq \; 0 \, \forall \; i, j \, , t \tag{11}$$

$$Q_{j,k,t} \geq 0 \;\; \forall \, j, k, t \tag{12}$$

$$Q_{k,z,t} \geq 0 \;\; \forall \;\; k, z, t \tag{13}$$

$$X_{i,t} \; \in \{0,1\} \, \forall i, t \tag{14}$$

$$Y_{j,t} \; \in \{0,1\} \, \forall j, t \tag{15}$$

$$Z_{k,t} \; \in \{0,1\} \, \forall k, t \tag{16}$$

In the above formulation, the objective function minimizes the supply chain total cost which includes fixed and variable costs. The variable costs consist of the purchasing costs, the production costs, and the distribution costs. While the fixed costs consist of the facilities opening costs, operating costs, and closing costs. The opening costs occur at the period t+1 only if the corresponding facility was closed on the previous period t. Simultaneously, for the closing costs, they occur at a period t only if the corresponding facility was opened at the period t-1. These two costs are related to the dynamic nature of the problem. At t=0, we suppose that all facilities are closed.

Constraint sets (2)-(4) prohibit the selection of ineffective actors. Constraint sets (5)-(7) stipulate that all shipments from a supplier, a plant, or a distribution center must not exceed their maximum capacity. Constraint sets (8)-(9) indicate a conservation of flow at each facility, while (10) requires that all the market demand must be met. A non-negativity on each shipment is imposed by constraint sets (11)-(13). Constraint sets (14)-(16) restrict every facility to be either open or closed.

3.5.2 *The model reformulation*

The multi-period nature of the problem is related to the first objective function formulation (1) which involves the closing and reopening costs. The formulation of these costs includes nonlinear components and makes the problem quadratic.

However, the binary quadratic problems are known to be NP-hard problems which are also practically difficult to solve (Liberti, 2007). Basically, the available solution procedures for the quadratic programming problem may be classified as attempting either to solve the problem directly or to transform it into an equivalent linear mixed-integer program, and then solve the latter problem.

In this thesis, we will use the second solution procedure, namely the linearization of the mathematical model using the method proposed by Fortet (1960). The method consists of linearizing a 0-1 polynomial programming problem by replacing each polynomial term $X_i * X_j$ with a single additional variable and two auxiliary linear constraints.

Therefore, the financial function is rewritten as:

$$\min f = \sum_{t\in T} \left[\sum_{i\in I} CF_{i,t} * X_{i,t} + \sum_{j\in J} CF_{j,t} * Y_{j,t} + \sum_{k\in K} CF_{k,t} * Z_{k,t}\right]$$

$$+ \left[\sum_{i\in I} CO_{i,t} * \left(X_{i,t} - XO_{i,t}\right) + \sum_{j\in J} CO_{j,t} * \left(Y_{j,t} - YO_{j,t}\right) + \sum_{k\in K} CO_{k,t} * \left(Z_{k,t} - ZO_{k,t}\right)\right]$$

$$+ \left[\sum_{i\in I} CC_{i,t} * \left(X_{i,t} - XC_{i,t}\right) + \sum_{j\in J} CC_{j,t} * \left(Y_{j,t} - YC_{j,t}\right) + \sum_{k\in K} CC_{k,t} * (Z_{k,t} - ZC_{k,t})\right]$$

$$+ \left[\sum_{i\in I}\sum_{j\in J} c_{i,j,t} * Q_{i,j,t} + \sum_{j\in J}\sum_{k\in K} c_{j,k,t} * Q_{j,k,t} + \sum_{k\in K}\sum_{z\in Z} c_{k,z,t} * Q_{k,z,t}\right] \qquad (17)$$

With

$XO_{i,t} = X_{i,t} * X_{i,t-1}$ ∀ i, t (18)

$YO_{j,t} = Y_{j,t} * Y_{j,t-1}$ ∀ j, t (19)

$ZO_{k,t} = Z_{k,t} * Z_{k,t-1}$ ∀ k,t (20)

$XC_{i,t} = X_{i,t} * X_{i,t+1}$ ∀ i, t (21)

$YC_{j,t} = Y_{j,t} * Y_{j,t+1}$ ∀ j, t (22)

$ZC_{k,t} = Z_{k,t} * Z_{k,t+1}$ ∀ k, t (23)

For linearization, the following constraints are added to the previous problem constraints:

Linearization constraints

$$XO_{i,t} \leq X_{i,t} \qquad \forall\, i \tag{24}$$

$$YO_{j,t} \leq Y_{j,t} \qquad \forall\, j \tag{25}$$

$$ZO_{k,t} \leq Z_{k,t} \qquad \forall\, k \tag{26}$$

$$XO_{i,t} \leq X_{i,t-1} \qquad \forall\, i \tag{27}$$

$$YO_{j,t} \leq Y_{j,t-1} \qquad \forall\, j \tag{28}$$

$$ZO_{k,t} \leq Z_{k,t-1} \qquad \forall\, k \tag{29}$$

$$XO_{i,t} \geq X_{i,t} + X_{i,t-1} - 1 \qquad \forall\, i \tag{30}$$

$$YO_{i,t} \geq Y_{i,t} + Y_{i,t-1} - 1 \qquad \forall\, j \tag{31}$$

$$ZO_{i,t} \geq Z_{i,t} + Z_{i,t-1} - 1 \qquad \forall\, k \tag{32}$$

$$XC_{i,t} \leq X_{i,t} \qquad \forall\, i \tag{33}$$

$$YC_{j,t} \leq Y_{j,t} \qquad \forall\, j \tag{34}$$

$$ZC_{k,t} \leq Z_{k,t} \qquad \forall\, k \tag{35}$$

$$XC_{i,t} \leq X_{i,t-1} \qquad \forall\, i \tag{36}$$

$$YC_{j,t} \leq Y_{j,t-1} \qquad \forall\, j \tag{37}$$

$$ZC_{k,t} \leq Z_{k,t-1} \qquad \forall\, k \tag{38}$$

$$XC_{i,t} \geq X_{i,t} + X_{i,t-1} - 1 \qquad \forall\, i \tag{39}$$

$$YC_{j,t} \geq Y_{j,t} + Y_{j,t-1} - 1 \qquad \forall\, j \tag{40}$$

$$ZC_{k,t} \geq Z_{k,t} + Z_{k,t-1} - 1 \qquad \forall\, k \tag{41}$$

The set of equations (18)-(23) represent the replacement of the product of the binary variables by a new additional variable. The constraint sets (24)-(41) was added to force the equality between the product of the binary variables and the new additional variable.

3.6 Case study

This section presents a case study supply chain design problem adapted from a real-life situation. The purpose is neither to show any advantage of the modeling process by comparing it with other MIP models, nor to exhibit the efficiency of problem solving by benchmarking the computation time to other algorithms. Indeed, we aim at illustrating the effectiveness and convenience of the product life cycle consideration in the supply chain design, by introducing a multi-criteria decision making and multi-objective models to select the effective supply chain actors in the different product life cycles' stages. We consider the case of a focal company which is in the launching process of a new product on the market, namely, the environmentally coal from the olive pomace. The company has to design its supply chain with a minimal cost, considering the product life cycle stages.

To reach this goal, we apply the two- phase proposed model.

Phase 1: A multi-criteria decision making problem to evaluate the potential actors' efficiency

Table 3.3, revised from Wang et al. (2009), lists an integral description of the different criteria and sub-criteria considered,and the corresponding original scale measurement. This table will be adapted to our case study for the three different business process types, namely procurement, production and distribution processes. Numerical and linguistic interval scales are used in this method. Figure 3.5 presents the linguistic rating on membership function corresponding to fuzzy numbers (Herrera et al. 2000).

Table 3.3: The core of factors on supply chain performance

Criteria	Attributes	Original scale
R&D	Design Technique Innovation	L L L
Cost	Normal unit cost Minimum order quantity Discount	N N N
Quality	Characteristic 1 Characteristic 2 Characteristic 3	N N N
Service	Flexibility Stockout Additioal service	N N L
Response	Normal delivery lead-time Requiring lead-time to changing volume Requiring lead-time to changing design Minimum delivery lead-time	N N N N
"L" means linguistic scale; "N" means numerical scale		

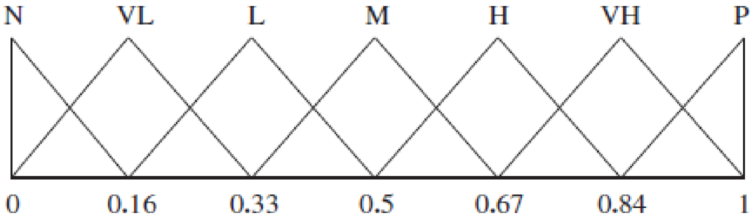


Figure 3.5:Linguistic rating on membership function corresponding to fuzzy number

The table 3.4 presents the data collection of the predefined criteria and sub-criteria, relative to the set of the potential suppliers.

Table 3.4:Data collection on supply performance

Criteria	Attributes	S1	S 2	S 3	S 4	S 5	S 6
R&D	Grinding technique	0.67	0.5	0.5	0.33	0.5	0.5
	Drying technique	0.67	0.67	0.5	0.67	0.67	0.33
	Innovation	0.5	0.5	0.67	0.5	0.67	0.5
Cost	Fixed cost in €	5000	3000	0	5000	0	3000
	Normal unit cost in €	55	50	52	53	53	55
	Minimum order quantity in Ton	2000	2000	1000	2000	2000	1000
Quality	Humidity	0.08	0.1	0.06	0.05	0.08	0.1
	Rate of oil	0.03	0.025	0.02	0.02	0.03	0.025
	Grain size in mm	2	2	1.5	3	2.5	3
Service	Packaging	90%	95%	85%	95%	99%	90%
	Stockout	2%	8%	5%	6%	8%	2%
	Additional service	99%	99%	95%	90%	95%	99%
Response	Normal delivery lead-time in week	4	3	3	2	4	4
	Requiring lead-time to changing volume in week	2	2	1	1	2	1
	Requiring lead-time to changing design in week	1	1	1	1	2	1

The AHP components weights:

The component weights and the different scores are given by pairwise comparisons, for each process at each product life cycle stage, following the AHP method described in section 3.4.1.

Considering the set of the potential suppliers, tables 3.5 and 3.6 give the criteria pairwise comparison and their relative AHP weights, at the introduction and the maturity stages respectively.

Table 3.5:Criteria pairwise comparison and relative weights at the introduction stage

	R&D	Cost	Quality	Service	Response	Weights
R&D	1	1/9	1/7	1/5	1/5	0.029
Cost	9	1	5	5	7	0.558
Quality	7	1/5	1	3	3	0.209
Service	5	1/5	1/5	1	3	0.126
Response	5	1/7	1/3	1/3	1	0.076

Table 3.6:Criteria pairwise comparison and relative weights at the maturity stage

	R&D	Cost	Quality	Service	Response	Weights
R&D	1	5	3	9	7	0.5128
Cost	1/5	1	1/3	5	3	0.129
Quality	1/3	3	1	7	5	0.2615
Service	1/9	1/5	1/7	1	1/3	0.0333
Response	1/7	1/3	1/5	3	1	0.0634

Table 3.7 gives the pairwise comparison for the sub-criteria relative to the criterion “R&D” and their corresponding weights for the same process “suppliers” at the introduction stage of the product life cycle.

Table 3.7:pairwise comparison of the sub-criteria relative to the criterion ‘R&D’ and relative weights

	Grinding technique	Drying technique	Innovation	Weights
Grinding technique	1	1/5	5	0.218
Drying technique	5	1	7	0.715
Innovation	1/5	1/7	1	0.067

Following the same logic, the different suppliers’ AHP-scores relative to the R&D criterion at the introduction stage are given by the table 3.8.

Table 3.8:AHP scores for the R&D criterion at the introduction stage

	S1	S 2	S 3	S 4	S 5	S 6
Grinding technique	0.505	0.116	0.116	0.029	0.116	0.116
Drying technique	0.23	0.23	0.057	0.23	0.23	0.222
Innovation	0.071	0.071	0.357	0.071	0.357	0.071

This same procedure has to be repeated for all the rest of the criteria and their corresponding sub-criteria at each product life cycle stage.

The remaining details for this case study will be given in the appendix.

In the sequel, to fit the supply chain strategy depending on the importance of the different criteria, three linguistic quantifiers are used, namely “At least half”, “Most”, and “As many as possible”.

However, the different criteria and sub-criteria’ importances are closely related to the different phases of the product life cycle. Inspired from Aitken et al. (2003), table 3.9 suggested different supply chain strategies adopted in the framework of this thesis to meet the market demand, in gaining the competitive advantages during the different phases of the product life cycle. These linguistic quantifiers expressing the criteria and sub-criteria importances, being subjective, could vary from one decision maker to another.

Table 3.9:Product criteria and supply chain strategy on product life cycle

Linguistic Quantifier \ Phase	Introduction	Growth	Maturity	Decline
At least half	R&D	Service	Cost	Service
Most	Quality Cost Response	Cost Quality Response	Quality Service Response	Cost Quality Response
As many as possible	Service	R&D	R&D	R&D

The AHP-OWA components weights and final scores:

Returning to our case study the aggregation function is of the form:

At least half of the important criteria are satisfied by an acceptable solution

is considered for the criterion R&D at the introduction stage.

Table 3.10 presents the ordered AHP scores and their corresponding weights, the AHP-OWA weights, and the final scores.

According to this table, it is noted that for the most important criterion in the introduction stage, namely, the R&D, the supplier S3 has the highest score, after comes the supplier S1, and so on.

Table 3.10:potential suppliers' final scores for the R&D criterion at the introduction stage

Suppliers	Ordered AHP Scores	AHP weights	AHP-OWA weights	Final scores
S1	0.505	0.218	0.436	0.349
	0.23	0.715	0.564	
	0.071	0.067	0	
S2	0.23	0.715	1	0.23
	0.116	0.218	0	
	0.071	0.067	0	
S3	0.357	0.067	0.132	0.511
	0.218	0.218	0.436	
	0.057	0.715	0.432	
S4	0.23	0.715	1	0.23
	0.071	0.067	0	
	0.029	0.218	0	
S5	0.357	0.067	0.132	0.246
	0.23	0.715	0.868	
	0.116	0.218	0	
S6	0.22	0.715	1	0.22
	0.116	0.218	0	
	0.071	0.067	0	

This procedure is then repeated for all the rest of the criteria at each product life cycle stage, and the overall aggregation function considered was of the form:

Most of the important criteria are satisfied by an acceptable solution

Table 3.11 presents the overall efficiency scores obtained by the potential suppliers at the introduction and the maturity stages.

Table 3.11:Potential suppliers' efficiency scores

Suppliers	S1	S2	S3	S4	S5	S6
Efficiency Score in the introduction phase	0.21	0.19	0.4	0.23	0.17	0.15
Efficiency Score in the maturity phase	0.07	0.26	0.21	0.17	0.12	0.04

It is interesting to notice that the supplier S3 which has obtained the highest score for the most important criterion, the R&D, at the introduction stage, has also obtained the highest overall efficiency score at this same stage. However, it was not the case for the supplier S1 which was ranked the second for the criterion R&D, but the third in the overall evaluation for the same introductory stage.

It is also worth noting that the supplier S3 moved from the first position in the introduction sage to the second one in the maturity stage, while the supplier S4 moved from the forth position in the introduction sage to the first one in the maturity stage.

Tables 3.12 and 3.13 list the multiple criteria and corresponding sub-criteria matrix for the producers and distributors performance respectively and the efficiency scores for all candidates.

From table 3.12, we can remark that the producer P1 kept the same first position in the introduction and maturity stages, whereas P2 moved from the second position in the introduction stage to the third one in the maturity stage. The producer P3, however, moved from the third position in the introduction stage to the second one in the maturity stage.

Table 3.12:Multiple attribute matrix on production performance and efficiency scores

Criteria	Attributes	P1	P 2	P 3
R&D	Grinding technique	0.84	0.5	0.5
	Drying technique	0.84	0.67	0.5
	Innovation	0.84	0.5	0.3
Cost	Normal unit cost in €	170	160	155
	Minimum order quantity in Ton	2000	1000	1000
	Discount	7%	5%	3%
Quality	Humidity	0.05	0.08	0.08
	Rate of oil	0.015	0.025	0.025
	Calorific in Mj per Kg	19.8	18.5	18
Service	Packing	0.84	0.67	0.5
	Stockout	2%	6%	8%
	Additional service	99%	90%	80%
Response	Normal delivery lead-time in week	8	10	12
	Requiring lead-time to changing volume in week	2	5	5
	Requiring lead-time to changing design in week	3	5	8
Efficiency Score in the introduction phase		0.75	0.18	0.06
Efficiency Score in the maturity phase		0.68	0.19	0.2

Table 3.13:Multiple attribute matrix on distribution performance and efficiency scores

Criteria	Attributes	D1	D 2	D 3
R&D	Technical market timing	0.84	0.67	0.5
	Distribution technique	0.84	0.84	0.67
	Marketing technique	0.67	0.67	0.5
Cost	Normal unit cost in €	19	19	18
	Minimum order quantity in Ton	500	500	1000
	Unit express delivery cost	22	21	20
Quality	Reliability	99%	90%	85%
	Stability	99%	98%	95%
	Quality business relashionships	0.84	0.67	0.5
Service	Flexibility	0.84	0.67	0.5
	In store advertising	0.67	0.5	0.16
	Continuity index in min	170	330	350
Response	Normal delivery lead-time in week	10	12	8
	Minimum delivery lead-time in week	7	7	5
	Requiring lead-time to changing volume in week	3	3	2
Efficiency Score in the introduction phase		0.47	0.32	0.09
Efficiency Score in the maturity phase		0.15	0.19	0.35

It is notable from this table that the distributor D1moved from the first position in the introduction stage to the last one in the maturity stage, the distributor D2 kept the same second position in these two stages.

Phase 2: The mathematical model for the supply chain design network.

The mathematical model is solved to identify the optimum solution since the introduction of the product to the market until the sales decline.

Figure 3.6 shows the sales distribution in Ton for the 3 different customer zones.

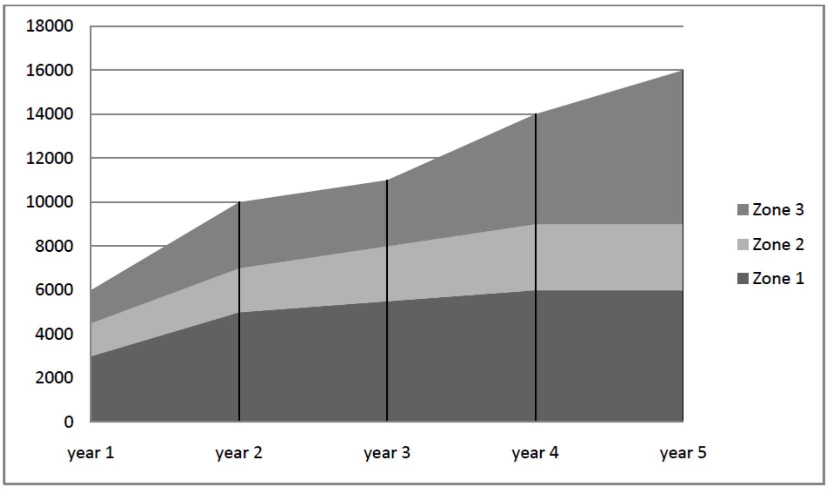
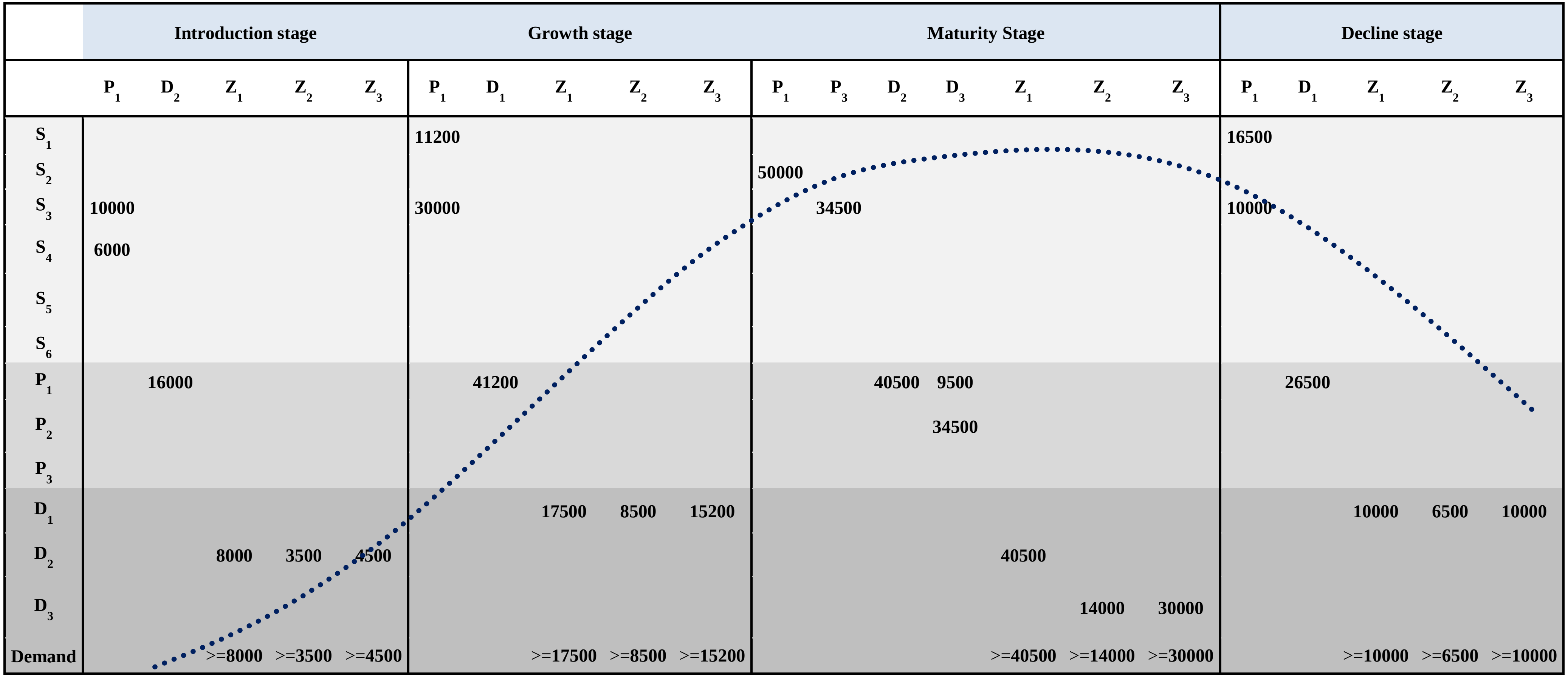


Figure 3.6:Sales distribution of the product in Ton

Figure 3.7 illustrates the deployment plan of the total supply chain during the product life cycle.

It is obvious that the transshipment solution for the supply chain network deployment changes from one stage to another. This is probably due to variables, namely the demand variation, as well as the efficiency scores variation. Indeed, different supply chain strategies could be adopted at different phases of the product life cycle, significantly influencing the supply chain actors’ selection decisions.

Using the same focal company as in the previous section, but keeping the same data on demand, tables 3.14 and 3.15 illustrate the optimal deployment plans for the supply chain network or the introduction and the maturity phase respectively.



	Introduction stage					**Growth stage**					**Maturity Stage**							**Decline stage**				
	P_1	D_2	Z_1	Z_2	Z_3	P_1	D_1	Z_1	Z_2	Z_3	P_1	P_3	D_2	D_3	Z_1	Z_2	Z_3	P_1	D_1	Z_1	Z_2	Z_3
S_1						11200												16500				
S_2											50000											
S_3	10000					30000						34500						10000				
S_4	6000																					
S_5																						
S_6																						
P_1		16000					41200						40500	9500					26500			
P_2														34500								
P_3																						
D_1								17500	8500	15200										10000	6500	10000
D_2			8000	3500	4500										40500							
D_3																14000	30000					
Demand			>=8000	>=3500	>=4500			>=17500	>=8500	>=15200					>=40500	>=14000	>=30000			>=10000	>=6500	>=10000

Figure 3.7:The deployment plan of the total supply chain

The optimal supply chain actors and the number of units to be shipped from each source to each destination is clearly depicted in this transshipment solution.

Table 3.14:Optimal supply chain network for the introduction stage

Introduction stage	P_1	D_1	Z_1	Z_2	Z_3
S_3	10000				
S4	6000				
P_1		16000			
D_1			8000	3500	4500
Demand			>=8000	>=3500	>=4500

Table 3.15:Optimal supply chain network for the maturity stage

Maturity stage	P_1	P_3	D_2	D_3	Z_1	Z_2	Z_3
S_2	4000						
S_3	4000	8000					
P_1			8000				
P_3				8000			
D_2					8000		
D_3						3500	4500
Demand					>=8000	>=3500	>=4500

The model demonstrates that the proposed method cannot only adopt the supply chain strategy according to the degree of concern at different phases, but also consider the trade-off effect to avoid selecting inefficient actors in the correspondent product life cycle stage.

From the listed results in table 3.15 for the maturity phase, it is interesting to notice that supplier 2, who was considered to be inefficient in the introduction phase, was selected as an efficient actor in the maturity phase, and similarly for distributor 3. This fact demonstrates that this method can adopt different supply chain strategies related to the product strategies of a focal company.

3.7 Model limits:

A case which can occur, and which may be a limitation of the model, is the one relating to the efficiency and the capacity constraints. Indeed, we can assume the following scenario:

It is possible that among the potential actors examined in phase I, the selected ones as the most efficient, cannot meet the needs of the supply chain, due to their capacity constraints, and that the rest of the potential actors are inefficient for selection.

When this scenario occurs, we propose four alternatives in order to solve the problem.

3.7.1 Review the expected efficiency value

In this case, we have to reconsider the expected efficiency value previously set by the decision maker. This is the easiest alternative to adopt, but nevertheless, we have to ask once more the decision maker, and he has to agree to reduce the efficiency limit value. However, it should be noticed that the efficiency bounds must be decreased within a reasonable limit because of its implications on the overall performance of the supply chain network. We then can select other actors still, but it is necessary that the new efficiency constraints be satisfied.

3.7.2 Review the sets of the potential actors

Here it is a question of revising the lists of the potential actors, and to add new ones who may be more effective and can meet the needs of the supply chain in terms of efficiency and capacity. This alternative could be the most relevant, but also the longest and the most complicated to perform. What makes it not very practical, is the need to redo all the steps of the first phase to aggregate the new data and recalculate the efficiency scores.

3.7.3 The penalty method

Generally, the penalty function method attempts to approximate a constrained optimization problem with an unconstrained one and then apply standard search techniques to obtain solutions. The approximation is accomplished in the case of penalty methods by adding a term to the objective function that prescribes a high cost for the violation of the constraints. Consider the problem:

$$Minimize\, \{f(x) : x \in S\,, x \in T\,\} \qquad\qquad P(1)$$

Where f is a continuous function on R^n and S is a constraint set in R^n.

The main idea of a penalty function method is to replace problem $P(1)$ by an unconstrained approximation of the form:

$$Minimize\, \{f(x) + \; cP(x), x \in T\,\} \qquad\qquad P(2)$$

Where c is a positive constant and P is a function on R^n satisfying (i) $P(x)$ is continuous, (ii) $P(x) \geq 0$ for all $x \in \mathrm{R}^n$, and (iii) $P(x) = 0$ if and only if $\in S$.

If the penalty function $P(x)$ grows quickly enough outside of S, the optimal solution of $P(1)$ will also be optimal for $P(2)$. Furthermore, any optimal solution of $P(2)$ will provide an upper bound on the optimum for $P(1)$, and this bound will in general be tighter than that obtained by simply optimizing $f(x)$ over T, Smith and Coit (1995).

In our case, the penalty function, replaces the efficiency constraints by adding a term to the objective function that consists of a penalty parameter and a measure of violation of the constraints.

We define the following penalty functions:

$$P_{i,t}(I) = \Delta_{i,t} X_{i,t} \quad ; \quad P_{j,t}(J) = \Delta_{j,t} Y_{j,t} \quad ; \quad P_{k,t}(K) = \Delta_{k,t} Z_{k,t}$$

with

$$\Delta_{i,t} = \max\{(\mathrm{e}_{\mathrm{exp},\mathrm{I},\mathrm{t}} - \mathrm{e}_{\mathrm{i},\mathrm{t}}), 0\}, \Delta_{j,t} = \max\{(\mathrm{e}_{\mathrm{exp},\mathrm{J},\mathrm{t}} - \mathrm{e}_{\mathrm{j},\mathrm{t}}), 0\}, \Delta_{k,t} = \max\{(\mathrm{e}_{\mathrm{exp},\mathrm{K},\mathrm{t}} - \mathrm{e}_{\mathrm{k},\mathrm{t}}), 0\}$$

Where

$e_{i,t}$: Mean efficiency score of the supplier i, at stage t

$e_{j,t}$: Mean efficiency score of the producer j, at stage t

$e_{k,t}$: Mean efficiency score of the distributor k, at stage t

$Eexp_{I,t}$: The minimum expected group efficiency average set forth by the decision maker for the suppliers at stage t

$Eexp_{J,t}$: The minimum expected group efficiency average set forth by the decision maker for the producers at stage t

$Eexp_{K,t}$: The minimum expected group efficiency average set forth by the decision maker for the distributors at stage t

c : The penalty value

The new problem objective function is then as the following:

$$\min f = \sum_{t\in T} \left[c * \left(\sum_{i\in I} P_{i,t}(I) + \sum_{j\in J} P_{j,t}(J) + \sum_{k\in K} P_{k,t}(K) \right) \right.$$

$$\left. + \sum_{i\in I} CF_{i,t} * X_{i,t} + \sum_{j\in J} CF_{j,t} * Y_{j,t} + \sum_{k\in K} CF_{k,t} * Z_{k,t} \right]$$

$$+ \left[\sum_{i\in I} CO_{i,t} * \left(X_{i,t} - XO_{i,t} \right) + \sum_{j\in J} CO_{j,t} * \left(Y_{j,t} - YO_{j,t} \right) + \sum_{k\in K} CO_{k,t} \right.$$

$$\left. * \left(Z_{k,t} - ZO_{k,t} \right) \right]$$

$$+ \left[\sum_{i\in I} CC_{i,t} * \left(X_{i,t} - XC_{i,t} \right) + \sum_{j\in J} CC_{j,t} * \left(Y_{j,t} - YC_{j,t} \right) + \sum_{k\in K} CC_{k,t} \right.$$

$$\left. * \left(Z_{k,t} - ZC_{k,t} \right) \right]$$

$$+ \left[\sum_{i\in I} \sum_{j\in J} c_{i,j,t} * Q_{i,j,t} + \sum_{j\in J} \sum_{k\in K} c_{j,k,t} * Q_{j,k,t} \right.$$

$$\left. + \sum_{k\in K} \sum_{z\in Z} c_{k,z,t} * Q_{k,z,t} \right]$$

Under the constraints (5)-(16) and (18)-(29).

This method allows the non effective potential actors, but whose efficiency scores are closer to the expected efficiency value to be selected, allowing us to meet the market demand.

It has however some drawbacks, namely the selection of non-effective actors, which could affect the overall efficiency of the supply chain.

3.7.4 Capacity extension

Capacity planning is among the most significant capital investment decisions that supply chain managers must periodically make. In the following, we propose an optimization model for the strategic capacity planning, which will allow capacity expansion for the effective supply chain actors that are selected.

In cases where the supply chain actors are still effective; even when the product goes from one stage to another of its product life cycle; but their respective capacities don’t allow them to meet the needs of the market, the proposed model will avoid the selection of new actors, but only a capacity expansion of the preselected ones, to the extent that this operation complies with the problem objective function and will not increase the supply chain total cost.

Additional model parameters:

$ce_{i,t}$	Unit cost of expanding the capacity of the supplier i at stage t
$ce_{j,t}$	Unit cost of expanding the plant j at stage t
$ce_{k,t}$	Unit cost of expanding the distribution center k at stage t
$ME_{i,t}$	Maximum expansion capacity of the supplier i at stage t
$ME_{j,t}$	Maximum expansion capacity of the plant j at stage t
$ME_{k,t}$	Maximum expansion capacity of the distribution center k at stage t

Additional model decision variables:

$EX_{i,t}$	=1 if the supplier capacity is expanded at stage t, 0 otherwise
$EY_{j,t}$	=1 if the plant is expanded at stage t, 0 otherwise
$EZ_{k,t}$	=1 if the distribution center is expanded at stage t, 0 otherwise
$CX_{i,t}$	Capacity added to the supplier i at stage t

$CY_{j,t}$ Capacity added to the plant j at stage t

$CZ_{k,t}$ Capacity added to the distribution center k at stage t

$$\begin{aligned}
\min \sum\nolimits_{t\in T} \Bigg[& \Bigg[\sum\nolimits_{i\in **I} CF_{i,t} * X_{i,t} + \sum\nolimits_{j\in J} CF_{j,t} * Y_{j,t} + \sum\nolimits_{k\in K} CF_{k,t} * Z_{k,t}\Bigg] \\
& + \Bigg[\sum\nolimits_{i\in I} CO_{i,t} * \left(X_{i,t} - XO_{i,t}\right) + \sum\nolimits_{j\in J} CO_{j,t} * \left(Y_{j,t} - YO_{j,t}\right) \\
& + \sum\nolimits_{k\in K} CO_{k,t} * \left(Z_{k,t} - ZO_{k,t}\right)\Bigg] \\
& + \Bigg[\sum\nolimits_{i\in I} CC_{i,t} * \left(X_{i,t} - XC_{i,t}\right) + \sum\nolimits_{j\in J} CC_{j,t} * \left(Y_{j,t} - YC_{j,t}\right) \\
& + \sum\nolimits_{k\in K} CC_{k,t} * \left(Z_{k,t} - ZC_{k,t}\right)\Bigg] \\
& + \Bigg[\sum\nolimits_{i\in I} \sum\nolimits_{j\in J} c_{i,j,t} * Q_{i,j,t} + \sum\nolimits_{j\in J} \sum\nolimits_{k\in K} c_{j,k,t} * Q_{j,k,t} \\
& + \sum\nolimits_{k\in K} \sum\nolimits_{z\in Z} c_{k,z,t} * Q_{k,z,t}\Bigg] \\
& + \Bigg[\sum\nolimits_{i\in I} ce_{i,t} * EX_{i,t} + \sum\nolimits_{j\in J} ce_{j,t} * EY_{j,t} + \sum\nolimits_{k\in K} ce_{k,t} * EZ_{k,t}\Bigg]\Bigg]
\end{aligned}$$

Subject to the constraints:

(2)-(4) ,(8)-(16) , (18)-(29), and

Capacity limits constraints:

$$\sum_{j=1}^{n} Q_{i,j,t} \leq cap_{i,t} * X_{i,t} + CX_{i,t} \quad \forall\, i\,, t \tag{30}$$

$$\sum_{k=1}^{p} Q_{j,k,t} \leq cap_{j,t} * Y_{j,t} + CY_{j,t} \quad \forall j\,, t \tag{31}$$

$$\sum_{z=1}^{q} Q_{k,z,t} \leq cap_{k,t} * Z_{k,t} + CZ_{k,t} \quad \forall k\,, t \tag{32}$$

$$CX_{i,t} \leq ME_{i,t} \quad \forall\, i\,, t \tag{33}$$

$$CY_{j,t} \leq ME_{j,t} \quad \forall\, j\,, t \tag{34}$$

$$CZ_{k,t} \leq ME_{k,t} \quad \forall\, k\,, t \tag{35}$$

An extended site is obligatory opened:

$$EX_{i,t} \leq X_{i,t} \quad \forall\, i\,, t \tag{36}$$

$$EY_{j,t} \leq X_{j,t} \quad \forall\, j\,, t \tag{37}$$

$$EZ_{k,t} \leq X_{k,t} \quad \forall\, k\,, t \tag{38}$$

Non-negativity Constraints :

$$EX_{i,t} \geq 0 \,\forall\; i, t \tag{39}$$

$$EY_{j,t} \geq 0 \;\forall\, j, t \tag{40}$$

$$EZ_{k,t} \geq 0 \;\forall\; k, t \tag{41}$$

The constraint sets (30)-(32) stipulate that all shipments from a given supply chain actor must not exceed its initial capacity plus the capacity added. The constraint sets (33)-(35) state that the capacity added to each facility must not exceed its maximum capacity extension. The constraint sets (36)-(38) prohibit extensions to be made for closed facilities. Non-negativity on each capacity extension is imposed by constraint sets (39)-(41).

If we take the same case study as previously, figure 3.8 presents the fluctuations in the capacity of the supply chain actors of the different processes, over the product life cycle.

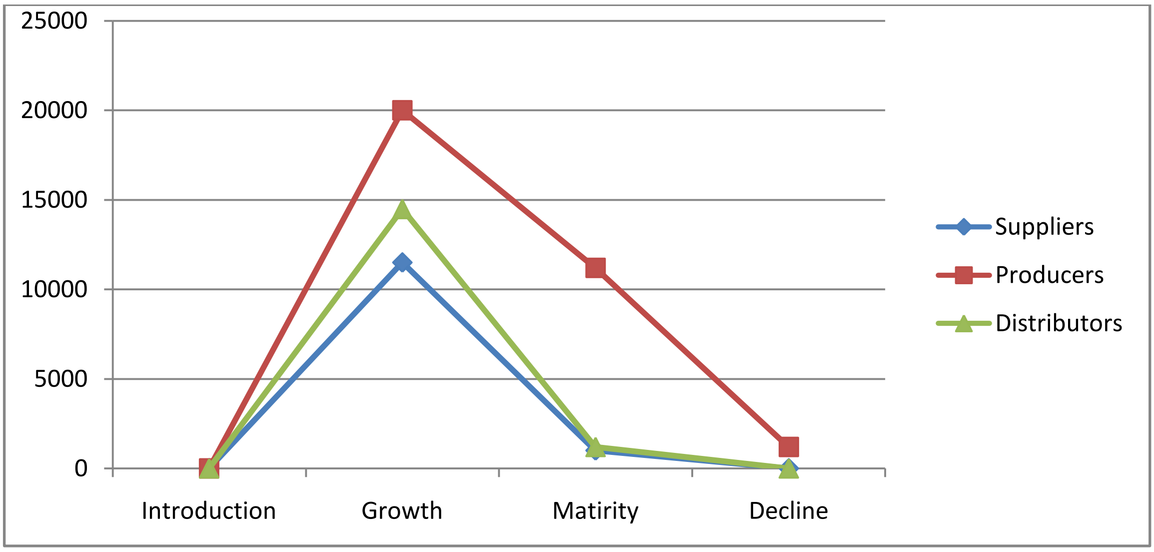


Figure 3.8:Fluctuations in capacities over the product life cycle

We can clearly understand ,from this figure, that the capacity extension reaches the highest level during the growth phase, which is predictable with the increasing of the market demand. The supply chain total cost however moves from 72 327 800 euro, in the case without a capacity expansion to 71 022 200 euro in the case when we allow the capacity expansion of the selected actors, which represents a total gain of 1.8% on the total cost.

3.8 Conclusion

This chapter focuses on the design of a supply chain network for a product from its introduction to the market to its decline stage. To achieve this goal, we have proposed a two-phase multi-criteria supply chain design model. In the first phase, we proposed to solve a multi-criteria decision making problem, taking into account different criteria set by the decision maker as well as the variation of the importance of these criteria and the corresponding sub-criteria according to the decision maker’s preferences, through the product life cycle stages. The combination of two aggregators was used for this, namely, the AHP and the OWA operators, which allowed modeling situations where the number of sub-criteria needed to satisfy a higher order concept, can be expressed in terms of fuzzy linguistic quantifiers. In the second phase, we proposed a mathematical model for a multi-period supply chain design. This methodology should assist managers in effectively designing a supply chain network by considering a number of criteria such as efficiencies of selecting actors, capacity limits, and market demand. While the traditional network design models identify the optimal network by minimizing the total cost, our method integrates additional important aspects of performance into the decision analysis. From a managerial perspective, this methodology conceives of a network that can meet the needs of the market by offering low costs, high on-time delivery rates, high quality levels, and high service quality, according to the market expectations for each product life cycle stage, which is not easily possible with traditional cost minimization approaches. The proposed model can also be applied by companies for reengineering an existing supply chain network in order to improve the overall performance. In such a situation, a firm can utilize the proposed method for evaluating the performance of existing suppliers, producers, and distribution centers in the network, and involve reduction of supply base in decisions by eliminating poorly performing suppliers, shutting down inefficient producers and reallocating resources to improve the performance for a given phase of the product life cycle.

Although the proposed methodology has proven an ability to design an effective multi-period supply chain network, this does not exclude the fact that it may present some limitations mainly related to the filtering out of the inefficient actors and to the efficiency bounds set by the decision maker. However, some solutions were proposed to overcome such problems.

In the next chapter, we will extend the mathematical model of our methodology to a multi-objective supply chain network design model.

CHAPTER 4

A product-driven sustainable supply chain design

4.1 Introduction

In the previous chapter, we proposed a two-phase method to design a multi-period supply chain network which takes into account the different phases the product goes through during its life cycle. The only objective considered in this method was to minimize the supply chain total cost.

In this chapter, we propose a method to design a sustainable multi-period supply chain with product life cycle consideration, while respecting the triple bottom line (3BL) concept. This concept, also known as ‘three Ps” refers succinctly to "people, planet and profit".

In recent years, supply chains have grown tremendously. They have focused only on the economic performance to optimize the costs or Return On Investments (ROIs), that cannot alone sustain the development of supply chain operations. The impact of different activities involved in supply chains such as the process of manufacturing, warehousing, distributing etc. on environment and social life of city residents cannot be ignored.

Correspondingly, the concepts of Green Supply Chain Management (GSCM) and Sustainable Supply Chain Management (SSCM) have emerged. They emphasize the importance of implementing environmental and social concerns along with economical factors in supply chain planning.

Other perspectives from the management field insist on the sustainability, supply chain management should strive for enterprise governance, business regulations, corporate responsibilities, and social justice.

The method proposed in this chapter is novel, since it deals with the important problem of designing supply chain networks to achieve sustainability from socio-economic-environmental perspective and takes, at the same time, the product life cycle into consideration.

The chapter is organized as follows: in Section 2, we define the problem, and provide a the literature review of prior works first, in the supply chain design with product life cycle considerations, and then in the environmental management field. In Section 3, we present the two-phase approach taking into consideration sustainability. We first explain the multi-criteria decision making problem method, and then provide details of the mathematical formulations for the model proposed. In section 4, we present a numerical example to validate the consistency of the proposed model. In section 5, we present some sensitivity analysis. We conclude this chapter by section 6, with some suggestions for future research in this area.

4.2 Problem definition

The overall goal, is to design a sustainable multi-level supply chain, taking into consideration the product life cycle.

According to the United Nation Global Compact, the Supply chain sustainability is the management of economic, environmental, and social impacts, and the encouragement of good governance practices, throughout the lifecycles of goods and services. The objective of supply chain sustainability is to create, protect and grow a long-term economic, environmental, and social value for all stakeholders involved in bringing products and services to market.

Figure 4.1 presents a multi-dimensional view for measuring the sustainability of supply chains.

As is shown in this figure, the performance of a supply chain can be measured according to three-dimension metrics derived from the three base lines of a sustainable supply chain, namely, social, economic, and environmental lines.

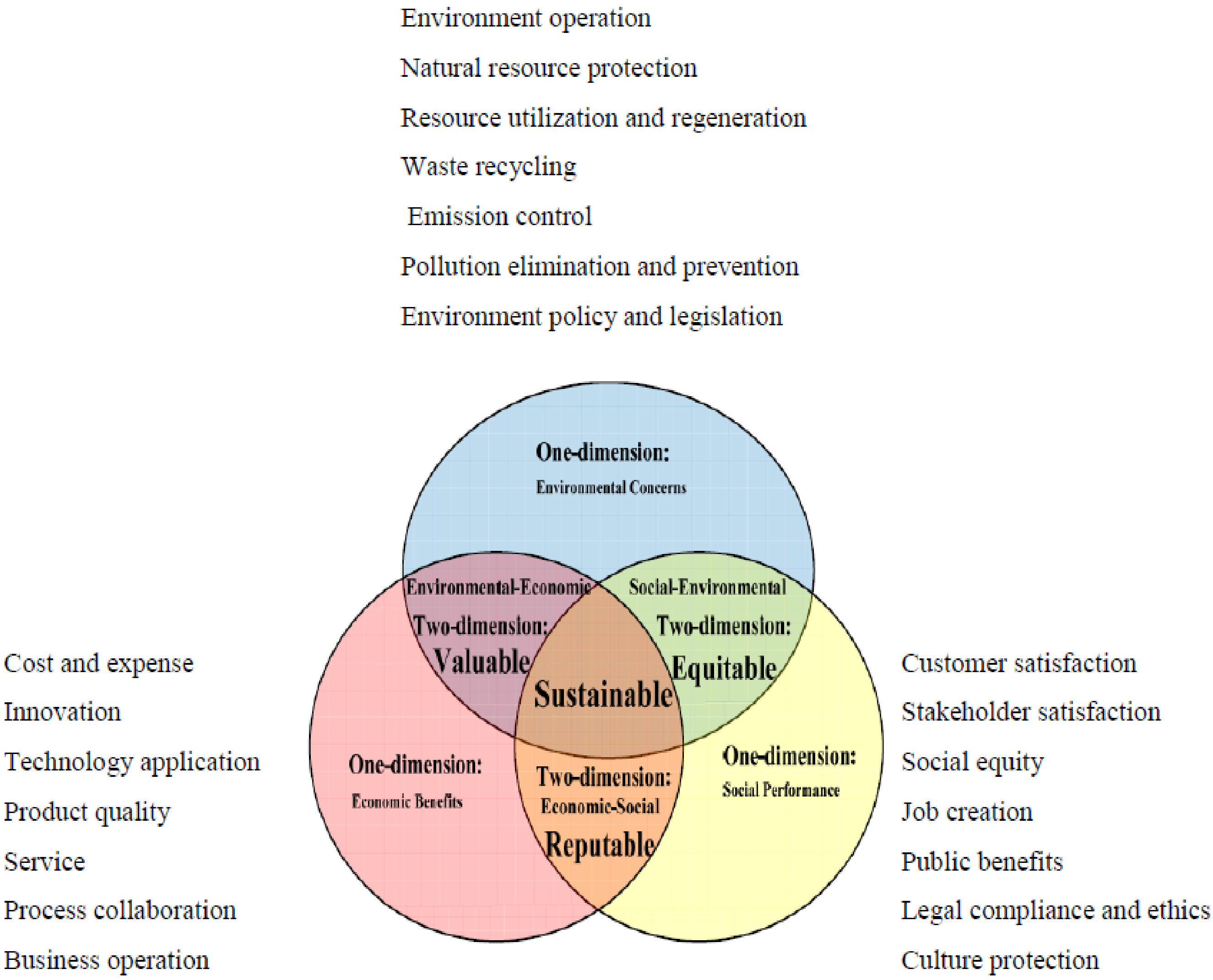


Figure 4.1: The Three Base Line of a sustainable supply chain, adapted from Zhong Hua Zhang, 2011

We can talk about one-dimensional metrics, when each of the three lines is considered individually. We may therefore be interested in either the economic dimension, or the environmental metrics, or also the social performance of the supply chain.

A two-dimension metric is a result of each combination of two one-dimensional metrics. They can be used to evaluate the degree of operations, processes, and activities integration in sustainability in supply chains.

The three-dimension metrics also called as sustainable metrics, are to consider the three one-dimensional metrics all together at a time.

A sustainable supply chain helps companies to protect the long-term viability of their product, trying to extend the time from the launch stage until the decline stage of the product, and to secure a social license to operate. Leading companies understand that they have a role to play throughout the lifecycle of their products and services, and that the supply chain sustainability is a key to maintain the integrity of a brand, ensure business continuity and manage operational costs.

The first action in developing a supply chain sustainability strategy is to evaluate the business case for the product and understand its external landscape. This action, formalizing the decision to launch a new product on the market, includes several steps, such as:

4.2.1 The advisability study

This step of preliminary project, allows studying the project application and deciding if the concept is viable. This step is to issue validating the customer’s demand, against the overall objectives of the organization.

This step represents eventually the base of the design of the supply chain, as it is at this stage that the whole demand for the product is estimated, and the life cycle of the product could be defined according to the variation in demand over time.

Even more, the identification of the different wholesalers and the various customer zones should be made at the end of this study.

4.2.2 The feasibility study

This step is to analyze the economic, organizational and technical feasibility of the project. Hence, requirements' analysis has to be done. From the summary analysis of the requirements, it should be a rough estimate of the different costs of investment and operation of the project (in terms of human and material resources), the expected lead-times, and the potential return on investment. Based on these estimates, the Steering Committee may consider continuing the project, and if necessary provide a methodological organization therefore.

This second step is also a very important one for the supply chain design. Indeed, at the end of this step, we should have an idea about the different potential actors in the chain, in terms of the proposed costs for raw materials, production and distribution costs, in terms of the quality offered, the different lead-times, and even the innovation.

The collected data ,at this stage, regarding the various potential actors, will serve to evaluate them from an economical point of view.

It is clear, therefore, that following these two steps, the project is studied from a single perspective, namely the economical side. However, in real life, to ensure that the study was complete and that the project will be approved by the authorities, any preliminary draft should include a third study, namely the impact assessment study.

4.2.3 The impact assessment study

An impact study is a collective reflection which aims at assessing the consequences of all factors, including the environmental project in an attempt to reduce, mitigate or compensate for adverse impacts.

The awareness in the 1970s of the need to limit the damage of nature was embodied in laws forcing to reduce noise and pollution, and to mitigate the impacts of large projects. To do so, the environmental impact studies became mandatory prior to the completion of facilities or structures, which by their size or by the importance of their impact on the natural environment, could affect it.

In this context, the ISO 14001 standards were addressed to economic operators and constructive business leaders to understand that the implementation of a strategic approach can make the investments profitable, since these standards are in favor of the protection of the environment.

Indeed, the approach of ISO 14001 requires the company to conduct a review of all the deep areas where activities have an environmental impact.

It is an approach that has several advantages for the company. Benefits include reduced costs of waste management, an evident energy saving, cheaper distribution costs, ...

To these advantages is added a better image of the company with the regulatory authorities along with the international contractors, national ones, or those in the public sector. The adoption of ISO 14001 standards allows companies to be better perceived by the agencies that are responsible for environmental issues. The main criteria that must be analyzed on the environmental point, are the impacts on soil, air, water, and fauna and flora (the human being is considered). Analyzes of the impact of emissions on the atmosphere, from the chemical, the visibility, the toxicity, or the opacity point of view, the impact of these programs on fauna and flora, and even the study of the impact on geology, topography, hydrology, and hydrogeology. Furthermore, the willingness of countries to meet the Kyoto Protocol goal, pushed them to encourage manufacturers to reduce their emissions.

The Kyoto Protocol is a legally binding agreement under which industrialized countries will reduce their collective emissions of greenhouse gases by 5.2% compared to the year 1990. The goal is to lower the overall emissions from six greenhouse gases - carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, HFCs, and PFCs - calculated as an average over the five-year period of 2008-2012. And recently, in December 2012, delegates from almost 200 countries have extended until 2020 the Kyoto Protocol for fighting climate change.

Moreover, the law on the carbon tax, which has begun to be applied in most developed countries, discourages emissions by making polluters pay in proportion to their emissions.

This law has pushed manufacturers to be increasingly vigilant towards their carbon emissions, and to be careful not to exceed the emission requirements, so as to minimize the tax liability in this context.

In addition to the environmental side, this impact study could also consider the social consequences of the project, especially when it comes to the implementations of sites. Indeed, the consequences of these implementations are often positive for the host countries.

This could result in jobs' creation and a decrease in the unemployment rate, a transfer of know-how and techniques, and a gradually increase of the living standards in the host country.

If positive impacts on countries that benefit from these locations are highlighted, we must not forget, however, the negative impact on the countries that may suffer from relocation.

Therefore, a complete understanding of the issue of relocation requires the two perspectives. Offshoring has many social implications in countries undergoing relocations. The main effects are the generation of layoffs and indirect job losses. They could even lead to the bankruptcy of some subcontractors.

The more these studies are detailed and comprehensive, the more they will help design an efficient supply chain for the product.

According to Nagurney (2009) and Chen et al. (2004), the adoption of multiple criteria and multiple objectives in designing supply chain networks represents the system-optimization perspective of SCN integration.

Indeed, after defining the product life cycle in the first advisability study, in feasibility and impact assessment studies, a set of criteria is taken into consideration to analyze the economical, environmental and social feasibility of the project, and to evaluate the different potential supply chain actors.

The pinpointing of such criteria and of their importance is strongly linked to the product life cycle and its different phases.

We can note that, at the macro-economical level, according to the marketing strategy adopted at each product life cycle stage, the decision to establish contractual relationships with suppliers, or to set up or to relocate production facilities or warehouses because of the lower costs can be weakened by the consideration of structural factors such as:

- The ability to have a web of local suppliers, or producers with real guarantees of reliability in terms of quality, time delivery, respect for commercial contracts, quality of the services and goods produced, etc..

Indeed, the quality criterion of the product as well as the service level criterion could be very important at the introduction stage of the product than at the other phases. While, the criterion cost is very important at the growth and maturity stages. So, to be selected during these stages, the supply chain actors should respond well to these criteria.

- The political and social instability in the host country, is particularly likely to make the ways to ensure the physical security of the entity implanted too expensive.
- The state policy towards foreign investment, which, as far as possible, should not be fluctuating; has to be verified, instead.
- The operation of the public services, the reliability of the administration (including its level of possible corruption) and the extent of the regulatory and compliance, in particular with regard to the right intellectual property to protect the company from the risks of counterfeit.

It is instructive to observe, in this regard, that there are even re-localization phenomena, which cause the closure of a facility and the opening of a new one. These phenomena provide the evidence of a poor feasibility study by the company, which resulted in losses that the re-localization is actually able to avoid. This was the case with many companies having noted deterioration in the quality of production or services, or after some customers' complaints.

The challenging issues are how to achieve a sort of balance among the different business goals, social concerns, and the environmental impacts of different activities in a product-driven supply chain.

This part of the thesis focuses on the problem of designing a product-driven sustainable supply chain network considering the (3BL) Triple Bottom Lines of maximizing economic returns, minimizing environmental impacts, and maximizing social performance for the supply chain. The proposed method is novel and deals with the important problem of designing supply chain networks to achieve sustainability from a socio-economic-environmental perspective while considering the product life cycle.

4.3 *The resolution methodology:*

The developed two-phase approach is based on the AHP-OWA procedure and the weighted goal programming method, incorporating both quantitative and qualitative factors.

Thus, as in the previous chapter, the resolution procedure will be conducted in two phases separately. The first one focuses on the performance and the effectiveness' evaluation of each potential actor at each product life cycle stage, while the second phase focuses on the supply chain network design. Figure 4.2 depicts the decision making process involved in the supply chain network design. The decision maker in this framework is top executive acting as a broker.

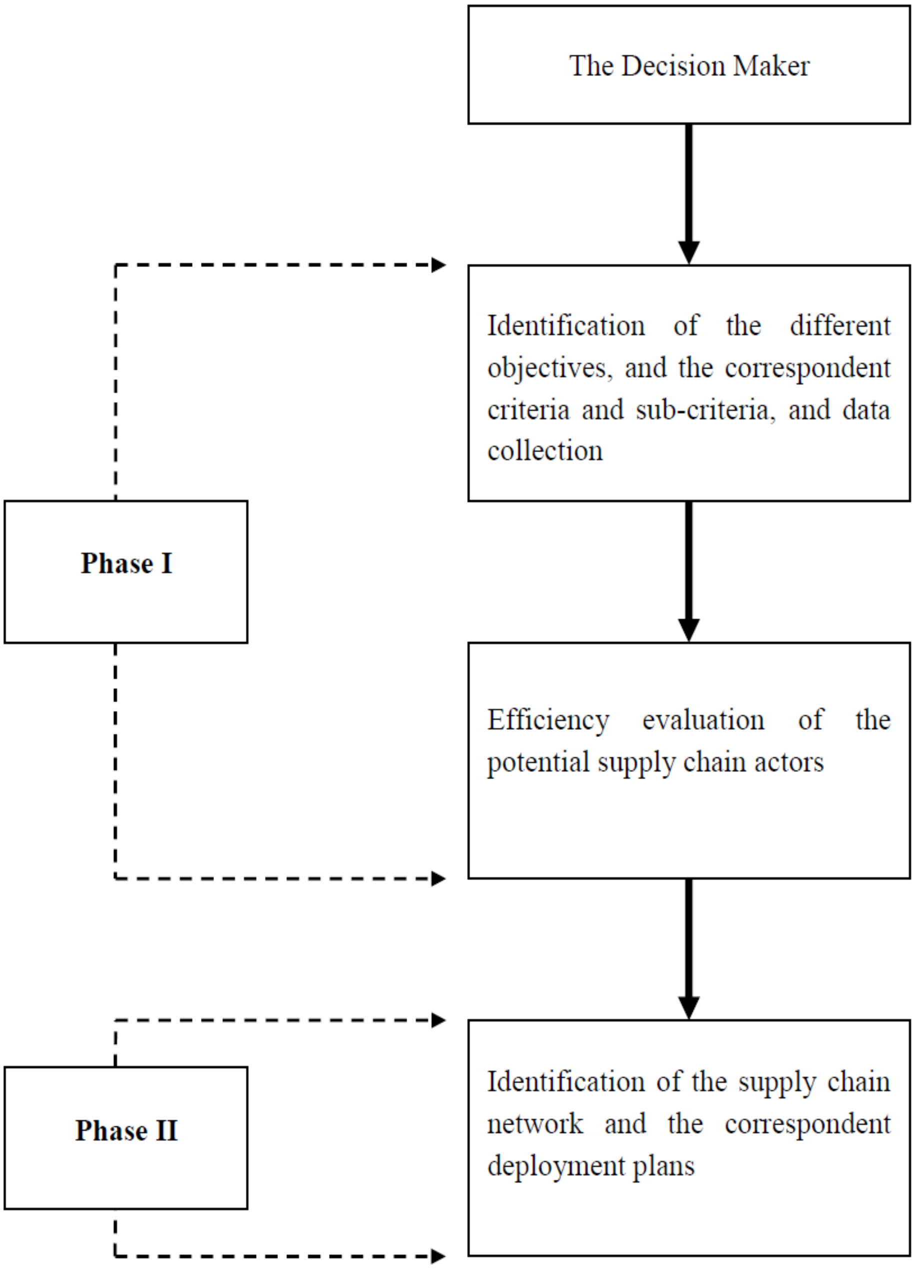


Figure 4.2: Phases for the supply chain network design

Phase I: A multi-attribute decision making problem:

The overall goal being to design a product-driven sustainable supply chain, we have three different objectives to be optimized namely the economic, environmental, and social objectives.

Each of the three objectives is broken down into a set of criteria, each of them is, in turn decomposed into a set of sub-criteria.

This was translated into the hierarchical scheme shown in figure 4.3.

From the collected data in the beginning, following the advisability study, the feasibility study and the impact assessment study, we can proceed to the evaluation of the potential supply chain actors, according to the objectives, the criteria and the sub-criteria fixed by the decision maker as well as to their correspondent importances.

As these importances vary in accordance to the product life cycle, and to the supply chain strategy that is appropriate to each stage. An exhaustive assessment for all the potential actors for each supply chain level separately, is then required at each stage.

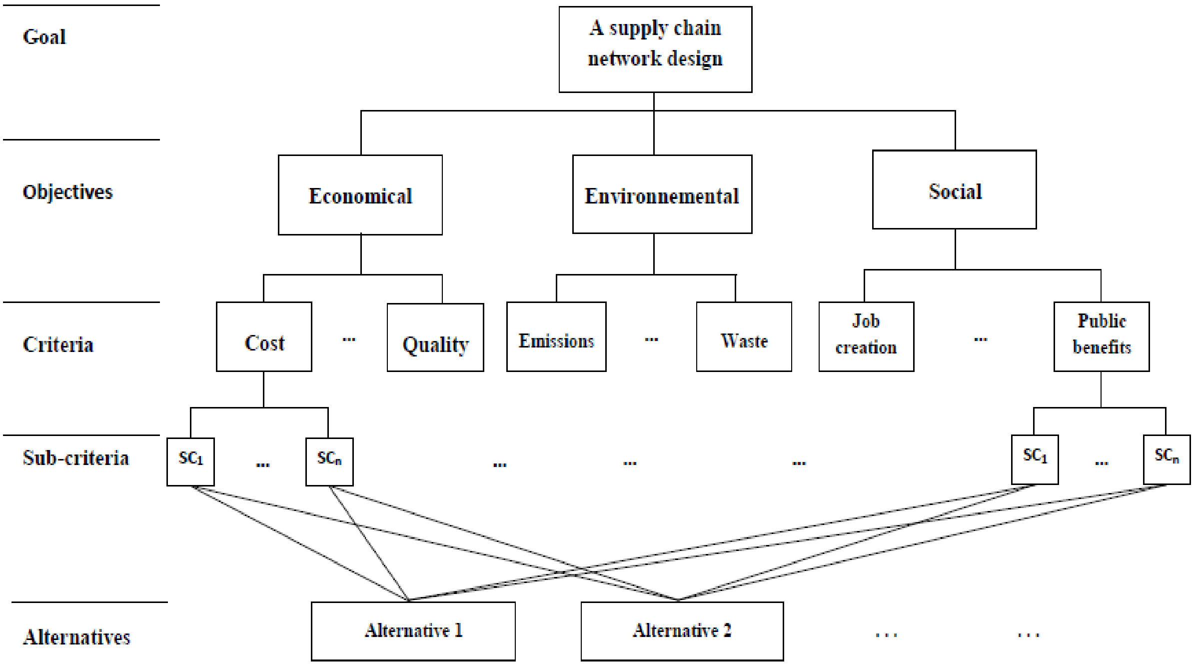


Figure 4.3: Criteria hierarchy

This evaluation will be carried out by using the combination of two methods, namely the AHP and the OWA. The above problem is solved separately for each of the three business process types.

The implementation of this combination, at each product life cycle stage, involves five major steps (See the chapter 3, section 3.4 for more details) :

(i) Developing an AHP hierarchy (figure 4.3) for each supply chain level separately, by defining the different criteria and sub-criteria corresponding to each level.

(ii) A pair-wise comparison for all the elements of the hierarchical structure; objectives, criteria, sub-criteria and alternatives; using the ratio scale of comparative judgments proposed by Saaty (1980).

(iii) Specifying the linguistic quantifier Q corresponding to each criterion and to each objective, in accordance to the supply chain strategy used at the correspondent product life cycle stage (see chapter 3)

(iv) Generating a set of ordered weights associated with Q, and

(v) Computing the overall efficiency evaluation for each i-th alternative by means of the OWA combination function.

This method generates an efficiency score for each candidate in each process and at each stage. Phase I essentially identifies the candidates who will be selected for the network, by referring to their obtained efficiency scores and to an expected efficiency average fixed by the decision maker for each supply chain process.

This identification is formalized by efficiency constraints that will be added to the mathematical model in the next optimization phase.

Phase II: The multi-objective supply chain network design

The existing the literature on logistics is extremely rich in terms of mathematical models that aim at designing supply chain networks, but there are no proposed mixed integer linear models that take into account both economic, environmental, and social criteria for the design of a multi-period supply chain.

To fill in this gap, in this part of the thesis, we propose a mixed integer linear programming model to design a sustainable multi-period and product-driven supply chain.

To ensure the supply chain sustainability, we set three objectives to be achieved.

The first one is related to the economic impact, it focuses on minimizing the supply chain total cost.

The second objective is rather related to the supply chain environmental impact, and focuses on minimizing the CO2 emissions across the whole chain.

And finally, because of the surrounding context of difficult economic times, we have used the prospects for maximizing the number of job creations as the main measure of the supply chain social impact.

Under each of these objectives, we can find a set of criteria and sub-criteria laid down by the decision maker, and which vary according to the supply chain process.

The second phase handles the identification of actors in the chain, as well as the optimal allocation of material from selected suppliers to manufacturers and to warehouses while still achieving the three above cited objectives.

The model formulation

The mixed integer linear programming model developed in this section, aims at selecting suppliers from a candidate set of suppliers, as well as to locate a given number of production producers and distributors, subject to capacity restrictions.

We assume that the customer's zone locations and his specific demand estimates for the given product, at the different life cycle stages, are given in advance. The potential producer and distributor locations as well as their capacities are also known. For each open supplier, producer and distributor, a decision must be made on the total units of products that need to be transported from the selected supplier, to the open producer, and then to the open distributor, and the total units of the product that need to be distributed from the open distributor based on a given service level. In addition, we assume that the production of one unit of a product requires one unit of the producer capacity. The similar assumption is considered for suppliers and distributors.

Notations

Before formulating the model, we introduce the basic parameter notations and definitions. We define the problem parameters and decision variables as follows:

$d_{i,j}$	Distance, in Km, between the supplier i, and the producer j
$d_{j,k}$	Distance, in Km, between the producer j, and the distributor k
$d_{k,z}$	Distance, in Km, between distributor k and the customer zone z
ε_i	Fixed energy requirement for a supplier i, in Kwh
ε_j	Fixed energy requirement for a producer j, in Kwh
ε_k	Fixed energy requirement for a distributor k, in Kwh
α_i	CO2 emission factor, for the supplier i, in Ton per Kwh
α_j	CO2 emission factor, for the producer j, in Ton per Kwh

α_k	CO2 emission factor, for the distributor k, in Ton per Kwh
α_s	CO2 emission factor for transportation, in Ton per Ton.Km
$JC_{i,t}$	Number of jobs created due to the opening of the supplier i at stage t
$JC_{j,t}$	Number of jobs created due to the opening of the producer j at stage t
$JC_{k,t}$	Number of jobs created due to the opening of the distributor k at stage t

The remaining model parameters and decision variables are the same used in chapter 3, in section 3.5.

We suppose that the fixed costs of the closing sites include, as the case may show, either the economic redundancy allowance for employees following a permanent closure of the site or a temporary one if there's a possible reopening later.

As mentioned before, our model has three objectives: to minimize the supply chain total cost, to minimize the total CO2 emissions, and to maximize the number of created jobs throughout the product life cycle.

The total cost of the supply chain includes the fixed opening and closing of the sites, the fixed costs to operate each of these sites, purchasing costs, production costs, transportation and distribution cost. Therefore, the objective function to be minimized is given by:

$$\begin{aligned}
\min f_1 \; = \; & \sum\nolimits_t \left[\left[\sum\nolimits_{i=1}^{m} CF_{i,t} * X_{i,t} + \sum\nolimits_{j=1}^{n} CF_{j,t} * Y_{j,t} + \sum\nolimits_{k=1}^{p} CF_{k,t} * Z_{k,t} \right] \right. \\
& + \left[\sum\nolimits_{i \in I} CO_{i,t} * X_{i,t} * \left(1 - X_{i,t-1}\right) \right. \\
& \left. + \sum\nolimits_{j \in J} CO_{j,t} * Y_{j,t} * \left(1 - Y_{j,t-1}\right) + \sum\nolimits_{k \in K} CO_{k,t} * Z_{k,t} * \left(1 - Z_{k,t-1}\right) \right] \\
& + \left[\sum\nolimits_{i \in I} CC_{i,t} * X_{i,t} * \left(1 - X_{i,t+1}\right) \right. \\
& \left. + \sum\nolimits_{j \in J} CC_{j,t} * Y_{j,t} * \left(1 - Y_{j,t+1}\right) + \sum\nolimits_{k \in K} CC_{k,t} * Z_{k,t} * (1 - Z_{k,t+1}) \right] \\
& + \left[\sum\nolimits_{i=1}^{m} \sum\nolimits_{j=1}^{n} c_{i,j,t} * Q_{i,j,t} + \sum\nolimits_{j=1}^{n} \sum\nolimits_{k=1}^{p} c_{j,k,t} * Q_{j,k,t} \right. \\
& \left. \left. + \sum\nolimits_{k=1}^{p} \sum\nolimits_{z=1}^{q} c_{k,z,t} * Q_{k,z,t} \right] \right] \qquad (1)
\end{aligned}$$

The second objective function is to minimize the total CO2 emissions in all the supply chain, which includes the emissions in all facilities, the emissions that may occur during the transportation of the product between the facilities as well as during the product delivery from distributors to customers. This objective function is expressed as follows:

$$\begin{aligned}
\min f_2 = & \sum_{i \in I} \alpha_i \varepsilon_i X_{i,t} + \sum_{j \in J} \alpha_j \varepsilon_j Y_{j,t} + \sum_{k \in K} \alpha_k \varepsilon_k Z_{k,t} \\
& + \sum_{i \in I} \sum_{j \in J} \alpha_s d_{ij} Q_{i,j,t} \\
& + \sum_{j \in J} \sum_{k \in K} \alpha_s d_{jk} Y_{j,k,t} + \sum_{k \in K} \sum_{z \in Z} \alpha_s d_{kz} Z_{k,z,t} \qquad (2)
\end{aligned}$$

And finally, the third objective that maximizes the job creations is represented as follows:

$$\max f_3 = \sum_t \left[\sum_{i\in I} JC_{i,t} * X_{i,t} * \left(1 - X_{i,t-1}\right) + \sum_{j\in J} JC_{j,t} * Y_{j,t} * \left(1 - Y_{j,t-1}\right) + \sum_{k\in K} JC_{k,t} * Z_{k,t} * \left(1 - Z_{k,t-1}\right)\right] \quad (3)$$

s.t

Efficiency constraints:

$$e_{i,t}X_{i,t} \geq Eexp_{I,t}\, X_{i,t} \quad \forall\, i,t \qquad (4)$$

$$e_{j,t}Y_{j,t} \geq \; Eexp_{J,t}\, Y_{j,t} \;\; \forall\, j,t \qquad (5)$$

$$e_{k,t}Z_{j,t} \geq Eexp_{K,t}\, Z_{k,t} \quad \forall\, k,t \qquad (6)$$

Capacity limits constraints:

$$\sum_{j=1}^{n} X_{i,j,t} \leq cap_{i,t} * \; X_{i,t} \quad \forall\, i\,,t \qquad (7)$$

$$\sum_{k=1}^{p} Y_{j,k,t} \leq cap_{j,t} * \; Y_{j,t} \quad \forall j\,,t \qquad (8)$$

$$\sum_{z=1}^{q} Z_{k,z,t} \leq cap_{k,t} * Z_{k,t} \quad \forall k\,,t \qquad (9)$$

Flow conservation constraints

$$\sum_{i=1}^{m} XQ_{i,j,t} - \sum_{k=1}^{p} Q_{j,k,t} = 0 \quad \forall\, j\,,t \qquad (10)$$

$$\sum_{j=1}^{n} Q_{j,k,t} - \sum_{z=1}^{q} Q_{k,z,t} = 0 \quad \forall\, k\,,t \qquad (11)$$

Total market demand satisfaction constraint:

$$\sum_{k=1}^{p} Q_{k,z,t} \geq \; D_{z,t} \;\; \forall\, z,t \qquad (12)$$

Non-negativity constraints

$Q_{i,j,t} \geq 0 \; \forall \; i, j, t$ (13)

$Q_{j,k,t} \geq 0 \; \forall \; j, k, t$ (14)

$Q_{k,z,t} \geq 0 \; \forall \; k, z, t$ (15)

$X_{i,t} \in \{0,1\} \; \forall i, t$ (16)

$Y_{j,t} \in \{0,1\} \; \forall j, t$ (17)

$Z_{k,t} \in \{0,1\} \; \forall k, t$ (18)

$i = 1, \dots, m,$

$j = 1, \dots, n,$

$k = 1, \dots, p,$

$z = 1, \dots, q$

The model reformulation

To linearize the economic and the social objective functions, (1) and (3), we use the same linearization technique as proposed by Fortet (1959),and that we have already detailed in the previous chapter and which involves replacing each product of two binary variables by a single additional variable and two auxiliary linear constraints.

Therefore, the economic function is rewritten as:

$$\min f_1 = \sum_{t\in T} \left[\sum_{i\in I} CF_{i,t} * X_{i,t} + \sum_{j\in J} CF_{j,t} * Y_{j,t} + \sum_{k\in K} CF_{k,t} * Z_{k,t}\right]$$

$$+ \left[\sum_{i\in I} CO_{i,t} * \left(X_{i,t} - XO_{i,t}\right) + \sum_{j\in J} CO_{j,t} * \left(Y_{j,t} - YO_{j,t}\right) + \sum_{k\in K} CO_{k,t}\right.$$

$$\left. * \left(Z_{k,t} - ZO_{k,t}\right)\right]$$

$$+ \left[\sum_{i\in I} CC_{i,t} * \left(X_{i,t} - XC_{i,t}\right) + \sum_{j\in J} CC_{j,t} * \left(Y_{j,t} - YC_{j,t}\right) + \sum_{k\in K} CC_{k,t}\right.$$

$$\left. * \left(Z_{k,t} - ZC_{k,t}\right)\right]$$

$$+ \left[\sum_{i\in I}\sum_{j\in J} c_{i,j,t} * Q_{i,j,t} + \sum_{j\in J}\sum_{k\in K} c_{j,k,t} * Q_{j,k,t}\right.$$

$$\left. + \sum_{k\in K}\sum_{z\in Z} c_{k,z,t} * Q_{k,z,t}\right] \qquad (19)$$

And the social function is rewritten as :

$$\max f_3 = \sum_{t} \left[\sum_{i\in I} JC_{i,t} * \left(X_{i,t} - XO_{i,t}\right) + \sum_{j\in J} JC_{j,t} * \left(Y_{j,t} - YO_{j,t}\right) + \sum_{k\in K} JC_{k,t}\right.$$

$$\left. * \left(Z_{k,t} - ZO_{k,t}\right)\right] \qquad (20)$$

With

$XO_{i,t} = X_{i,t} * X_{i,t-1}$ ∀ i, t (21

$YO_{j,t} = Y_{j,t} * Y_{j,t-1}$ ∀ j, t (22)

$ZO_{k,t} = Z_{k,t} * Z_{k,t-1}$ ∀ k,t (23)

$XC_{i,t} = X_{i,t} * X_{i,t+1}$ ∀ i, t (24)

$YC_{j,t} = Y_{j,t} * Y_{j,t+1}$ ∀ j, t (25)

$ZC_{k,t} = Z_{k,t} * Z_{k,t+1}$ $\forall$ k, t (26)

For linearization, the following constraints are added to the previous problem constraints:

Linearization constraints

$XO_{i,t} \leq X_{i,t}$ $\forall i$ (27)

$YO_{j,t} \leq Y_{j,t}$ $\forall j$ (28)

$ZO_{k,t} \leq Z_{k,t}$ $\forall k$ (29)

$XO_{i,t} \leq X_{i,t-1}$ $\forall i$ (30)

$YO_{j,t} \leq Y_{j,t-1}$ $\forall j$ (31)

$ZO_{k,t} \leq Z_{k,t-1}$ $\forall k$ (32)

$XO_{i,t} \geq X_{i,t} + X_{i,t-1} - 1$ $\forall i$ (33)

$YO_{i,t} \geq Y_{i,t} + Y_{i,t-1} - 1$ $\forall j$ (34)

$ZO_{i,t} \geq Z_{i,t} + Z_{i,t-1} - 1$ $\forall k$ (35)

$XC_{i,t} \leq X_{i,t}$ $\forall i$ (36)

$YC_{j,t} \leq Y_{j,t}$ $\forall j$ (37)

$ZC_{k,t} \leq Z_{k,t}$ $\forall k$ (38)

$XC_{i,t} \leq X_{i,t-1}$ $\forall i$ (39)

$YC_{j,t} \leq Y_{j,t-1}$ $\forall j$ (40)

$ZC_{k,t} \leq Z_{k,t-1}$ $\forall k$ (41)

$XC_{j,t} \geq X_{i,t} + X_{i,t-1} - 1$ $\forall i$ (42)

$YC_{j,t} \geq Y_{j,t} + Y_{j,t-1} - 1$ $\forall j$ (43)

$ZC_{k,t} \geq Z_{k,t} + Z_{k,t-1} - 1$ $\forall k$ (44)

To solve the proposed mathematical model, and satisfies the three goals, a weighted goal programming technique is applied.

The weighted goal programming technique

The roots of the goal programming technique lie in a paper by Charnes et al. (1955) in which they deal with the executive compensation methods. A more explicit definition is given by Charnes and Cooper (1961) in which the term “goal programming” is first used.

The goal programming is an important technique for allowing the decision makers to consider several objectives in finding a set of acceptable solutions. It has been accomplished with various methods such as Lexicographic (Preemptive), Weight (Archimedean), and MINIMAX (Chebyshev) achievement functions (Romero, 2004).

It can also be said that the goal programming has been, and still is, the most widely used technique for solving multi-criteria decision-making problems (Romero, 2004).

In general, the purpose of this technique is to minimize the deviation between the achievements of goals and their acceptable aspiration levels.

It is a special compromise multi-criteria method assuming that the decision maker knows goals’ values and their relative importance (Liu, 2008). It is designed to consider many goals simultaneously when searching for a compromise solution and is supported by a mathematical programming optimization potential (Martel and Aouni, 1998). Applied philosophy of compromise solution searching defines a variety of goal programming techniques (Jones and Tamiz, 2010). Each type of achievement function utilized leads to different goal programming variants. In this chapter, weighted goal programming (WGP) will be applied.

WGP is resting on Archimedean achievement function minimizing the sum of weighted deviations from target values. They are measured using positive and negative deviational variables defined for each goal separately, presenting either over- or underachievement of the goal. Negative deviation variables are included in the objective function for goals that are of the type ‘more is better’, and positive deviation variables are included in the objective function for goals of the type ‘less is better’. Since any deviation is undesired, the relative importance of each deviation variable is determined by associated weights, reflecting decision maker’s preferences among goals. For the objective function, it is typical that it minimizes undesirable deviations from the target goal levels and does not minimize or maximize the goals themselves (Ferguson et al., 2006).

The algebraic formulation of a WGP is given as:

$$\min g = \sum_{q=1}^{Q} [u_q n_q + v_q p_q]$$

s.t

$$\begin{aligned} & f_q(x) + n_q - p_q = b_q \qquad q = 1, \dots, Q \\ & x \in F \\ & n_q, p_q \geq 0 \qquad (34) \end{aligned}$$

Where $f_q(x)$ is a linear function of x, and b_q the target value for that objective. n_q and p_q represent the negative and positive deviations from this target value. u_q and v_q are the respective positive weights attached to these deviations in the achievement function g.

These weights take the value zero if the minimization of the corresponding deviational variable is not important to the decision maker. F is an optional set of hard constraints as found in linear programming.

In addition, a major issue of debate within the GP community has concerned the use of normalization techniques to overcome incommensurability. Incommensurability in a WGP occurs when deviational variables measured in different units are summed up directly, as is the case for the proposed mathematical model in this chapter.

This simple summation will cause an unintentional bias towards the objectives with a larger magnitude. This bias may lead to erroneous or misleading results.

One suggestion to overcome this difficulty is to divide each objective through by a constant pertaining to that objective. This ensures that all objectives have roughly the same magnitude. Such a constant is known as normalization constant. This leads to the revised algebraic format for a WGP:

$$\min g = \sum_{q=1}^{Q} \left[\frac{u_q n_q}{k_q} + \frac{v_q p_q}{k_q} \right]$$

s.t

$$f_q(x) + n_q - p_q = b_q \qquad q = 1, \dots, Q$$

$$x \in F$$

$$n_q, p_q \geq 0 \qquad (35)$$

where k_q is the normalization constant for the q-th objective.

Within WGP, all deviations are expressed as a ratio difference (i.e., (desired – actual)/desired) = (deviation)/desired)). In this case, any marginal change within one observed goal is of equal importance, no matter how distant it is from target value (Rehman and Romero 1987).

The model is then formulated as follows:

$$\min \sum \left(\frac{u_1 p_1}{k_1} \right) + \left(\frac{u_2 p_2}{k_2} \right) + \left(\frac{v_3 n_3}{k_3} \right) \qquad (36)$$

s.t

(4) - (18)

(21) - (33)

$f_1 - p_1 + n_1 = b_1$ (37)

$$f_2 - p_2 + n_2 = b_2 \tag{38}$$

$$f_3 - p_3 + n_3 = b_3 \tag{39}$$

$$n_q, p_q \quad \geq 0 \quad \forall\, q = 1,2,3 \tag{40}$$

Where

u_1	Weight of the economical objective determined using the AHP in the phase 1
u_2	Weight of the environmental objective determined using the AHP in the phase 1
v_3	Weight of the social objective determined using the AHP in the phase 1
k_1	Normalizing constant for the objective 1
k_2	Normalizing constant for the objective 2
k_3	Normalizing constant for the objective 3
b_1	Target value for the objective 1
b_2	Target value for the objective 2
b_3	Target value for the objective 3

4.4 Numerical example

This section presents a small-scale supply chain design problem adapted from a real-life situation. The purpose is neither to show any advantage of the modeling process by comparing it with other MIP models, nor to exhibit the efficiency of problem solving by benchmarking the computation time to other algorithms. Indeed, we aim at illustrating the effectiveness and convenience of the product life cycle consideration in the sustainable supply chain design, by introducing a multi-criteria decision making and multi-objective models to select the effective supply chain actors in the different product life cycles' stages.

We consider the case of a focal company which is on the edge of the launching process of a new product on the market, namely, the environmentally coal from the olive pomace. The company has to design a sustainable supply chain with a minimal cost, minimal CO2 emissions and maximal jobs made available, considering the product life cycle stages.

The multiple attribute matrices and the efficiency scores for the introduction and maturity phases, obtained from phase I, are shown in tables 4.1, 4.2 and 4.3, for the suppliers, producers and distributors respectively. The last line in each table represents the efficiency scores of the potential actors at the corresponding product life cycle stage.

The mathematical model is then solved to identify the optimum supply chain network.

Figure 4.4 shows the sales' distribution in Ton for the 3 different customer zones.

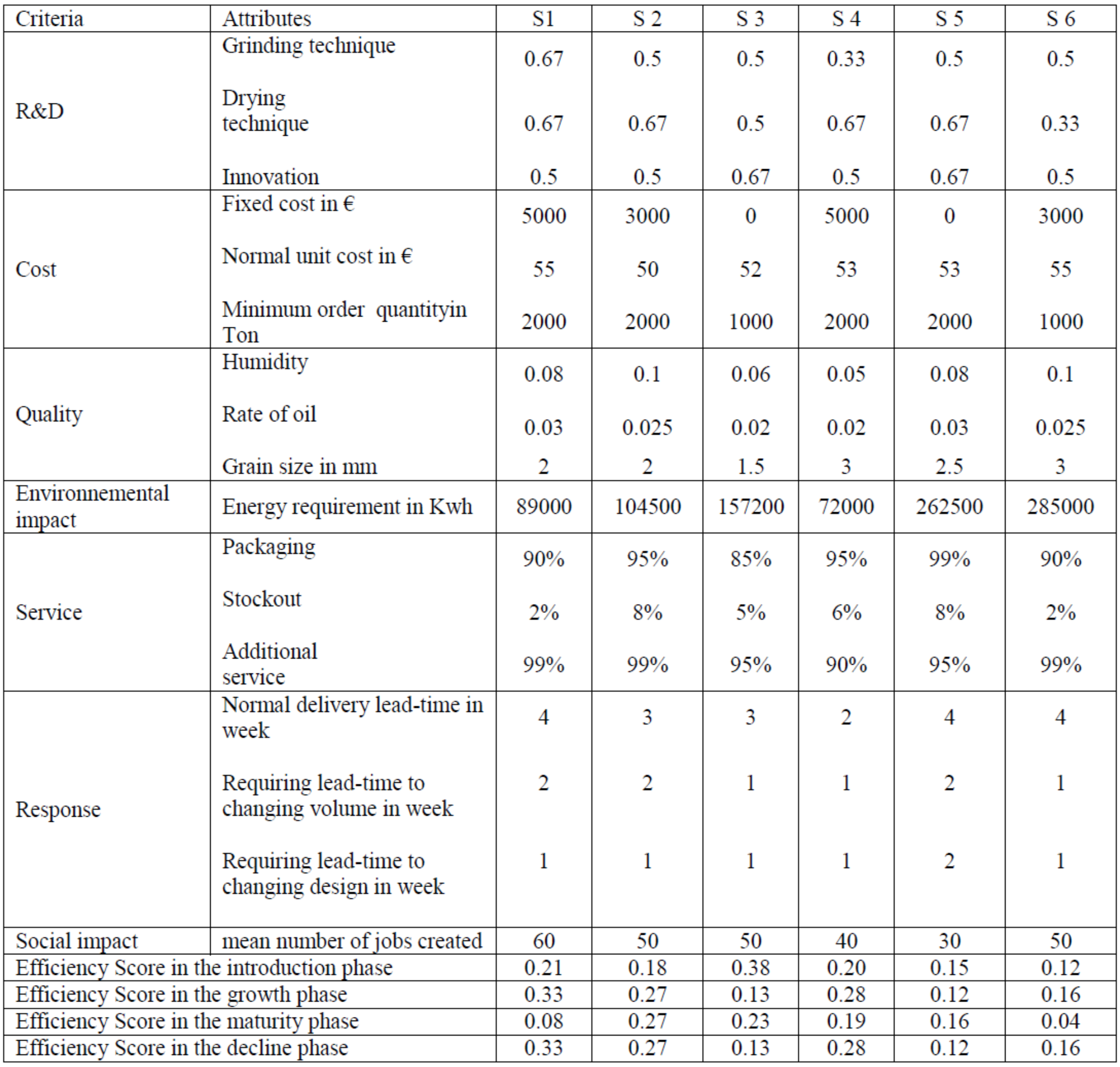
Fixing the target levels to f_1^* , f_2^* and f_3^*; the optimal solution values of the mono-objective problem under f_1 , f_2 and f_3 respectively. Table 4.4 illustrates the optimal deployment plans for the supply chain network for the four different stages of the product life cycle. The optimal supply chain actors and the number of units to be shipped from each source to each destination are clearly depicted in this transshipment solution.

In this table, we can clearly remark the change of the network and the flows from one phase to another, but this change could be due to the variation of two factors, namely the demand, and the efficiency scores of the different actors.

To better see the contribution of the first phase of this model, we solved the same problem again, but by maintaining the same demand data for the four product life cycle stages.

Table 4.5 and 4.6 show the optimal deployment plans for the supply chain network for the introduction and the maturity phases, respectively.

Table 4.1: Multiple attribute matrix on supply performance and efficiency scores



Criteria	Attributes	S1	S 2	S 3	S 4	S 5	S 6
R&D	Grinding technique	0.67	0.5	0.5	0.33	0.5	0.5
	Drying technique	0.67	0.67	0.5	0.67	0.67	0.33
	Innovation	0.5	0.5	0.67	0.5	0.67	0.5
Cost	Fixed cost in €	5000	3000	0	5000	0	3000
	Normal unit cost in €	55	50	52	53	53	55
	Minimum order quantityin Ton	2000	2000	1000	2000	2000	1000
Quality	Humidity	0.08	0.1	0.06	0.05	0.08	0.1
	Rate of oil	0.03	0.025	0.02	0.02	0.03	0.025
	Grain size in mm	2	2	1.5	3	2.5	3
Environnemental impact	Energy requirement in Kwh	89000	104500	157200	72000	262500	285000
Service	Packaging	90%	95%	85%	95%	99%	90%
	Stockout	2%	8%	5%	6%	8%	2%
	Additional service	99%	99%	95%	90%	95%	99%
Response	Normal delivery lead-time in week	4	3	3	2	4	4
	Requiring lead-time to changing volume in week	2	2	1	1	2	1
	Requiring lead-time to changing design in week	1	1	1	1	2	1
Social impact	mean number of jobs created	60	50	50	40	30	50
Efficiency Score in the introduction phase		0.21	0.18	0.38	0.20	0.15	0.12
Efficiency Score in the growth phase		0.33	0.27	0.13	0.28	0.12	0.16
Efficiency Score in the maturity phase		0.08	0.27	0.23	0.19	0.16	0.04
Efficiency Score in the decline phase		0.33	0.27	0.13	0.28	0.12	0.16

Table 4.2: Multiple attribute matrix on production performance and efficiency scores

Criteria	Attributes	P1	P 2	P 3
R&D	Grinding technique	0.84	0.5	0.5
	Drying technique	0.84	0.67	0.5
	Innovation	0.84	0.5	0.3
Cost	Normal unit cost in €	170	160	155
	Minimum order quantityin Ton	2000	1000	1000
	Discount	7%	5%	3%
Quality	Humidity	0.05	0.08	0.08
	Rate of oil	0.015	0.025	0.025
	Calorific in Mj per Kg	19.8	18.5	18
Environnemental impact	Energy requirement in Kwh	1310.000	1762.500	1260.000
Service	Packing	0.84	0.67	0.5
	Stockout	2%	6%	8%
	Additional service	99%	90%	80%
Response	Normal delivery lead-time in week	8	10	12
	Requiring lead-time to changing volume in week	2	5	5
	Requiring lead-time to changing design in week	3	5	8
Social impact	mean number of jobs created	10	15	20
Efficiency Score in the introduction phase		0.71	0.21	0.08
Efficiency Score in the growth phase		0.73	0.18	0.06
Efficiency Score in the maturity phase		0.69	0.19	0.21
Efficiency score in the decline phase		0.73	0.18	0.06

Table 4.3: Multiple attribute matrix on distribution performance and efficiency scores

Criteria	Attributes	D1	D 2	D 3
R&D	Technical market timing	0.84	0.67	0.5
	Distribution technique	0.84	0.84	0.67
	Marketing technique	0.67	0.67	0.5
Cost	Normal unit cost in €	19	19	18
	Minimum order quantity in Ton	500	500	1000
	Unit express delivery cost	22	21	20
Quality	Reliability	99%	90%	85%
	Stability	99%	98%	95%
	Quality business relashionships	0.84	0.67	0.5
Environnemental impact	Energy requirement in Kwh	900.000	837.500	1200.000
Service	Flexibility	0.84	0.67	0.5
	In store advertising	0.67	0.5	0.16
	Continuity index in min	170	330	350
Response	Normal delivery lead-time in week	10	12	8
	Minimum delivery lead-time in week	7	7	5
	Requiring lead-time to changing volume in week	3	3	2
Social impact	mean number of jobs created	60	55	40
Efficiency Score in the introduction phase		0.49	0.33	0.09
Efficiency score in the growth phase		0.57	0.22	0.1
Efficiency Score in the maturity phase		0.16	0.21	0.35
Efficiency score in the decline phase		0.57	0.22	0.1

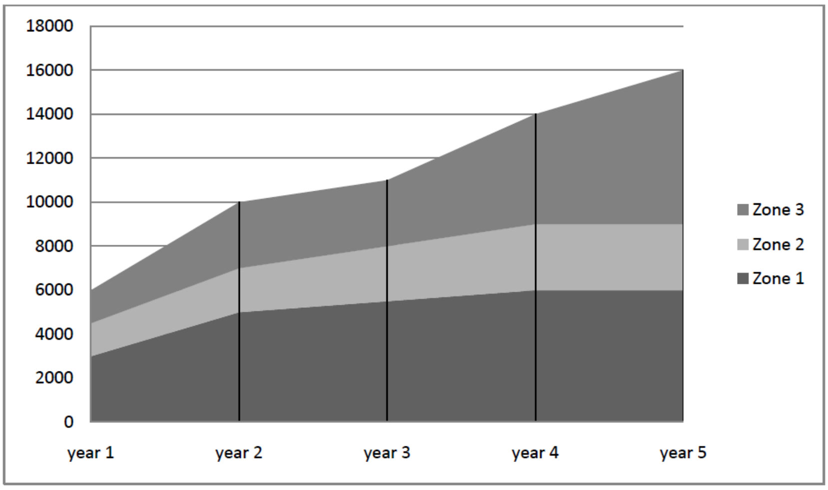
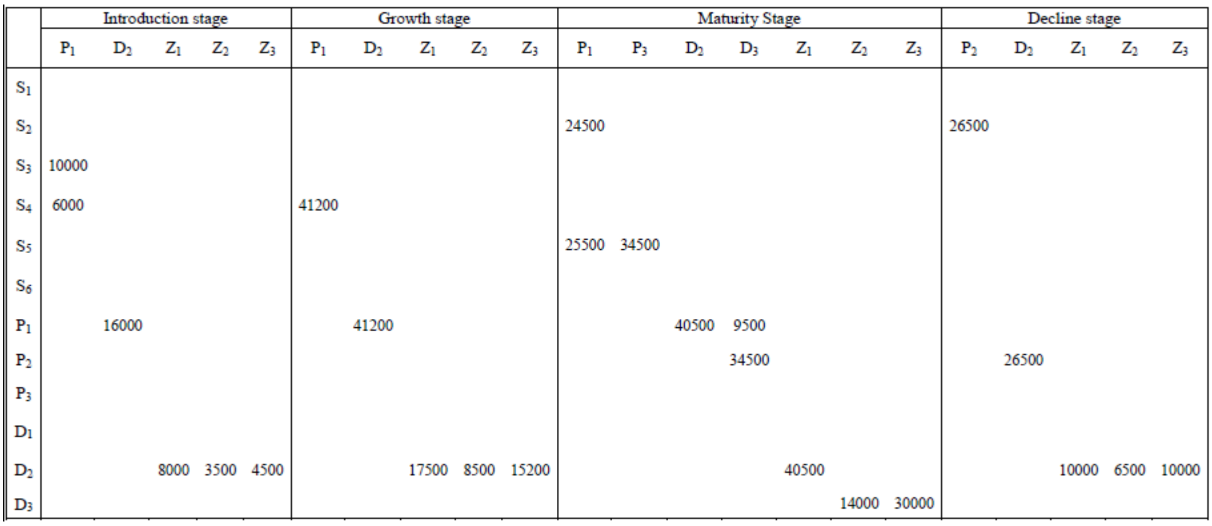


Figure 4.4: Sales distribution of the product in Ton

Table 4.4: The optimal supply chain network



	Introduction stage					Growth stage					Maturity Stage							Decline stage				
	P_1	D_2	Z_1	Z_2	Z_3	P_1	D_2	Z_1	Z_2	Z_3	P_1	P_3	D_2	D_3	Z_1	Z_2	Z_3	P_2	D_2	Z_1	Z_2	Z_3
S_1																						
S_2											24500							26500				
S_3	10000																					
S_4	6000					41200																
S_5											25500	34500										
S_6																						
P_1		16000					41200						40500	9500								
P_2														34500					26500			
P_3																						
D_1																						
D_2			8000	3500	4500			17500	8500	15200					40500					10000	6500	10000
D_3																14000	30000					

Table 4.5: Optimal supply chain network for the introduction stage

Introducion stage	P_1	D_2	Z_1	Z_2	Z_3
S_3	16000				
P_1		16000			
D_2			8000	3500	2500
Demand			>=8000	>=3500	>=4500

Table 4.6: Optimal supply chain network for the introduction stage

Maturity stage	P_1	D_3	Z_1	Z_2	Z_3
S_2	16000				
P_1		16000			
D_3			8000	3500	4500
Demand			>=8000	>=3500	>=4500

Comparing the two tables 4.5 and 4.6, we can infer that the proposed approach cannot only adopt the supply chain strategy according to the degree of concern at different phases, but also consider the trade-off effect to avoid selecting inefficient actors in the correspondent product life cycle stage.

From the results listed in table 4.6 for the maturity phase, it is interesting to notice that supplier 2, who was considered to be inefficient in the introduction phase, was selected as an efficient actor in the maturity phase, and similarly for the distributor 3.

4.5 Sensitivity analysis

We examined the sensitivity of the supply chain performance due to a variation in the objective weights' values. Figure 4.5 shows the goals satisfaction levels of the whole supply chain from the introduction to the decline phase of the product life cycle.

From the results shown in this figure, we realize that, apart from the three special cases where we have considered a single objective at a time, the three objectives are almost fully achieved. Indeed, we could remark that, in the worst cases, the economical objective was achieved to 80%, while the environmental and the social objectives were achieved to 86% and 55%, respectively.

Always except special cases, we noticed that, almost the same supply chain actors were selected, but the flows circulating between these actors are, however, different. This is possibly due to the efficiency constraints.

Therefore, it can be concluded that fluctuations in the choice of the objective weights don't affect significantly the supply chain structure, while it notably affects the global supply chain network.

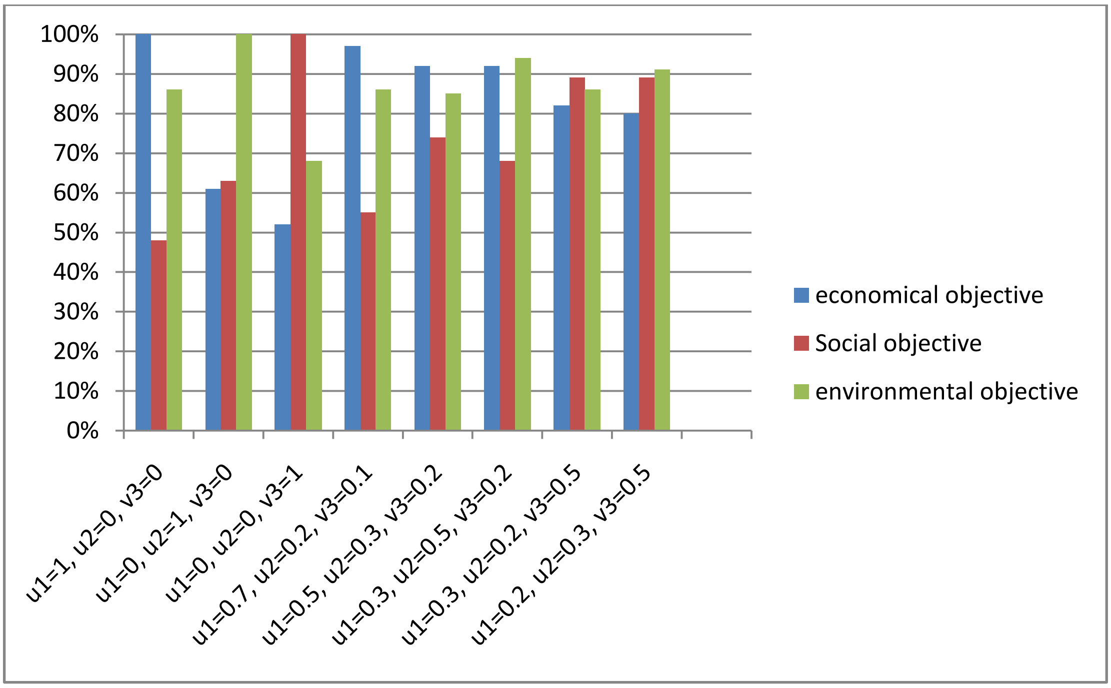


Figure 4.5: Sensitivity by changing objective weights

4.6 Conclusion and perspectives

In this chapter, a detailed sustainable supply chain network design, at the different product life cycle stages, is optimized taking simultaneously into account economic, environmental and social aspects. This allows for the effective selection of the different entities, namely suppliers, production facilities, and distribution centers, as well as the deployment plans which identify the optimal allocation of material between the selected actors. This problem is modeled as a multi-objective optimization problem and resolved using the weighted goal programming approach.

The case of production and delivery of multiple products that are in different product life cycle stages is another interesting issue that needs to be considered.

CHAPTER 5

A Supply chain design under product life cycle uncertainty

5.1 Introduction

In the previous chapters, we have assumed that the product has a classical life cycle. However, in the reality this is not always the case. Indeed, some products have very atypical life cycles, whose curves are very different from the classical one.

To tackle this problem, in this chapter, we propose a stochastic model to design a robust supply chain network, taking into account the different product life cycle scenarios.

The idea of the life cycle of a product is commonly used by the marketing professionals, this explains the presence of extensive researches focusing on this theory in the marketing the literature.

Indeed, each product follows its own life cycle, characterized by four phases: initiation, growth, maturity, and decline. The respective durations of these phases, as well as that of the total life cycle are highly variable depending on the products, and each phase is characterized by its growth rate, sales' volume, profitability, and adopted marketing strategies. In many situations, it is difficult to accurately determine the life cycle of a product. This depends on both the product and the market in which it is commercialized.

The concept of life cycle is not to be called into question. In contrast, its representation, by the classical curve is not always true. Indeed, many products have very different curves, as shown in figure 5.1.

After the introduction phase, some products have difficulty in finding buyers, and therefore they experience a failure since the launching phase, and move directly to the decline phase.

Other products may experience a very rapid adoption, but consumers also grow weary very quickly. The product in this case does not reach the maturity phase, and goes directly to the decline phase. These phases can also be lengthened or shortened.

In this chapter, the main question is: How to take into account the product life cycle uncertainty on the supply chain design? To address this issue, a strategic stochastic programming based model is proposed. Such a stochastic model seeks a solution which is appropriately balanced between some alternative product life cycle scenarios identified by field experts.

This chapter is structured as follows: the next section will present the main topic of this chapter. Subsequently, we present the proposed two-stage mathematical model, and indicate how the deterministic model may be extended using stochastic programming techniques, according to the available information on the uncertain factors. A test problem is solved, and the results of the stochastic programming and the deterministic approaches are presented in section 4. Finally, a conclusion and directions for future researches are presented.

5.2 The main topic

The life cycle theory has been extensively used in marketing. The PLC is the most well-known one, in which the time horizon is divided into four stages based on the variation on the overall sales' level.

Theoretically, the product life cycle should begin with the introductory stage, then growth, maturity and finally the decline stage.

According to the marketing researches, unit sales are low in introduction, because few consumers are attentive to the product.

With consumers' awareness and appreciation, unit sales begin to raise at an increasing rate. This heralds the beginning of the growth stage.

After a while, unit sales attain a plateau, and the product is in the maturity stage. The majority of the mass-market has lastly procured the product. As consumers gradually leave the product for its most recent counterparts, unit sales will decrease immediately. Thus, the withdrawal of the product from the market becomes imminent.

Anyhow, this scenario remains the most classical.

In fact, since the introduction of the idea of the PLC, numerous managerial-oriented articles and book have discussed this theory, and they all reached agreement on the fact that there may be a variety of life cycle curves, that could be different from the classical one.

The classical PLC shape, that we used previously, was only one of 12 types of PLC patterns discovered by investigators. In figure 5.1, we can distinguish these 12 different curves.

The researches that led to these different patterns shown in figure 1 have been quite different.

According to Rink and Swan (1979), about 15 of different studies of consumer nondurables and durables, as well as four studies of industrial goods, have shown that some products have indeed validated the classical PLC curve.

However, it is very important to define the life cycle curve since the early stage, prior to the SC design, as the PLC directs the supply chain to the appropriate market strategy in each stage. Appropriate strategies, such as pricing, promotions, model changes, distribution channels, service level, and others, are different according to the stages.

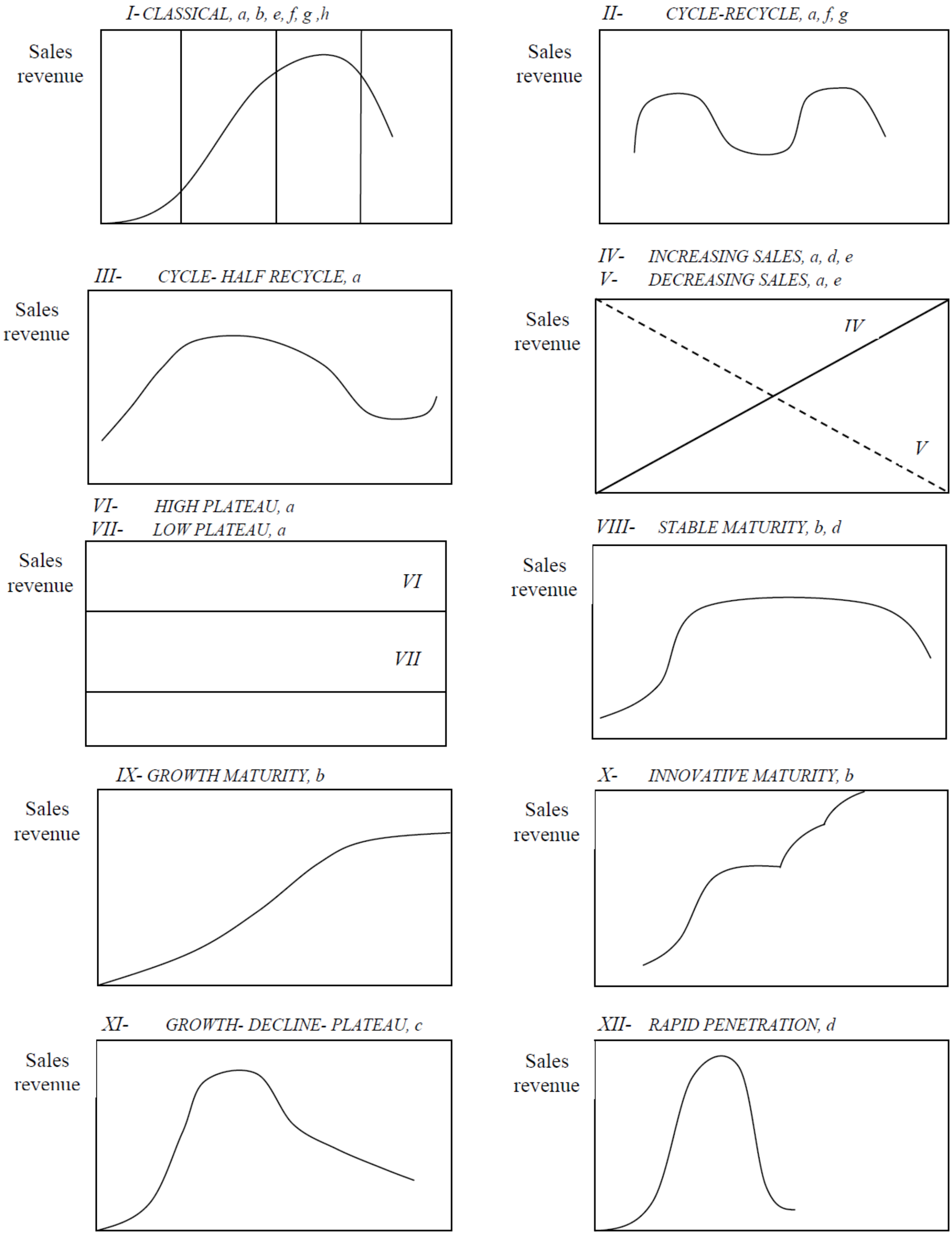


Figure 5.1: The different PLC curves, adapted from Rink and Swan (1979)

[a] Adapted from Cox [34]

[b] Adapted from Buzell [20]

[c] Adapted from Headen [55]

[d] Adapted from Fzederixion [46]

[e] Adapted from Buzzell and Nourse [19]

[f] Adapted from Hinkle [59]

The introductory stage is a period of a moderate growth since the new product is gradually introduced to the market. During this stage, the first customers are still pioneers, and competition is supported. The costs involved in the launch (commercial expenses, technological, marketing ...) are often higher than the benefits. So, the sales of very common products today such as DVD, have stagnated for a period and had a difficult start before to be developed. Advertising expenses must be important, to inform consumers and encourage them to buy the product and also to ensure the distribution of the product to the maximum number of retailers. Indeed, the more a product is distributed, the more it will be visible by the consumer and therefore the results will be better in its introductory stage.

The growth stage is characterized by an increase in sales of the product through word to mouth favorable to bring new customers. New competitors are also entering the market, attracted by the possibilities of development (which may even be beneficial for the product). During this phase, growth should be supported as long as possible by improving the product's quality, expanding its assortment to reach more customers, continuing communication campaigns and lowering gradually the prices.

Also, the distribution channels have to be boosted to be able to respond much easier and quicker to the expansion of customer needs.

The maturity phase is longer than the two previous phases, and is characterized by a slowdown of the product's sales. In addition to that, competition is sharper than that in the previous phases, and the company must reduce its prices. In the maturity phase, creativity is needed in order to keep old customers and attract new ones, and the marketing manager must extend the market by entering new segments, and modify the product by adding new features to boost sales.

The decline phase is characterized by a collapse in sales. This stage is generally due to several factors, including the technological breakthroughs, the changes in tastes or habits, or also the arrival of cheaper foreign products. The company may decide either to withdraw from the market or to keep the product on the market. The marketing manager must boost sales of the product by investing in modernizing the product, and seeking how to retain its customers.

Since a supply chain is dynamic and chaotic, it should be able to easily adapt its different partners in order to get a competitive advantage. Certainly, the supply chain structure must be very robust to deal with the unpredictable market demand, the uncompromising levels of competition, and the different product life cycle patterns.

As uncertainty is one of the characteristics of product-driven supply chain networks, the strategic phase has to take into account uncertain information.

In this chapter, we present a stochastic programming based method that seeks a solution which is appropriately balanced between some alternative product life cycle scenarios, identified by field experts. We apply the stochastic models to a representative real case study. The interpretation of the results will give more insight into decision-making under uncertainty for the supply chain design.

Since the aim is to develop insights for problems with real-world dimensions, the construction of the stochastic models deliberately follows a rather simple technique, which may be potentially used to extend, in a reasonable manner, any large supply chain design model in which uncertainty is an issue and a relatively small set of realistic scenarios can be identified.

5.3 Problem statement

Further to the launching of a new product on the market, a company has to design its supply chain for a fixed horizon time H, so as to minimize its total cost while considering the product life cycle uncertainty. To meet this objective, we propose a stochastic mathematical model.

This model aims at selecting, for whatever scenario, a set of suppliers to provide a given number of plants already located to supply a collection of distributor centers. In turn, the selected distributors supply a set of wholesalers with specified demand quantities of the product, so as to minimize the supply chain total cost.

As mentioned, the case at hand concerns the design of a multi-level supply chain network in which suppliers, manufacturers, and distribution tasks are to be selected across a set of potential ones.

In the model set-up for this problem, we use as an objective function the supply chain design total costs.

These costs are fixed costs for processing, opening or closing the facilities, as well as variable purchasing, manufacturing and distributing costs based on amounts of product processed and respectively shipped between sites. The objective function is determined for the whole product life cycle.

Consequently fixed costs for opening or closing the facilities vary from one site to another, over the planning horizon. Processing costs depends only on the type of facility.

The distribution costs are supposed to be proportional to the amount and the distance over which it is transported. The transportation costs of the product between the different actors are assumed to be CIF costs (including Cost, Insurance, and Freight).

The underlying model can be verbally described as:

Minimize the sum over the product life cycle stages of the total supply chain costs =

Sum of (fixed processing costs + fixed opening costs + fixed closing costs) +

Sum of (purchasing materials costs + production costs + distribution costs).

Subject to:

1. Supplier's capacity limits,
2. Production capacity limits of the plants,
3. Distributor's capacity limits,
4. Market total demand satisfaction,
5. Flow conservation constraints,

The stochastic extensions proposed below, further concentrate on finding the appropriate supply chain actors. The focus on the supply chain design issue is motivated by the fact that investments are made on long run and are based on uncertain information. Since these networks are expensive and difficult to change, establishing a more robust design for the supply chain network becomes a central issue at stake. Therefore the models are primarily configured with a variable infrastructure to assess who are the actors to be selected, but they can be configured as well with all the fixed infrastructure to investigate operational aspects of candidate network configurations.

5.4 Data and uncertainty

Especially when uncertainties are involved, a thorough data analysis, related to the distribution of sales and to the specifications of the product life cycle stages, is needed before going into the actual modeling phase. Among others, such an analysis should establish the relations between the possible actors' capacities and the assumed range of supply levels, as well as the relations between the most likely levels of supply and demand.

The scenario generation has important implications at two levels of discussion. Generally, the outcomes of any scenario-based method will depend on the input, which in turn will rely on the experience and guidance of domain experts. It is therefore necessary that those authorities identify critical scenarios and that the results are carefully interpreted relative to the scenario definition. However, within any established scenario scheme, more robustness is expected to be achieved by accounting for multiple alternatives than just for one or few possibilities.

This is a necessary priori analysis of the data, in order to achieve an effective model. In general, if given one or more capacities, multiple supply levels are deemed relevant, clearly all the corresponding scenarios should be accounted for. Moreover, if probabilities were to be associated with them in a non-symmetric distribution, this would be one more reason not to use only its end point values.

5.5 The stochastic programming approach

Define Ω as the set of all possible scenarios and $\omega \in \Omega$ as a particular scenario. In order to describe the main ideas of the stochastic approach, we use here a brief notation for the deterministic model: all the integer decision variables are included into one vector y of dimension m and all the continuous decision variables are included into one vector x of dimension n. The notation for the coefficients is adjusted accordingly: f is the m-dimensional vector of the fixed costs for opening facilities and c is the vector of dimension n containing the rest of the coefficients in the objective function. Then the concise deterministic model for scenario ω can be stated as:

$$
\begin{aligned}
&\min \quad fy + c(\omega)x \\
&\text{S/t} \\
&W_0(\omega)x \geq 0 \\
&Ty - W_1(\omega)x \geq 0 \\
&W_2(\omega)x - \quad W_3(\omega)x = 0 \\
&W_4(\omega)x \geq d(\omega) \\
&y \in \{0,1\}^m \\
&x \in R^n \\
&x \geq 0
\end{aligned}
$$

The four constraint types represent the efficiency constraints, the capacity constraints, the flow conservation constraints, and the market demand satisfaction constraint respectively.

In a stochastic programming approach, probabilities are associated with scenarios and a solution is sought which is suitably balanced against the various scenarios (see Birge and Louveaux, 1997; Kall and Wallace, 1994). The stochastic solution is not optimal in general for any of the individual scenarios. In a context as considered here, the probabilities assigned to scenarios are of subjective nature. They can be as well called weights and seen as reflecting a relative importance in an uncertain environment. However, passing to a probabilistic framework provides a convenient scheme for organizing ideas that mathematically fall into the same patterns. Although subjective in nature, such probability specifications can support a meaningful sensitivity analysis and guide the selection of an appropriate configuration. Generally, a stochastic programming approach searches a solution relative to an assumed probabilistic data structure, which may or may not reflect accurately the reality at a later moment, but should reflect as accurate as possible the available information for present decisions. We use such an approach in the sequel to address specific questions about the impact of the product life cycle uncertainty on the network design.

5.6 Uncertainty on Product life cycle

Define Ω as the set of all possible product life cycle scenarios and $\omega \in \Omega$ as a particular scenario. Only the right hand side parameter *d* is determined to change in demand for each scenario. In order to approach this uncertainty, we extend the deterministic model above to the following two-stage stochastic model: the first stage corresponds to the investments that must be made for opening facilities prior to knowing the actual realizations of the random parameters and the second stage corresponds to the allocation of flows through the established network after the values of the random parameters become known. Consequently the location variables y are assigned as first stage variables and the allocation variables x are assigned as second stage variables. For each pair (y, x) ,the performance measure is given by the second stage program as the minimum total cost that can be achieved in the network given by location y and under scenario x. The decision y is evaluated by this way across all scenarios and the expected total cost is recorded as the indicator of the decision. The first stage program aims then at minimizing this indicator over the set of all possible first stage decisions. So the two-stage stochastic programming model states as :

$$\min \quad fy + E_{\omega}[Q(y,\omega)]$$

s/t

$$y \in \{0,1\}^m$$

Where

$$Q(y,\omega) = \min \ cx$$

s/t

$$W_0(\omega)x \geq 0$$

$$Ty - W_1(\omega)x \geq 0$$

$$W_2(\omega)x - \quad W_3(\omega)x = 0$$

$$W_4(\omega)x \geq d(\omega)$$

$$x \in R^n$$

$$x \geq 0$$

5.6.1 *The model*

Notations:

Ω	the set of product life cycle scenarios
ω	a particular product life cycle scenario
p_{ω}	the probability of occurrence of the scenario ω

The remaining model parameters and decision variables are the same used in chapter 3, in section 3.5.

In order to tackle the product life cycle uncertainty, the previous two-stage stochastic model is implemented, where the first stage deals with determining the investments made for the opening facilities prior to knowing the actual realizations of the random parameters, and the second stage involves the optimal deployment plan after the values of the random parameters become known.

5.6.2 The mathematical formulation

The mathematical formulation of the addressed problem is described in the following lines.

$$\begin{aligned}\min\ f = \ & \sum_{t}\Bigg[\Bigg[\sum_{i=1}^{m} CF_{i,t} * X_{i,t} + \sum_{j=1}^{n} CF_{j,t} * Y_{j,t} + \sum_{k=1}^{p} CF_{k,t} * Z_{k,t}\Bigg] \\ & + \Bigg[\sum_{i\in I} CO_{i,t} * X_{i,t} * \left(1 - X_{i,t-1}\right) \\ & + \sum_{j\in J} CO_{j,t} * Y_{j,t} * \left(1 - Y_{j,t-1}\right) + \sum_{k\in K} CO_{k,t} * Z_{k,t} * \left(1 - Z_{k,t-1}\right)\Bigg] \\ & + \Bigg[\sum_{i\in I} CC_{i,t} * X_{i,t} * \left(1 - X_{i,t+1}\right) \\ & + \sum_{j\in J} CC_{j,t} * Y_{j,t} * \left(1 - Y_{j,t+1}\right) + \sum_{k\in K} CC_{k,t} * Z_{k,t} * (1 - Z_{k,t+1})\Bigg] \\ & + E_{\omega} C(X,Y,Z)\Bigg] \qquad (1)\end{aligned}$$

S.t

$X_{i,t} \in \{0,1\}\ \forall i,t$ (2)

$Y_{j,t} \in \{0,1\}\ \forall j,t$ (3)

$Z_{k,t} \in \{0,1\}\ \forall k,t$ (4)

Where

$$\begin{aligned}C(X,Y,Z) = \min \sum_{\mathrm{t}} \Bigg[& \sum_{i=1}^{m}\sum_{j=1}^{n} c_{i,j,t} * Q_{i,j,t} + \sum_{j=1}^{n}\sum_{k=1}^{p} c_{j,k,t} * Q_{j,k,t} \\ & + \sum_{k=1}^{p}\sum_{z=1}^{q} c_{k,z,t} * Q_{k,z,t}\ \Bigg] (5)\end{aligned}$$

s.t

Efficiency constraints:

$$e_{i,t}X_{i,t} \geq e_{exp,I,t}\, X_{i,t} \quad \forall\, i,t \tag{6}$$

$$e_{j,t}Y_{j,t} \geq \; e_{exp,J,t}\, Y_{j,t} \;\; \forall\, j,t \tag{7}$$

$$e_{k,t}Z_{k,t} \geq e_{exp,K,t}\, Z_{k,t} \quad \forall\, k,t \tag{8}$$

Capacity limits constraints:

$$\sum_{j=1}^{n} Q_{i,j,t} \leq cap_{i,t} * \; X_{i,t} \quad \forall\, i\,,t \tag{9}$$

$$\sum_{k=1}^{p} Q_{j,k,t} \leq cap_{j,t} * \; Y_{j,t} \quad \forall j\,,t \tag{10}$$

$$\sum_{z=1}^{q} Q_{k,z,t} \leq cap_{k,t} * Z_{k,t} \quad \forall k\,,t \tag{11}$$

Flow conservation constraints

$$\sum_{i=1}^{m} Q_{i,j,t} - \sum_{k=1}^{p} Q_{j,k,t} = 0 \quad \forall\, j\,,t \tag{12}$$

$$\sum_{j=1}^{n} Q_{j,k,t} - \sum_{z=1}^{q} Q_{k,z,t} = 0 \quad \forall\, k\,,t \tag{13}$$

Total market demand satisfaction constraint:

$$\sum_{k=1}^{p} Q_{k,z,t} \geq \; D_{z,t} \;\; \forall\, z,t \tag{14}$$

Non-negativity constraints

$$Q_{i,j,t} \;\geq\; 0 \,\forall\; i,j\,,t \tag{15}$$

$$Q_{j,k,t} \geq 0 \;\, \forall\, j,k,t \tag{16}$$

$$Q_{k,z,t} \geq 0 \;\, \forall\;\, k,z,t \tag{17}$$

and

$$E_{\omega}C(X,Y,Z) = \sum_{\omega \in \Omega} p_{\omega} \times C(X,Y,Z) \tag{18}$$

Constraint sets (2) – (4) restrict every facility to be either open or closed. Constraints (6) – (8) prohibit the selection of ineffective actors. These efficiency constraints are the same used in the mathematical model proposed in chapter 2. Efficiency scores are calculated based on the AHP-OWA procedure. (for more details, see the chapter 2, section 4).

In the above formulation, the objective function minimizes the supply chain total cost, which includes fixed and variable costs. The variable costs consist of the purchasing costs, the production costs, and the distribution costs. While the fixed costs consist of the facilities opening costs, operating costs, and closing costs. The opening costs occur at the period t+1 only if the corresponding facility was closed on the previous period t. Simultaneously, for the closing costs, they occur at a period t only if the corresponding facility was opened at the period t-1. These two costs are related to the dynamic nature of the problem.

Constraint sets (9)-(11) stipulate that all shipments from a supplier, a plant, or a distribution center, must not exceed its maximum capacity. Constraint sets (12)-(13) indicate a conservation of flow at each facility, while (14) requires that all the market demand must be met. A non-negativity on each shipment is imposed by constraint sets (15)-(17). The multi-period nature of the problem is related to the objective function formulation, which involves the closing and reopening costs. The formulation of these costs includes nonlinear components. The model is then linearized and based on the available the literature in this field, (See the previous chapters for more details, and Fortet (1959)).

5.7 *Experimental results*

This section presents a small-scale (6 suppliers, 3 producers and 3 distributors) supply chain design problem adapted from a real-life situation.

According to the research department of the whole company, four different product life cycle scenarios are possible.

Scenario 1: (the classical product life cycle) introduction - Growth - Maturity – Decline

Scenario 2: Introduction – growth –Maturity

Scenario 3: Introduction - Decline

Scenario 4 : Introduction – Growth

The respective occurrence probabilities of these scenarios, are : p_1=0.6; p_2=0.15; p_3=0.1; p_4=0.15

Important data used in implementations are presented in Table 5.1.

Table 5.1: Data used in implementations

Description	Value
Unit material costs	[47, 68]
Unit distribution costs	[5,40]
Unit production cost	[260, 340]
Fixed cost to operate Suppliers	[3.000, 5.000]
Fixed cost to operate Plants	[21.000, 35.000]
Fixed cost to operate Distributors	[42.000 , 60.000]
Fixed cost to open or close Suppliers	[3.000, 150.000]
Fixed cost to open or close Plants	[8.000, 180.000]
Fixed cost to open or close Distributors	[4.000 , 160.000]
Cumulative sales	[0, 90.000]

Denoting by a classical solution, the solution which considers only the classical product life cycle scenario, we refer to the following percentages for verifying the relevance of our results:

Δ_ω^{St} : the difference in % between the supply chain total cost given by the optimal solution of each scenario ω in Ω and the supply chain total cost given by the stochastic solution for the same scenario.

Δ_{ω}^{Cl} : the difference in % between the supply chain total cost given by the optimal solution of each scenario ω in Ω and the supply chain total cost given by the classical solution for the same scenario.

Δ_{E}^{St}: the difference in % between the expected supply chain total cost given by the optimal solution of each scenario ω in Ω and the expected supply chain total cost given by the stochastic solution for the same scenario.

Δ_{E}^{Cl} the difference in % between the expected supply chain total cost given by the optimal solution of each scenario ω in Ω and the expected supply chain total cost given by the classical solution (if we consider the classical product life cycle) for the same scenario.

A comparison of the different results; supply chain optimal total cost, the stochastic minimal total cost, and the classical minimal total cost; for each scenario is presented in table 5.2.

The following table shows the different results obtained for Δ_{ω}^{St} , Δ_{ω}^{Cl} , Δ_{E}^{St} , and Δ_{E}^{Cl} for the supply chain design problem considered.

Table 5.2: Table of results

Scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	65668400	65589500	65589500	0.1201	0
2	84553500	82187800	84106300	2.7979	2.2810
3	9968300	9665680	10963100	3.0358	11.8344
4	79126800	79050200	84300800	0.0968	6.2284
Expected	64949915	64505968	65758415	$\Delta_{E}^{St} = 0.6835$	$\Delta_{E}^{Cl} = 1.9046$

From the table 5.2, we remark that the expected minimal total cost generated by the stochastic solution is 0.6835% from the expected optimal total cost while the expected minimal total cost generated by the classical solution is 1.9046% from this same expected optimal total cost value.

5.8 Sensitivity analysis

5.8.1 Sensitivity analysis by changing the scenarios' probabilities

To better analyze these results, we proposed to vary the probabilities of occurrence of the different scenarios and see the behavior of the two methods with respect to different scenarios that can happen.

Table 5.3: Table of results for the scenarios' probabilities: (0.05, 0.85, 0.05, 0.05)

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_ω^{St}	Δ_ω^{Cl}
1	65935400	65589500	65589500	0.5246	0
2	83295300	82187800	84106300	**1.3296**	2.2810
3	10583000	9665680	10963100	**8.6679**	11.8344
4	83406800	79050200	84300800	**5.2233**	6.2284
Expected	78797265	64505968	65758415	**1.5513**	1.9046

Table 5.4: Table of results for the scenarios' probabilities: (0.1, 0.1, 0.7, 0.1)

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_ω^{St}	Δ_ω^{Cl}
1	65828000	65589500	65589500	0.3623	**0**
2	82844400	82187800	84106300	**0.7926**	2.2810
3	10246600	9665680	10963100	**5.6694**	11.8344
4	82362800	79050200	84300800	**4.022**	6.2284
Expected	30276140	29448726	31073830	**2.7329**	5.2298

Table 5.5: Table of results for the scenarios' probabilities: (0.05, 0.1, 0.1, 0.75)

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	65791400	65589500	65589500	0.3069	**0**
2	84337100	82187800	84106300	2.5485	**2.2810**
3	10456200	9665680	10963100	**7.5603**	11.8344
4	79935400	79050200	84300800	**1.1074**	6.2284
Expected	72720450	71752473	76012015	**1.3311**	5.6038

Results’ interpretation

From the results ,given by the previous tables, we can conclude that in most cases, the stochastic method gives better results than the classical one.

Moreover, if we look more closely at the results given by the two different methods for the scenario with the highest probability of occurrence, except the classical scenario, we can remark that in all presented cases, the best results were given by the stochastic method.

In table 5.3 for example, scenario 2 has the highest probability of occurrence. If in reality, scenario 2 happens, the stochastic method will present a cost deviation of 1.3296 % from the optimal cost, while the classical solution cost deviation will be of 2.2810 %.

Likewise, in table 5.4, for scenario 3, then the stochastic method will present a cost deviation of 5.66794 % from the optimal cost, while the classical solution cost deviation will be of 11.8344 %.

In table 5.5, the probability of occurrence of scenario 4 was the highest. If in reality, this scenario will happen, the cost proposed by the stochastic method will be 1.1074% greater than the optimal cost, while the classical cost will be greater by 6.2284% .

We can see that in all the presented cases, the stochastic method still presents a deviation from the optimality. But this deviation is always less than that of the classical method. This deviation from the optimality could be interpreted as an insurance, or an additional cost to be paid by investors to always guarantee the effectiveness of their chain, and ensure to meet the total market demand, whatever the scenario happened, even for the least likely scenario.

5.8.2 Sensitivity analysis by changing the problem size

In this section, we keep the same probabilities given by experts (see the first example, table 5.2) and we try to generate other random instances, trying to change the size of the problem, while respecting the real data ranges (given in table 5.1).

- Case1:

Table 5.6: Table of results for 6 suppliers- 6 producers – 6 distributors

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	63777700	63552200	63552200	0.35	**0**
2	80903700	79680500	---	1.51	---
3	10641200	9665680	10415700	9.1674	**7.2**
4	81005100	79508300	---	**1.8478**	---
Expected	63617060	62976208	---	**1.0074**	---

- Case 2:

Table 5.7: Table of results for 10 suppliers- 10 producers – 10 distributors

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	30500200	30335400	30335400	0.5403	**0**
2	29997700	29665100	30763300	**1.1088**	3.5698
3	8388660	7989200	8436600	**4.7619**	5.3031
4	28692800	28413500	28783100	**0.9734**	1.2841
Expected	27942561	27711950	27976860	**0.8253**	0.9469

- Case 3:

Table 5.8: Table of results for 30 suppliers- 10 producers – 10 distributors

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	17075200	16761800	16761800	1.8354	**0**
2	10403300	9945700	10174700	4.3986	**2.2507**
3	6435500	6225100	6785400	**3.2694**	8.2574
4	13080100	12224400	14669200	**6.5420**	16.6662
Expected	14411180	14005105	14462205	**2.8178**	3.1607

- Case 4:

Table 5.9: Table of results for 30 suppliers- 30 producers – 30 distributors

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	27838700	27556600	27556600	1.0133	**0**
2	20628300	19955200	20596200	3.2630	**3.1122**
3	11002000	10991100	12597100	**0.0991**	12.7490
4	27020700	26788300	26992300	0.8601	**0.7558**
Expected	24950770	24644595	24931945	1.2271	**1.1525**

- Case 5:

Table 5.10: Table of results for 50 suppliers- 50 producers – 30 distributors

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	33462300	33255500	33255500	0.6180	**0**
2	30124700	29988700	30058800	0.4515	**0.0023**
3	12197500	10988500	13515800	**9.9119**	18.6989
4	34697200	34627700	34686700	0.2003	**0.1701**
Expected	31020415	30744610	31016705	0.8891	**0.8773**

- Case 6:

Table 5.11: Table of results for 80 suppliers- 80 producers – 80 distributors

scenarios	Stochastic cost	Optimal cost	Classical cost	Δ_{ω}^{St}	Δ_{ω}^{Cl}
1	29029100	28899100	28899100	0.4478	**0**
2	27654600	27577600	27613100	0.2784	**0.1286**
3	22187700	19988100	22786700	9.9136	12.2817
4	28964300	28734500	29223300	**0.7934**	1.6726
Expected	28129065	27785085	28143590	**1.2229**	1.2738

Results' interpretation

By analyzing the overall presented results, we can notice that in most cases, the best average result is given by the stochastic method. However, for the few cases that present the opposite result, we notice that the difference between costs given by the two methods is really too low. This is the case for results given by tables 5.9 and 5.10.

Indeed, in table 5.9, the classical method cost presents a deviation of 1.1525% from the optimality, whereas the classical method cost presents a deviation of 1.2271%.

The same thing for table 5.10, where the classical method cost presents a deviation of 0.8773% from the optimality while, the classical method cost presents a deviation of 0.8891%.

- Analyzing the results based on the worst cases.

We note that in the worst situation, if the stochastic solution result is not the best result, it is however very close to that of the classical solution. In tables 5.7, 5.8, 5.10 and 5.11, the worst stochastic solution results deviations from the optimal results are respectively of 4.7619% versus 5.3031% for the classical method, 6.542% versus 16.6662% for the classical method , 9.9119% versus 18.6989% for the classical method, and 9.9136% versus 12.2817% for the classical method.

In table 5.9, the worst stochastic solution results deviation from the optimal results is of 3.263% versus 3.1122% for the classical method. We observe that the difference between the two results is very low and could be negligible.

In table 5.6, the worst stochastic solution results deviations from the optimal results is of 9.16%, while, in the worst case the classical method could not give results for the appropriate scenario.

Some of the most important weaknesses of the classical method are:

- Unresponsiveness: as the case presented in the table 5.6.

Indeed, in this case, we can see that the solution ,given by the classical method, is unable to meet several scenarios that can happen, (scenarios 2 and 4 in this instance).

This could result in multiple damages to investors, who could be in a very difficult position, especially for the out of stock case. In this case, the market demand cannot be met, and this could incur costs of delays or unmet orders. Though, these high additional costs could be avoided when using the stochastic method.

- Failure to meet the efficiencies

Indeed, when considering the classical scenario only, and that we are in reality faced with a different scenario, the efficiencies of the preselected actors may not achieve the efficiency level, fixed by the decision makers. This of course reduces, either slightly or significantly, the supply chain global efficiency.

5.9 Conclusion

In this chapter, we investigated the problem of designing a supply chain under uncertainty on the product life cycle. We used a stochastic programming approach to solve this problem. Based on the comparison between the two methods, we generally conclude that the solutions obtained by the stochastic programming approach are better than those obtained by the deterministic one where only the classical product life cycle scenario is considered. The results obtained point out the effectiveness of the product life cycle uncertainty consideration in the supply chain design.

CHAPTER 6

Conclusion

Effective supply chain design calls for robust analytical models and design tools. Previous works in this area were mostly Operation Research oriented without considering manufacturing aspects. Recently, researchers have begun to realize that the decision and integration effort in supply chain design should be driven by the manufactured product, specifically, product characteristics and product life cycle. In addition, decision-making processes should be guided by a comprehensive set of performance metrics.

According to these metrics, a supply chain actors' assessment process becomes important and routine, especially for those companies that manufacture products with short life cycles. Moreover, these performance metrics are very different and closely dependent on the product life cycle stages.

Indeed, effective supply chain design and management are envisioned as a solution to meet the constantly changing needs of the customer at a low cost, high quality, short lead times, and a high variety.

In this thesis, we proposed models for a multi-period supply chain network design, highlighting the importance of considering the product life cycle in this strategic supply chain level.

In chapter 3 of this thesis, a two-phase mathematical programming approach was proposed for effective supply chain network design. In phase I of the decision making process, multi-criteria efficiency models are utilized to evaluate the performance of suppliers, manufacturers and distributors depending on the product life cycle stage. In phase II, a mixed integer programming problem is utilized to design the multi-period supply chain network and to solve the transshipment problem in order to identify optimal allocation decisions subject to the actors' efficiencies, capacities, and the market demand satisfaction constraints.

An example is used to demonstrate a company's establishment of a comprehensive and objective mechanism of assessment, to screen out potential actors by considering product strategies at different phases of the product life cycle.

A potential extension to the methodology includes the case of multiple suppliers furnishing different sets of parts/components. The case of production and delivery of multiple products across multiple time periods is another interesting issue that needs to be considered.

Chapter 4 presented an extension of the second step of the methodology proposed in chapter 3. We proposed a multi-objective sustainable supply chain network design problem.

We formulated the problem as a Weighted Goal Programming model which aims at achieving three goals, the economic, environmental and social goals, which are respectively: (i) total costs goal, (ii) CO2 emissions goal, and (iii) total number of jobs created goal. We conducted a sensitivity analysis for the case study and we observed that, improving the building technology, which directly affects the energy requirement for each site, can decrease CO2 emission of the whole network. Also, the total cost increase is expected to be in conflict with the other two goals that aim at reducing the CO2 emission, and to maximize the total number of jobs created in the whole supply chain. Regarding the influence of some parameters on the supply chain configuration, we found that a small variability of goals' weight does not affect the supply chain structure, but only affects significantly the supply chain network. This may be due to the efficiency constraints, which have a great impact on the supply chain actors' selection in the proposed model . Indeed, these constraints remain unchanged against the variation of the goals' weights.

The research presented in this chapter could be extended through designing new solution methods to solve this multi-objective supply chain network design model, such as heuristics and metaheuristics.

Chapter 5 presented a supply chain design problem which includes explicitly uncertainty on the product life cycle. We used two-stage stochastic programming formulation to model the problem.

The results obtained pointed out that supply chain design methods which do not include uncertainty obtain inferior results if compared to models that formalize it implicitly.

The stochastic model, for some possible scenarios, could handle data uncertainty with a reasonable increase in total costs compared to the deterministic model. However, it can respond to any possible scenario that can arise. Therefore it can be concluded that the proposed two-stage programming model can be used as a robust model in real cases.

Many possible future research directions can be defined in the area of supply chain network design under uncertainty. For example addressing uncertainty for all variable costs at each product life cycle stage, and potential locations of supply chain actors may be attractive directions for future research. Moreover, time complexity, when the size of the problem and the number of scenarios increase, are not addressed in this chapter.

Mathematical models and the two-phase method proposed in this thesis could serve as a basis for dealing with product-driven supply chain network design problems.

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Appendix A

More details on how to calculate the suppliers’ efficiency scores in the introduction stage, for the example presented in section 3.6 in chapter 3, are given in the following tables.

Table A.1. Pairwise comparison of the sub-criteria relative to the criterion ‘Cost’ and relative weights

	Fixed cost	Normal unit cost	Minimum order quantity	Weights
Fixed cost	1	5	1/7	0.173
Normal unit cost		1	1/9	0.054
Minimum order quantity			1	0.772

Table A.2. AHP scores for the cost criterion at the introduction stage

	S1	S 2	S 3	S 4	S 5	S 6
Fixed cost	0.025	0.075	0.398	0.025	0.398	0.075
Normal unit cost	0.056	0.069	0.349	0.069	0.349	0.105
Minimum order quantity	0.036	0.451	0.232	0.121	0.121	0.036

Table A.3. Pairwise comparison of the sub-criteria relative to the criterion 'Quality' and relative weights

	Humidity	Rate of oil	Grain size	Weights
Humidity	1	3	5	0.617
Rate of oil		1	5	0.296
Grain size			1	0.066

Table A.4. AHP scores for the criterion 'Quality' at the introduction stage

	S1	S 2	S 3	S 4	S 5	S 6
Humidity	0.101	0.031	0.295	0.428	0.111	0.03
Rate of oil	0.068	0.189	0.409	0.124	0.139	0.068
Grain size	0.2	0.2	0.421	0.066	0.066	0.042

Table A.5. Pairwise comparison of the sub-criteria relative to the criterion 'service' and relative weights

	Packaging	Stockout	Additional service	Weights
Packaging	1	5	1/7	0.085
Stockout		1	1/9	0.617
Additional service			1	0.296

Table A.6. AHP scores for the criterion ‘Service’ at the introduction stage

	S1	S 2	S 3	S 4	S 5	S 6
Packaging	0.056	0.18	0.023	0.18	0.502	0.056
Stockout	0.276	0.276	0.071	0.027	0.071	0.276
Additional service	0.394	0.025	0.125	0.072	0.025	0.356

Table A.7. Pairwise comparison of the sub-criteria relative to the criterion ‘Response’ and relative weights

	Normal delivery LT	Requiring LT to changing volume	Requiring LT to changing design	Weights
Normal delivery LT	1	5	9	0.721
Requiring LT to changing volume		1	7	0.227
Requiring LT to changing design			1	0.051

Table A.8. AHP scores for the criterion ‘Response’ at the introduction stage

	S1	S 2	S 3	S 4	S 5	S 6
Normal delivery LT	0.044	0.178	0.178	0.025	0.512	0.044
Requiring LT to changing volume	0.055	0.055	0.277	0.277	0.055	0.277
Requiring LT to changing design	0.227	0.045	0.227	0.227	0.045	0.227

Linguistic Quantifiers for the different criteria in the introduction stage:

R&D: At least half

Cost: Most

Quality: Most

Service: As many as possible

Response: Most

Table A.9. OWA weights for the criterion ‘R&D’ in the introduction stage

S1			S2			S3		
Ordered AHP scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.505	0.218	0.436	0.23	0.714	1	0.357	0.066	0.132
0.23	0.714	0.564	0.116	0.218	0	0.116	0.218	0.436
0.071	0.066	0	0.071	0.066	0	0.057	0.714	0.432
S4			S5			S6		
Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.23	0.714	1	0.357	0.066	0.132	0.22	0.714	1
0.071	0.066	0	0.23	0.714	0.436	0.116	0.218	0
0.029	0.218	0	0.218	0.218	0.432	0.071	0.066	0

Table A.10. OWA weights for the criterion ‘Cost’ in the introduction stage

S1			S2			S3		
Ordered AHP scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.056	0.054	0	0.451	0.772	0.944	0.398	0.173	0
0.036	0.772	1	0.075	0.173	0.056	0.349	0.054	0
0.025	0.173	0	0.069	0.054	0	0.232	0.772	1
S4			S5			S6		
Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.121	0.772	0.944	0.398	0.173	0	0.105	0.054	0
0.069	0.173	0.056	0.349	0.054	0	0.075	0.173	0
0.025	0.054	0	0.121	0.772	1	0.036	0.772	1

Table A.11. OWA weights for the criterion ‘Quality’ in the introduction stage

S1			S2			S3		
Ordered AHP scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.2	0.085	0	0.2	0.085	0	0.421	0.085	0
0.101	0.617	0.634	0.189	0.297	0.164	0.409	0.296	0.164
0.068	0.297	0.366	0.031	0.617	0.836	0.295	0.617	0.836
S4			S5			S6		
Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.428	0.617	0.634	0.139	0.296	0	0.068	0.296	0
0.124	0.296	0.366	0.111	0.617	1	0.042	0.085	0.162
0.066	0.085	0	0.066	0.085	0	0.03	0.617	0.838

Table A.12. OWA weights for the criterion ‘Service’ in the introduction stage

S1			S2			S3		
Ordered AHP scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.394	0.296	0	0.276	0.617	0.234	0.125	0.296	0
0.276	0.617	0.824	0.18	0.085	0.17	0.071	0.617	0.824
0.056	0.085	0.176	0.025	0.296	0.596	0.023	0.085	0.176
S4			S5			S6		
Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.18	0.085	0	0.502	0.085	0	0.356	0.296	0
0.072	0.617	0.404	0.071	0.296	0	0.276	0.617	0.824
0.027	0.296	0.596	0.027	0.617	1	0.056	0.085	0.176

Table A.13. OWA weights for the criterion ‘Response’ in the introduction stage

S1			S2			S3		
Ordered AHP scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.227	0.051	0	0.178	0.721	0.842	0.277	0.227	0
0.055	0.227	0	0.055	0.227	0.158	0.227	0.051	0
0.044	0.721	1	0.045	0.051	0	0.178	0.721	1
S4			S5			S6		
Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights	Ordered AHP Scores	Corresponding AHP weights	OWA weights
0.512	0.721	0.842	0.055	0.227	0	0.277	0.227	0
0.277	0.227	0.158	0.045	0.051	0	0.227	0.051	0
0.227	0.051	0	0.044	0.721	1	0.044	0.721	1

Table A.14. The AHP-OWA scores for the different criteria at the introduction stage

	S1	S 2	S 3	S 4	S 5	S 6
R&D	0.35	0.23	0.51	0.23	0.25	0.22
Cost	0.03	0.43	0.23	0.12	0.12	0.03
Quality	0.09	0.06	0.31	0.32	0.11	0.03
Service	0.24	0.11	0.06	0.04	0.03	0.24
Response	0.04	0.16	0.18	0.47	0.04	0.04

Linguistic Quantifiers for the overall criteria aggregation in the introduction stage: Most

Table A.15. The aggregation weights

S1			S2			S3		
Ordered scores	Corresponding weights	Aggregation weights	Ordered Scores	Corresponding weights	Aggregation weights	Ordered Scores	Corresponding weights	Aggregation weights
0.35	0.051	0.442	0.43	0.129	0	0.51	0.5128	0.442
0.24	0.033	0.066	0.23	0.512	0.6834	0.31	0.2614	0.5064
0.09	0.261	0.492	0.16	0.063	0.12766	0.23	0.1289	0.0516
0.04	0.063	0	0.11	0.033	0.066	0.18	0.0633	0
0.03	0.128	0	0.06	0.261	0.1234	0.06	0.033	0
S4			S5			S6		
Ordered Scores	Corresponding weights	Aggregation weights	Ordered Scores	Corresponding weights	Aggregation weights	Ordered Scores	Corresponding weights	Aggregation weights
0.47	0.0633	0	0.25	0.5128	0.442	0.24	0.0333	0
0.32	0.2614	0.0494	0.12	0.1289	0.2414	0.22	0.5128	0.4916
0.23	0.5128	0.9506	0.11	0.2614	0.3166	0.04	0.0633	0.1266
0.12	0.1289	0	0.04	0.0633	0	0.03	0.1289	0.2578
0.04	0.0333	0	0.03	0.0333	9	0.03	0.2614	0.124

Table A.16. The final efficiency scores for the suppliers at the introduction stage

	S1	S 2	S 3	S 4	S 5	S 6
Efficiency scores	0.21	0.19	0.4	0.23	0.17	0.15