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A CONTRIBUTION TO SUPPLY CHAIN DESIGN UNDER UNCERTAINTY

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Abstract

In today's context of extended supply chains (SCs), business processes and partners, several factors can increase the chances of disruptions in supply chains, such as losses of customers due to intense competition, supply shortage due to uncertain sourcing, managing large number of supply chain partners, unpredictable failures, breakdowns, etc.

Predicting and responding to changes across a global supply chain require sometimes dealing with incomplete and uncertainty information. Accordingly, we should propose approaches to minimize vulnerability to possible sources of disruptions, considering expert judgments and using relevant decision aiding techniques. Building disruption-resistant supply chains can guarantee the availability of supply despite the presence of disruptive events (changing demand, breakdowns, etc.), and offer customers a competitively priced product in industries of already very tight profit margins.

In this thesis, some models are developed to provide control of supply chains disruptive factors, allowing minimizing vulnerability to some recurrent and substantial disruptions in order to design efficient and disruption-resistant supply chains.

Building a disruption-resistant or disruption-remedying supply chain nowadays has become the ultimate objective of intelligent organisations. This thesis therefore focuses on how to build models of reliable supply chain design. The proposed models enable building disruption-resistant SCs by the reduction of vulnerability to disruptions coming from unreliable suppliers, production sites, and distribution sites.

The dissertation may be presented in three main steps:

1- Building a multi-objective model of reliable actor selection for designing disruption-resistant supply chain.

2- Making a review of different concepts and types of risks related to supply chains and then offering an approach for quantifying risks.

3- Developing a reliability-based optimization model for mitigating supply chain disruptions under uncertainties of solicitation and supply

Résumé

Dans le contexte actuel des chaînes logistiques, des processus d'affaires complexes et des partenaires étendus, plusieurs facteurs peuvent augmenter les chances de perturbations dans les chaînes logistiques, telles que les pertes de clients en raison de l'intensification de la concurrence, la pénurie de l'offre en raison de l'incertitude des approvisionnements, la gestion d'un grand nombre de partenaires, les défaillances et les pannes imprévisibles, etc.

Prévoir et répondre aux changements qui touchent les chaînes logistiques exigent parfois de composer avec des incertitudes et des informations incomplètes. Chaque entité de la chaîne doit être choisie de façon efficace afin de réduire autant que possible les facteurs de perturbations. Configurer des chaînes logistiques efficientes peut garantir la continuité des activités de la chaîne en dépit de la présence d'événements perturbateurs.

L'objectif principal de cette thèse est la conception de chaînes logistiques qui résistent aux perturbations par le biais de modèles de sélection d'acteurs fiables. Les modèles proposés permettent de réduire la vulnérabilité aux perturbations qui peuvent avoir un impact sur la continuité des opérations des entités de la chaîne, soient les fournisseurs, les sites de production et les sites de distribution.

Le manuscrit de cette thèse s'articule autour de trois principaux chapitres:

1 - Construction d'un modèle multi-objectifs de sélection d'acteurs fiables pour la conception de chaînes logistiques en mesure de résister aux perturbations.

2 - Examen des différents concepts et des types de risques liés aux chaînes logistiques ainsi qu'une présentation d'une approche pour quantifier le risque.

3 - Développement d'un modèle d'optimisation de la fiabilité afin de réduire la vulnérabilité aux perturbations des chaînes logistiques sous l'incertitude de la sollicitation et de l'offre.

I dedicate this thesis to

My parents,
My husband,
My beloved children: Selma and Ahmed, hoping that this work will encourage them to overcome obstacles and go ahead confidently in their lifetime.

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INTRODUCTION

I. Supply chain and related concepts

In today's changing markets intelligent organisations find it crucial to rely on effective supply chain (SC) networks. Nowadays, a wide range of tools and models are increasingly deployed to enhance supply chain management in several fields and industries to resist disruptions that they are exposed to and so to successfully remain competitive.

To start we give some definitions of SC. The literature offers a variety of definitions of supply chain. Among the most common definitions, Ganeshan *et al.* (2000) defines a supply chain as a system of suppliers, manufacturers, distributors, retailers, and customers in which materials flow downstream from suppliers to customers and whereas information flows in both directions.

According to Stevens (1989), a supply chain is defined as a connected series of activities concerned with planning, coordinating and controlling materials, parts, and finished goods from supplier to customer. It is concerned with two distinct flows (material and information) through the organization.

Jayashankar *et al* (1996) defines a supply chain as a network of autonomous or semi-autonomous business entities collectively responsible for procurement, manufacturing, and distribution activities associated with one or more families of related products.

Lee and Billington (1995) defines a supply chain as a network of units that procure raw materials, transform them into intermediate goods and then final products, and deliver the final products to customers through a distribution system.

Based on the definitions presented in the literature, it is assumed here that a supply chain is represented by a network of suppliers, manufacturers and distribution centers whose purpose is to procure materials, transform these materials into intermediate and finished products, and distribute the finished products to the customers. In practice, supply chains have multiple-end products with shared components and facilities.

The manufacturer places orders to and receives raw-materials or intermediate products from the supplier, the distribution center places orders to and receives finished or intermediate products from the manufacturer, and, in turn, the retailer places orders to and receives finished products from the distribution center. The supplier / manufacturer linkage, the manufacturer / distribution center linkage, and the distribution centers / customer linkage are serviced by diversified transportation modes.

The primary role of a supplier is sourcing, i.e. the activities of procurement and shipment of raw materials and goods to the manufacturer. The manufacturer's primary role is the transformation of raw materials or intermediate products into intermediate or finished products. The distribution center has two primary roles, namely storage and redistribution, i.e. receiving large quantities of products, storing them for specific periods, and shipping small quantities to individual stores or to the retailer.

Note that a supply chain might be zero-echelon, one echelon or multi-echelon. Aikens (1985) defines echelons as levels or as the number of warehouses located between manufacturers and customers. For instance, a zero-echelon model is a model without warehouses, and consists of an allocation of customers directly to manufacturers.

On the other hand, models dealing with supply chain management might be related to the process of planning, implementing, and controlling one or a combination of operations of procurement, production, and distribution. The main models concerning procurement and distribution consist, respectively, of supplier selection and facility location (distribution network).

Aikens (1985) made a classification of the main considerations of distribution/location models. These may be classified according to:

1. Whether the underlying distribution network (arcs and/or nodes) is capacitated or incapacitated.

2. The number of warehouse echelons, or levels (zero, single, or multiple).

3. The number of products (single or multiple).

4. Whether the underlying cost structure for arcs and/or nodes is linear or nonlinear.

5. Whether the planning horizon is static or dynamic.

6. Whether the patterns of demand are: deterministic or stochastic.

In the literature another term related to supply chains is found: “supply chains network”. 'This term refers especially to enlarged supply chains where the network is composed of spread entities of different forms that are integrated as a network. According to Sha & Che (2006), this designation refers to the fact that many individual companies are involved, and that different processes and activities are closely integrated so as to substantially improve the value of products and services to meet the ultimate goal of customer demand. An important distinction between the two organisations is that in supply chain design (SCD) we deal with problems of supplier selection and facility location. In contrast, supply chains network design deals with partner selection (Sha & Che, 2006).

In this thesis, the proposed approaches and models can be well applied to ordinary supply chains as well as to enlarged supply chains networks, assuming multiple-echelons and multiple-products.

SC concepts explanation is very important to what follows since the main purpose of this dissertation is to explore disruptions that may affect SC actors and develop models to remedy to these disruptions. The main concepts that we focus in this thesis are the considerations of SC design, the decision levels in SC design, the information and knowledge required to model SC design and performance and reliability used in the context of this study. Each of these concepts is important to this dissertation and therefore deserves a detailed explanation. We start the next paragraph with an explanation of the objectives of SC management.

II. The objectives of the supply chain management

"Supply Chain Management is the set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores so that merchandise is produced and distributed at the right quantity, to the right locations, and at the right time, in order to minimize system wide costs while satisfying service level requirements" (Simchi-Levi et al., 2000).

The objectives of supply chain management concern satisfying the customer effectively. This means to fulfill customer requests with maximum profit or minimum cost (generally, if demand is deterministic these objectives are the same).

For a long time the objective of supply chains was to either maximize profit, which is the overall value generated by the fulfillment of customer requests, or to minimize the sum of all costs incurred by the supply chain to produce and distribute the final product to the end customer.

However, in recent years many companies have experienced numerous disruptions that compel them to change the vision of their objectives. Neglecting disruptions resulting from unexpected events may cause more than high costs on the long term objectives of a company. Building a disruption-resistant or disruption-remedying supply chain nowadays has become the ultimate objective of intelligent organisations. This results in investment in reliable actors (suppliers, plants, and DCs), contingency strategies, etc. Although this can be costly, it ensures that the supply chain will survive disruptions, and thus hopefully prevents much higher costs and serious inconveniences.

The ultimate objective should be not only to minimize common costs (fixed costs of sites, and variable costs of production and distribution of products), but also to reduce vulnerability due to disruptions, by reducing possible sources of loss and damage due to uncertainty and risk. Note that uncertainty is defined as incomplete knowledge of parameters and events. In turn, risk is defined as the probability of the occurrence of events that would have an impact upon objectives. This is measured in terms of consequences and likelihood (Singhal and Hendricks 2005).

Supply chain design (SCD)

As discussed above, the supply chain is a network of suppliers, factories, warehouses, and distribution centers through which raw materials are procured, transformed, and delivered to the customer. In this thesis, we are interested in the supply chain design problem, which involves both strategic and tactical level decisions and is made for a long-term horizon. (See table 1)

The *strategic decision level* defines the supply chain configuration, including supplier selection, mode of transportation, manufacturing site location, and distribution center location, facility location.

On the *tactical decision level*, the production and inventory levels of the supply chain are planned and scheduled to meet customer demand.

Table 1 - Some Definitions of Supply Chain Design

Author	Supply Chain design definitions
Diaby and Martel (1993)	Network design (location-allocation) problems deal with strategic decisions related to the number, size, and location of warehouses, as well as the assignment of customers and products to warehouses. These decisions involve tradeoffs between investment costs, including inventory carrying and transportation costs, but at a very aggregate level.
Cornu'ejols, Nemhauser, and Wolsey (1990)	Given a set of potential sites, a set of clients, and relevant profit and cost data, the goal is to find a maximum-profit plan giving the number of facilities to open, their locations and an allocation of each client to an open facility.
Pomper (1975)	Strategic decisions focus on the development of a worldwide manufacturing policy. These decisions are those which normally result from the capital-planning, budgeting process within the firm, i.e. location, technology, capacity, and time-phasing of new facilities. Tactical decisions set the sourcing pattern, i.e. how much each plant is to manufacture and to what country is sent its output in order to supply the company's world markets.
Shulman (1991)	The task is to select the time schedule for installing facilities at different locations to optimize the total discounted costs for meeting customer demands specified over the time-period referred to as the planning horizon.

III. Decision levels in supply chain design

Supply chain planning is concerned with the coordination and integration of key business activities undertaken by an enterprise, from the procurement of raw materials to the distribution of the final products to the customer. The decision making process in these highly complex and interacting networks can be decomposed according to the time horizons considered (Gupta & Maranas, 1999). This process results in the following temporal classification of the decisions/models: strategic, tactical and operational.

Supply chain design decisions are often said to belong to two decision levels: the *strategic*, and the *tactical* levels. Even though there is no unified use of these terms, these following paragraphs give their definitions in connection with the content of this dissertation.

1. Strategic Level

This section addresses strategic level decisions, which determine the configuration of the SC by prescribing supplier selection, facility location (plants and distribution centers), production technologies, plant capacities, and transportation modes.

Long-term decisions are made on the *strategic* level. Especially, decisions related to the size, the number, and the geographic location of plants and distribution centers.

According to (Sahinidis, Grossmann, Fornari & Chathrathi, 1989; Sahinidis & Grossmann, 1991; Norton & Grossmann, 1994), strategic or long-term planning models aim to identify the optimal timing, the location, and the size of additional investments in processing networks over a relatively long time horizon, usually ranging from five to ten years.

Decisions made on the strategic level are of course interrelated. For example, decisions on transportation modes are influenced by decisions on geographical placement of plants and distribution centers. Modeling and simulation are frequently used for analyzing these interrelations, and for the evaluation of the impact of strategic level decisions on the supply chain.

The main strategic decisions related to the configuration of the supply chain considered in this thesis are:

- *Supplier selection;*

- *Facility location;*

- *Selection of capacity options.*

Suppliers must be evaluated according to criteria which support the competitive strategy of the company. Supplier selection is closely related to the strategic objectives of the company, the selection is made once the company has fixed his long term objectives and accordingly the suitable competitive strategy and related criteria to achieve them.

Suppliers are no longer an entity that can be easily replaced. Their selection requires analyzing varied and complicated criteria rather than simple ones. In that sense, approaches and models dealing with supplier selection should support wisely these new requirements.

Facility location concerns the decisions to choose the suitable sites to locate the facilities so as to be optimally linked to suppliers and customers(Cust.).

Capacity options are defined as various possibilities of investing in equipment. The purpose is to increase or decrease the capacity of a site of the supply chain network, allowing for adjustment to fluctuating demand. These investments might relate to purchasing new equipment, reconditioning existing equipment, replacing old equipment, etc. Note that capacity is expressed in units of volume. In addition, all these investment possibilities concerning capacity have impacts on the configuration of the sites.

2. Tactical Level

Tactical level decisions prescribe material flow management, including production planning and inventory planning. It deals with material flow from suppliers towards production plants, from there to distributions centers, and finally to end-user customers.

On the tactical level medium term decisions are made. They are related to the flow of materials between the supply chain actors, such as materials requirement planning, production planning, inventory planning, and distribution planning.

- Material requirement planning concerns which supplier to use to supply which raw material and toward which plant.
- Production planning involves determining which products to produce and where to produce them.
- Inventory planning is concerned with managing inventories throughout the supply chain.

- Distribution planning is concerned with deciding from which plant to supply which distribution centers.

According to Gupta & Maranas (2003), Dimitriadis, Shah, & Pantelides (1997) and McDonald & Karimi (1997), midterm tactical models are intermediate in nature. These models address planning horizons of one to two years and incorporate some features from both the strategic and operational models.

The main tactical decisions related to the configuration of the supply chain considered in this thesis are:

- *Supply quantities; (how much business has to be allocated to each supplier)*

- *Production quantities;*

- *Flows of materials from a network site to another*

Figure 1 summarises the considerations of SC design models that are: the echelons, facility location and supplier (Sup.) selection decisions. The figure also presents the hierarchy decision system in SC, starting from the configuration of the SC to the material flow management and finally to scheduling (control) decision.

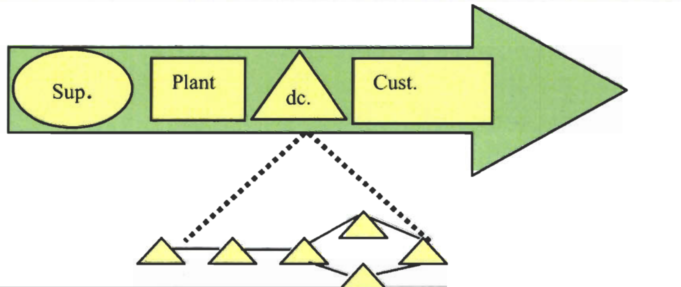
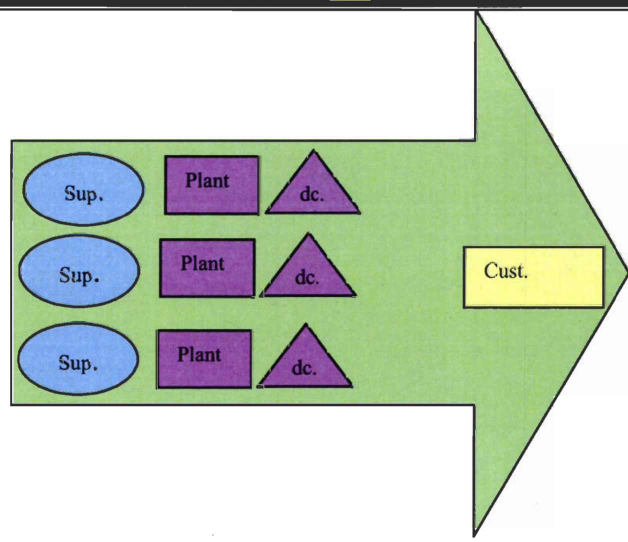
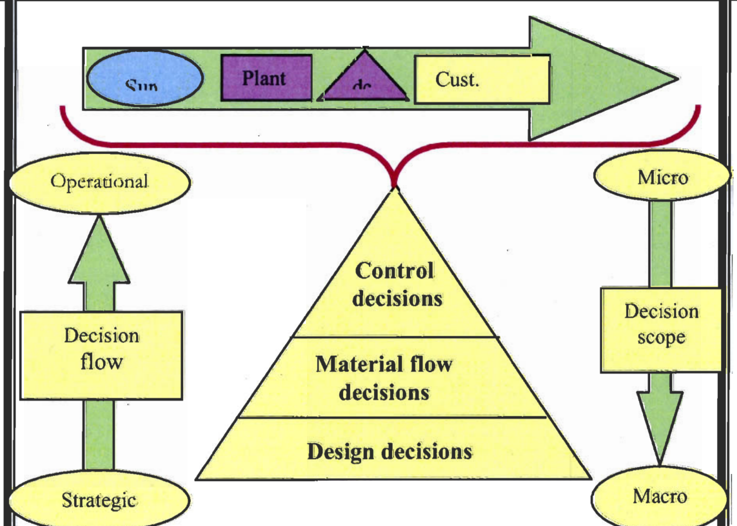
Model considerations	Schematic	Description
Zero- echelon, Single-echelon, or Multiple-echelons		Echelons are the number of warehouses located between manufacturers and customers.
Facility Location or Supplier Selection		- The objective of the facility location problem is to determine the optimal location of plants, warehouses and distribution centers. -How many suppliers the company needs, and how much business has to be allocated to each supplier are the main considerations of supplier selection.
Decision Levels		- Strategic level decisions determine the configuration of the SC. -Tactical level decisions prescribe material flow management.

Figure 1- Supply Chain Models Considerations

IV. Information and knowledge requirements

In a supply chain, in order to make appropriate strategic and tactical decisions, information is indispensable. Decision support systems provide decision makers with useful information to guide their thoughts and actions. Sufficient Information enables the decision-makers to achieve the supply chain objectives through better and effective decisions and actions. However, for many reasons this information may be incomplete due to: uncertainty, imprecision or randomness.

According to Roy (1989), formal models used in decision-aiding processes are subject to many sources of uncertainty, imprecision, and ignorance. Information used to set technical and economical parameter values may be incomplete due to: lack of appropriate technology to collect and process data, instruments and statistics which can be imprecise (e.g., tolerance for precision in measurement, confidence intervals in statistics), measurement can be arbitrary and subjective (e.g., in the case of this thesis incorporate preferences of the Decision Maker to asses ratios of performance criteria), etc. On the other hand, even when the information is available, it is by no means simple to predict the future with certainty. Making successful decisions sometimes involves coping with uncertainty.

Many authors divide decision-making environments, as a function of the nature of information, into three categories: certainty, risk, and uncertainty (Rosenhead, Elton, and Gupta 1972). In certainty situations, we have complete knowledge of the decision parameters. We then say they are deterministic. In uncertain situations, we have incomplete knowledge of the decision parameters, which are said to be uncertain, and furthermore, no information about probabilities is known. In risk situations, decision parameters are uncertain and their values are governed by probability distributions which are known by the decision maker. (Snyder 2003).

Whether the information is presented in terms of data, solutions or recommendations based on the findings, they will be truly useful only if the way they are conditioned by the contingency, arbitrariness and ignorance that lie behind sources, is taken into account explicitly (Roy 2002).

In case of incomplete information, we collect data from discrete processes, expert opinions, surveys, etc., transform this information into knowledge, and then use this knowledge effectively to make appropriate decisions for enhancing the achievement of objectives.

In the context of this thesis, we need in the second chapter subjective information to express preferences about performance criteria required to derive related AHP[1] ratios of SC actors. When considering multi-criteria decision aiding, as we intend to do in this chapter, the proposed multi-objective SCD model incorporate parameters related to the preferences of the Decision Maker (DM) related to specific performance criteria. Eliciting parameter values about preferences is problematical, for that reason we use AHP as a method of criteria performance measurement. Since we dispose of complete knowledge of the decision parameters then a certainty situation is considered.

In the forth chapter to construct a reliable SC design model we need to assess reliability of each SC actor with the purpose to build a reliable SCD that perform well when disruption occurs. For that purpose stochastic information is required which is expressed as independent probability distributions on the parameters of the problem. We estimate reliability as uncertain parameter through building probability distribution for that parameter.

V. Performance and reliability

In supply chains, many manufacturing and logistic operations are designed to maximize profit and minimize costs with little information about supply chain actors and little information on the decision-making environment. Sometimes, purchasing contracts with suppliers are negotiated and sourcing decisions are often made with very little information about their historical sourcing behaviours in terms of dealing with disruptions and uncertainty.

Designing and building disruption-resistant supply chain systems require the selection of reliable actors which can resist to disruptions. For this reason, supply chains should have a better understanding of their actors' environment and should consider the factors that could have an impact on their performance.

Clearly, we are seeing nowadays an increasingly complex and risky environment. A number of new trends during the last decade have caused the supply chain activities from first supplier to end customer to change increasingly. That is why public interest in disruptions and the field of risk analysis is growing and expanding throughout the system.

At first, a detailed description of disruption-resistant SC needs to be provided, especially the concept of "disruption" in the context of this study.

[1] the Analytic Hierarchy Process

The specific definition of "disruption" being employed in this study is a disturbance or failure that affects the continuity of an activity. Note that SC disruptions may arise from many sources, and oftentimes without warning, that makes them closely related to uncertainty. These disruptions can be entirely external to the organisation itself like environmental disruptions (e.g. natural disasters), or they can be internal to the organisation it self, rising for example from operational disruption (e.g. problems in scheduling). Disruptions can also arise from the interior of the SC, we divide these disruptions into ones whose sources come from *supply-side uncertainties* (including suppliers failure, supply uncertainties, facilities failure, machines breakdowns, etc.) and ones whose sources come from *demand-side uncertainties* (demand variability, customer loss, order cancellation, etc.). Disruptions can emanate from an actor of the SC or they may integrate all the SC actors. (See figure 2).

The figure 2 gives a summary of the portfolio of sources of supply chain disruptions. These disruptions are inferred from the types of risks which are in the origin of these disruptions presented in the work of Artebrant (2003) and Dormer et al. (2003). We propose to divide them into three categories:

- Internal disruptions to the organisation
    - Financial disruption concerns disturbance coming from the management of capital.
    - Operational disruption arises from aspects of running the business day-to-day, such as problems in scheduling (e.g. cancelled orders), accounting or information systems.
    - Employee disruption includes problems such incompetence due to work injuries, lack of motivation, stress, and discrimination among colleagues.
- External disruptions to the organisation
    - Market disruption related to financial transactions
    - Environment disruptions include natural disasters and catastrophes.
    - Property disruption concerns damage caused by fire, water, storms, and other natural disasters.
    - Criminal disruption represents sabotage, industrial espionage, and fraud.
    - Liability disruption may include responsibility of environment and product. Product liability means that a company must pay damage when their product has caused personal injury or property damage.

- Political disruption concerns new laws, nationalization, social revolution, government interventions, worldwide economic difficulties etc.

- Internal disruptions to the SC
    - Strategic disruption concerns events which may impact on the strategic level of the organisation, such as supply shortage, facilities failure, new competitors, demand variability, loss of customers, etc.

Especially, in this thesis we try to mitigate supply chain disruptions (see figure 2-a) through proposing models and approaches to selection of reliable suppliers and facilities. The main sources of these disruptions come from suppliers' failure, supply uncertainties, facilities failure, machines breakdown, demand variability, ect. In other words, the sources of these disruptions may come from any factor which may threat the availability of products provided by suppliers or facilities required to supply, produce or distribute the product. The sources of these disruptions are summarised in what we call *supply-side uncertainties* and *demand-side uncertainties*.

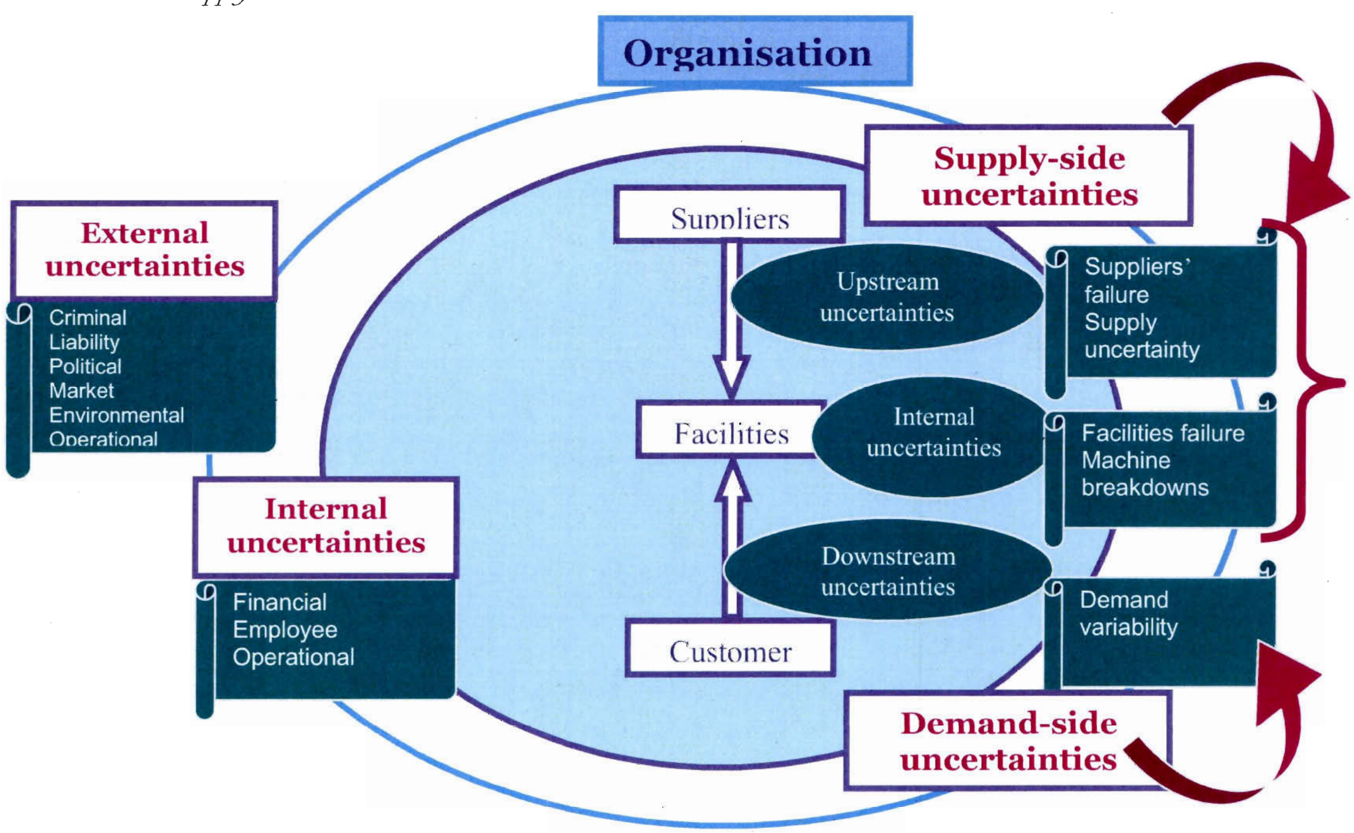


Figure 2-a– Supply chain disruptions sources

According to Singhal and Hendricks (2005), many companies have experienced significant supply chain disruptions in recent years. These companies have reported disappointing operating results as a direct result of these disruptions.

Singhal and Hendricks (2005) have studied nearly 800 examples of supply chain disruptions experienced by publicly traded firms over a period of 10 years. The authors published research results based on state-of-the-art estimation methodologies and statistical analysis, which examined and emphasized the negative linkages between supply chain disruptions and corporate performance. The authors found that supply chain disruptions such as supplier failures, manufacturing delays, and quality problems have deep and measurable impacts on a company's financial performance.

The challenge faced by industrial organisations concerns the wise use of available information about supply chain actors in order to ensure the effectiveness of their logistic systems and keep these systems reliable despite the changes in business environment. Reliability in the context of this dissertation refers always to the ability to perform well when disruptions occur.

The configuration of the supply chain is usually analyzed in terms of certain levels of expected performance as calculated by a specific set of indicators.

In general, performance indicators relate to measurements of the results of the supply chain management (cost, benefit, respect of commitments). More often these indicators of performance relate to the internal processes of organization of the supply chain (lead-time, quality, for instance). In the context of this dissertation, we introduce novel performance indicators to tackle the effect of disruption.

According to (Lorino 1996, 2001) the concept of performance indicators is a set of information "aiming to help an actor to lead the course of an action towards the achievement of an objective or guiding him to allow evaluating a result". In our study, this action consists in evaluating the performance and reliability of supply chain actors in order to decrease the whole SC vulnerability to disruptions.

Models describing supply chains are often based on approximations or simplifications using for some decision parameters static instead of dynamic features and deterministic rather than stochastic features, which call into question the validity of these models. Indeed, the models are generally deterministic and lead to the development of a single strategic plan and a single tactical plan, which supposedly does not perform well with respect to conditions of uncertain future environments.

However, to ensure effective planning, taking into account the sources of uncertainties and disruptions in an appropriate way is essential to limit the impact of disruptions upstream in the chain.

Our work, therefore, aims to construct models which mitigate sources of disruptions related to SC operations through selection of reliable SC actors. The objective is to find solutions to problems with supply chain design which perform well when disruptions occur.

VI. Motivation

An effective strategic supply chain design consists principally of the effective suppliers' selection and the optimal configuration of facilities which prescribes facility locations, production technologies, and capacity selection. However, the dynamics of the market create exposure to several disruptions (materials do not arrive on time, production facilities fail and customer behaviour changes, etc.) causing deviations from scheduled plans. In order to deal with exposure to risks and reduce vulnerability to disruptions, the performance and reliability of supply chain actors must be enhanced. Consequently, novel tools, approaches, and methods should be developed to improve the performance and reliability of SC actors in order to minimize the impact of disruptions.

The old vision of organisation stipulates that the higher the supply chain profitability, the more successful the supply chain. This is not enough nowadays; supply chain management success should be measured, not only in terms of supply chain profitability, but also in terms of the ability to resist disruptions. This is achievable not only through investment in technologies, facilities, and processes of transportation production and distribution of products through a profitable way, but also by the investment in reliable actors, partners, and contingency strategies (relying on standby suppliers for instance).

However, deploying policies to eliminate the occurrence of risks and disruptions can be excessively expensive. The challenge is to proactively manage supply chains in order to make them able to resist disruptions better, not, of course, to eliminate risk altogether.

Several challenging problems associated with supply chain design arise:

(1) How to use the available information to consider and evaluate supply chains actor dynamics;

(2) How to translate this information into comprehensible decision-making issues related to selection of effective supply chain actors, and to coordination of supply chain actor activities, which enable achievement of the objectives of profitability, and minimization of vulnerability to disruptions.

(3) How to use optimization techniques to model these decision-making issues.

The purpose of this work is thus to improve supply chain performance and reliability by developing models to minimise sources of disruptions related to SC actors operations. This thesis therefore focuses on how to build disruption-resistant supply chains.

As the effectiveness of the whole SC is conditioned by the effectiveness of all its actors, restricting selection processes to suppliers without an integration of plants and DCs and vice-versa can expose the SC to great disruptions. Just as suppliers play a vital role in the overall SC, it is likewise essential that plants and DCs transform and distribute products efficiently. The failure of one of these actors can severely disrupt the business continuity and the objectives of the SC. On the other hand, when selection processes of all the SC actors are based on one criterion (generally cost), there may be an equally undesirable impact on the business performance of the SC.

Effective SC actor selection involves determining appropriate suppliers and downstream plants and distribution centers. There are numerous potential features that must be considered for each actor. Thus, the key to strategic planning is the use of multiple criteria when making selection decisions concerning suppliers, plants, and distribution centers.

Instead of focusing on the improvement of supply chain efficiency only by means of reducing costs, current decision-making approaches become conscious of the need to include a variety of performance criteria to build more disruption-resistant supply chains, since they become more exposed to various risks than before.

In the first chapter we propose a multi-objective model based on various indicators of performance using both deterministic (quality, lead-time, etc.) and novel disruption-related criteria. The model enables building disruption-resistant SCs by the reduction of disruption sources coming from procurement, production, and distribution. The proposed model is built to select effective supply chain actors (suppliers, plants, and distribution centers (DC)). In basis of a variety of performance criteria using the Analytic Hierarchy Process (AHP); it uses multi-objective programming and considers an integrated, multi-product and multi-echelon SC system.

While the focus of the first chapter is building disruption-resistant supply chains by proposing a multi-objective model based on various indicators of performance using both normal conditions and certain disruption-related criteria, the second and third chapters concentrate on how quantify and mitigate some types of risks to improve supply chain reliability.

As effective risk analysis today comes to be at the core of the perspectives of major organisations, methods and approaches to analyse and assess risks which threaten industrial organisations are increasingly discussed in the literature. Risk analysis can be considered as an effective procedure that complements an organisation's overall management. A wide range of risks exists, each risk differs from another in terms of its priority, severity, and the knowledge available about it.

The purpose of this chapter is first to clarify the related notions of risk and uncertainty, and next to categorize risk types. The intention is also to define some of the primary drivers of supply chain disruptions and possible measures that should be undertaken to prevent them. Furthermore, the chapter seeks to show how to quantify risks by using the Bayesian approach, by assigning the appropriate probability to each risk occurrence.

Having presented the method for quantifying risk, we shall assume in the third chapter that the probability distributions of supply and solicitation are known, in order to assess reliability of suppliers, plants, and DCs. The purpose of the third chapter is first to assess the reliability of each SC actor (suppliers, plants, and DCs), and to formulate a reliability-based optimization model for supply chain design that mitigates disruptions due to uncertainty about solicitation and supply. The proposed model consists of selecting reliable actors. Reliable actor selection is based on redundancy (standby system) as a relevant contingency technique to counter risks of supply failure.

VII. Research contributions

According to what is presented previously, the contributions of this research can be classified under three headings:

(1) A new multi-objective model of effective actor selection for building disruption-resistant SCs.

(2) A review of concepts and types of supply chain risks and a new approach for risk quantification.

(3) A reliability-based optimization model for mitigating supply chain disruption assuming uncertainties of solicitation and supply.

The description of each group of contribution is explained in what follows.

(1) A multi-objective model of effective actor selection for building disruption-resistant SCs

The first objective of this study is to present the taxonomy of the criteria required to evaluate SC actors while proposing novel criteria related to disruptions and risks.

The second objective is the integration of the AHP with multi-objective optimization in SC design to consider decision-maker preferences about a variety of criteria and make a trade-off between quantitative and qualitative criteria for the evaluation of the actors of the SC.

In this chapter, we formulate a multi-objective model assuming the presence of conflicting, and even competing objectives. For instance, objectives related to suppliers concern cost minimization, quality score maximization, and delivery score maximization. Besides, the model considers objectives dealing with disruption-related criteria such as maximising the ability of actors (suppliers, plants and DCs) to handle disruption and the ability to provide backup supply for disrupted actors. The weighted sum method is then chosen among the various multi-objective programming methods to solve the multi-objective problem.

The purpose of the proposed model is the selection of the reliable suppliers, plants, and DCs which satisfy a set of objectives under a number of constraints, to simultaneously achieve a high level of efficiency in terms of cost reduction, by minimizing all business unit costs, and reducing vulnerability to supply chain disruptions.

In this chapter, we present a review of some already published papers addressing the problem of suppliers and facility selection and the performance criteria used to select the best suppliers and facilities while proposing novel disruption-related criteria. Next, we review the existing methods to assess actor or a business entity performance. Then, we use the previously examined criteria and apply the AHP method in order to get the appropriate relative ratios which reflect the performance evaluation of each entity. Next, we introduce evaluation ratios in order to build a multi-objective selection model of effective actors for building disruption-resistant supply chain (Figure2-b).

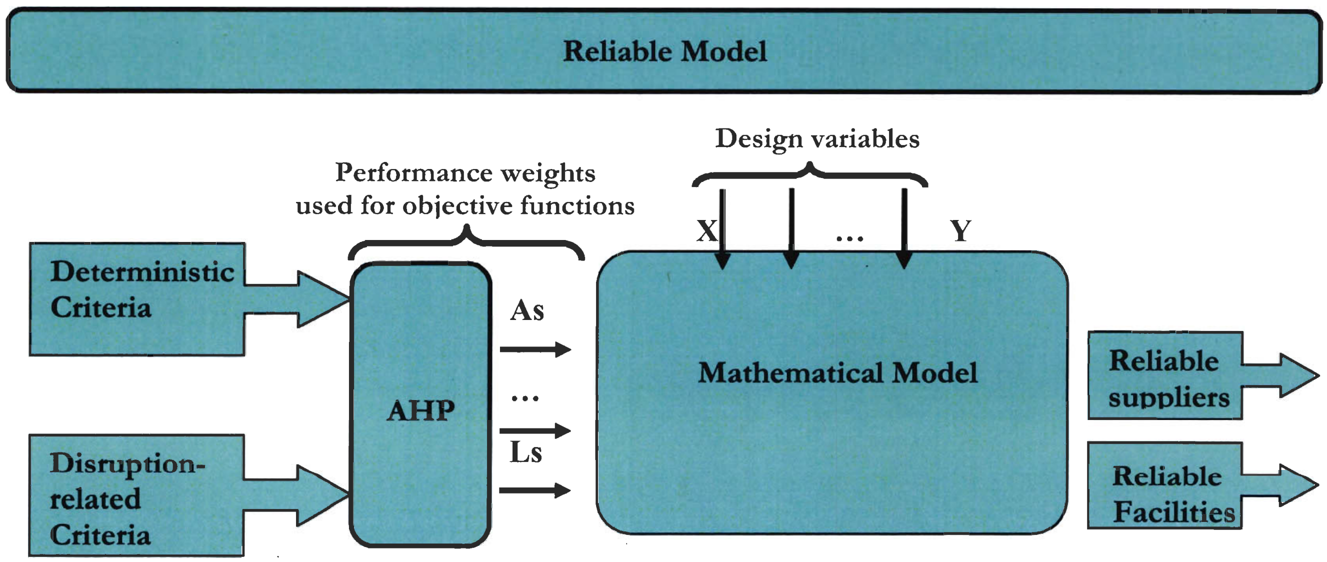


Figure 2-b - Framework of the model tackling with disruptions

We describe in detail, in this chapter, the proposed model, its assumptions, variables, and parameters.

(2) A review of concepts and types of supply chain risks and a new approach for risk quantification

In the manufacturing environment, uncertainties are so diverse as to create the risk of any number of disruptions throughout the system, from supply shortages and production discontinuity to unpredictable consumer behaviour and strikes. Furthermore, many practices and trends have contributed to supply chain vulnerability. Besides internal drivers (increased complexity, over-concentration of operations, poor planning and execution), there are external drivers which increase this vulnerability (competitive environment, disasters, etc.).

Supply chain disruptions can lead to poor performance. Furthermore, ignoring these disruptions can lead to huge loss. Accordingly, analysing and quantifying risk is the main purpose of the second chapter. The objective of risk assessment is to minimize its impact in terms of preventing and reducing future loss and damage. Note that risk is defined as the probability of the occurrence of events that would have a negative impact upon objectives. This is measured in terms of consequences and likelihood (Singhal and Hendricks 2005).

In this chapter, we try to consider risk analysis in modeling decision-making problems. We make the emphasis on the definition, the categorization, and the assessment of risk. We try first to classify and present the main categories of risks. Next, we present the primary drivers of supply chain disruptions to offer insights into the factors that can increase the chances of disruptions. Some of these major factors taken from the work done by Singal and Hendricks (2005) are discussed so that they may be taken as guidelines for managers.

After examination of the main concepts related to risk, the next step consists of proposing a method of its quantification using the Bayesian method. This method makes it possible to assign the appropriate probability distribution of complex and uncertain events, based on prior data and expert opinion. It is first necessary to identify and get sufficient knowledge about the risks related to the system. We can identify risks through audits, brainstorming, expert judgement, surveys, examining the frequency of previous events, examining local and overseas experience, etc. The following step consists of quantifying risks by assigning a weight to each risk which describes the probability of its occurrence using Bayesian approach. At the end, the manager will be able to model decision-making problems taking into account the priority and severity of the risks.

We also provide, in this chapter, an overview of the literature on SC design models under uncertainty. For a more comprehensive review, the reader is referred to Snyder and Daskin (2006), and Snyder (2003).

Most approaches to decision making under uncertainty fall into one of three categories: stochastic programming, robust optimization, or reliability optimization. In stochastic programming, the uncertain parameters are described by discrete scenarios, with a given probability of occurrence; the objective is to minimize the expected cost. In robust optimization, parameters may be described either by discrete scenarios or by continuous ranges; no probability information is known, however, and the objective is typically to minimize the worst-case cost or regret. (The regret of a solution under a given scenario is the difference between the objective function value of the solution under the scenario and the optimal objective function value for that scenario). Reliability optimization considers reliability of SC actors and seeks ones which perform well when a disruption occurs. In reliability optimization, various ways to formulate objectives that consider disruptions are possible. For example, one might try to minimize the expected failure cost by weighting the failure costs by the probability of each facility's disruption, or minimize the maximum failure cost (Note that failure cost is measured in terms of increase in transportation cost that results after the failure of a facility). (Snyder and Daskin 2006).

(3) A reliability-based optimization model for mitigating supply chain disruptions assuming uncertainties of solicitation and supply

Long term strategic decisions like those involving plant location, DC location and supplier selection remain settled for many years and are difficult to reverse once they are taken. Furthermore, they are always made in an uncertain environment.

This dynamic creates exposure to risks and disruptions which could affect the supply chain performance making modern supply chains very complex to manage and also more vulnerable to disruptions. Examples of possible disruptions include supply failures, disruptions due to natural disasters (such as earthquakes), to human errors, etc. The vulnerability of supply chains measures their ability to deal with risks, the impact, and the potential consequences of disruptions become more severe with increasing supply chain vulnerability. To counter the occurrence of disruptions and reduce vulnerability to risks, companies need to deploy appropriate tools and to build disruption-resistant supply chains.

Reliability-based optimization models of facility location and supplier selection presented in the literature are not only rare, they have one major flaw: they consider reliability of the supply chain actors as known. In this thesis, we present a new approach to assess the reliability of SC actors, as we can not cover all the types of uncertainties as sources of SC disruptions in a single research project, we have concentrated on the main strategic ones: uncertainties of solicitation and supply related to SC actors, because it is considered among the most leading in the financial performance of any company. The failure of one of these actors can severely disrupt the business continuity and the objectives of the whole SC (See Singal and Hendricks 2005).

The third chapter proposes a reliability-based optimization model for SCD to mitigate supply chain disruptions under uncertainties of solicitation and supply. The proposed model consists of selecting reliable suppliers among a redundant supply network (composed of standby suppliers) in order to counter the risks of supply failure, besides, the model incorporates the possibility of reliable configuration of the whole supply chain in terms of reliable facility selection. To assess the reliability of supply chain actors we use a method called the interference theory (an area drawn from load/stress mechanics). This method is based on probability distributions of uncertain events. Based on solicitations and supply probability distributions, the method makes it possible to assess the reliability of each supplier and facility.

VIII. Thesis disposition

The general introduction sets the framework for this thesis. We present an explanation of the research background and address the problem description. Next, we present the methodology and the contributions of the thesis research.

The introductory chapter gives also some definitions of supply chain, its objectives, related decisions, and especially makes the emphasis on the considerations of supply chain design processes and decisions. In the end, it includes a disposition of the chapters to follow.

The main subjects of the following chapters are focused on proposing approaches and models of improving the performance and reliability of supply chain. The literature review considered in the present thesis summarizes the preceding work, the opinions stated, and the observations carried out about the performance improvement approaches and models. It concerns, as well, the major contributions of the researchers that covered approaches and models which deal with risk, uncertainty and reliability.

The first chapter presents a review of some already published papers addressing the problem of supplier and facility selection and the common performance criteria while proposing novel disruption-related criteria to select the best suppliers and facilities. Furthermore, the chapter presents a review of the existing approaches and methods to assess supplier and facility performance. We propose a model of supply chain design using the integration of the AHP and multi-objective programming method to consider both quantitative and qualitative criteria in the selection of the best actors of the SC.

The second chapter considers the analysis and the quantification of risks for modeling decision making by using Bayesian methods.

The third chapter proposes an approach to reliability assessment for suppliers and facilities and formulates a reliability-based optimization model for supply chain design under uncertainties of solicitation and supply.

In the last chapter, we present the conclusion and some suggestions and ideas for future research features.

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CHAPTER I

A MULTI-OBJECTIVE SELECTION MODEL FOR BUILDING DISRUPTION-RESISTANT SUPPLY CHAINS

Problem

Strategic decisions made in SC design are often difficult to reverse in implementation, at least in the short term, if we wish to rectify decisions that have been already made. Corrective actions are usually expensive and time-consuming. Decision-makers should intervene proactively to minimize the effect of unexpected events by selecting the best factors and actors of the SC in an integrated manner.

The effectiveness of the whole SC is conditioned by the effectiveness of all its actors. Effective SC actor selection involves determining appropriate suppliers, downstream plants, and distribution centers. Restricting effective selection processes only to suppliers without integrating these with plants and DCs can make SCs vulnerable to disruptions.

Numerous potential features must be considered for each actor. Thus, the key to strategic planning is the use of multiple criteria when making selection decisions concerning suppliers, plants, and distribution centers.

Purpose

The first objective of this study is to present the taxonomy of the criteria required to evaluate SC actors while proposing novel criteria related to disruption and risk.

The second objective is to integrate the analytic hierarchy process (AHP) with multi-objective programming in SC design to consider a variety of criteria and to reach a trade-off between quantitative and qualitative criteria, considering both normal conditions criteria and disruption-related criteria in the selection of effective actors of the SC.

Computational results

The integrated model is applied using fictive data generated to represent approximately a real-world case of a manufacturing firm. The model can be useful to firms of different industries without restriction. The findings demonstrate that the proposed model gives coherent results in terms of best trade-off between the reliability enhancement and the incurred cost.

Originality/value

Although there is considerable research in the literature related to SC actor evaluation and selection processes, this study differs from the ones in the literature in that it proposes novel evaluation criteria dealing with risk and disruption and explaining in detail how the AHP can be applied to evaluate all SC actors and it can be integrated into a multi-objective SCD problem.

I. Introduction

Despite the differences that exist between the actors of the supply chain, they should typically operate in an integrated manner by coordinating their activities. Moreover, these actors should be highly cooperative when it comes to improving the performance of the supply chain as a whole and achieving objective such as on-time delivery, quality, and cost minimization. (Swaminathan *et al.*, 1998).

Companies nowadays operate in a highly competitive and changing world. Such a context compels companies to build effective supply chains and select effective and reliable actors.

As effectiveness of the whole SC is determined by the effectiveness of all its actors, restricting selection processes to suppliers without an integration of plants and DCs can expose the SC to great disruptions. Just as suppliers play a vital role in the overall SC, it is likewise essential that plants and DCs transform and distribute the products efficiently. The failure of one of these actors can severely disrupt the business continuity and the objectives of the SC. On the other hand, when the selection processes of all the SC actors are based on just one criterion (typically, cost), this may have an impact on the business performance of the SC, which is no less serious.

Effective SC actor selection involves identifying appropriate suppliers and downstream plants and distribution centers. Numerous potential features must be considered for each actor. Thus, using multiple criteria for suppliers, plants, and distribution centers selection decisions is the key to strategic planning.

In the literature most SCD have one of two weaknesses: 1-either they deal separately with problems of facility location (Snyder (2006), Verter and Dincer (1992), Sydner & Daskin (2005), Owen & Daskin (1998)) and problems of supplier selection (Vonderembse and Tracey (1999)), or they combine these problems without taking into consideration multi-criteria evaluation (Martel 2001 2005).

The traditional approach to decision-making, i.e. optimization of a single economic function, shows certain weaknesses on this level. Multi-criteria methods are better alternatives to enhance SC efficiency via efficient SC actor selection.

Furthermore, most multi-criteria models use criteria that deal with operational performance but do not deal with uncertainties and disruptive sources. Few decision-making systems and models simultaneously take into account strategic, tactical, and operational decisions, as well as risks and disruptions in the supply chain.

This is the motivation for SC design using multi-criteria evaluation for all the SC actors. Accordingly, to tackle this feature the AHP will be combined with a multi-objective programming to achieve an effective design of the whole SC, by proposing an integrated selection model of effective SC actors based on multi-criteria that consider risk treatment.

We assume that decision-making systems that consider risk should use one of the three main options of risk treatment:

- Statu-quo: do nothing to prevent risk and base actor selection on operational performance criteria only, while assuming the consequences of disruption once they occur.
- Optimize: reduce the sources of disruption by a multi-criteria selection of reliable actors based on certain disruption-related criteria in order to minimize the impacts of disruption.
- Transfer: hedging risks by transmitting their management to outsiders. This option is not considered in this study because it needs certain additional financial considerations related to hedging, which are beyond the scope of this research.

The Statu-quo and Optimize options will be compared and discussed at the end of this chapter.

The rest of this chapter is organized as follows: in the next section, we briefly review some previously published papers addressing the problem of supply chain actor selection and the criteria used in their effective evaluation. Next, we review the existing approaches and methods of assessing performance. We then describe in greater detail the model developed to select the most efficient supply chain actors, using a combination of the AHP and the weighted sum method. This is a Multi-objective Programming technique used to design the SC efficiently. A discussion ends this chapter.

II. Methods

In the two sections below, we aim to present in detail the most popular criteria in the literature used for evaluating supply chain actors, and propose additional criteria which deal with risk environment in order to fill the gap in the literature with respect to this feature. Next, we present a review of some performance-measuring methods, followed by the limitations and advantages of each method.

The second objective of this section is to propose a model that integrates the analytic hierarchy process (AHP) with multi-objective optimization in SC design in order to consider the trade-off between quantitative and qualitative criteria in the selection of the best SC actors.

1. Criteria evaluation of the main SC actors

Since the SC actor selection process addresses different functions within the company, it is considered a multi-objective decision-problem, involving many quantitative and qualitative criteria. Frequently, these evaluation criteria are in conflict with each other.

When a selection decision needs to be made, the company establishes a set of evaluation criteria that make it possible to compare potential performance features.

The main issues to be considered in multi-criteria selection are (Masella and Rangone, 2000):

- The identification of criteria to be considered in the evaluation of the SC actors. Several authors have focused their attention on that issue (Dickson, 1966; Hakansson and Wootz, 1975; Weber et al., 1991).

- The application of multi-criteria techniques which evaluate all the SC actors so that they can be selected efficiently (Weber et al., 1991; Nydick and Hill, 1992; Schniederjans and Garvin, 1997; Min, 1994; Chan and Chan, 2004; Ghodsypour and O'Brien, 1998).

The basic criteria typically used for supplier evaluation purposes are covered by Dickson (1966), which presents the main evaluation criteria (price, delivery, service, quality, etc.).

For facilities, the main criteria used were the ability to expand, consolidation accessibility, operating cost of a typical DC, property cost, property conditions, distance separating customers from DCs, ease of access, and availability and access to labour.

Nowadays, with changing supply chain dynamics these criteria are not sufficient. The set of criteria should be expanded to take into account new dimensions and represent the ability to deal with risks and disruptions.

Managers must be careful not to pay so much attention to exceptional events that they neglect risks. Risks can cause huge damage and lead to breakdowns and loss of credibility and performance.

a. Supplier evaluation criteria

Effective supplier selection, should allow for respecting customer orders terms and expectations. Furthermore, it should make it possible to give the company some real protection in times of shortages, strikes or other emergencies.

In order to select the best partners who are able to ensure that incoming materials meet relevant quality and quantity standards, we must evaluate the performance of each supplier.

A number of criteria must be simultaneously taken into account when selecting the best suppliers. In addition, it is necessary for the decision-maker:

- To identify the criteria that match the company's objectives, and,
- to make a trade-off between conflicting quantitative and qualitative criteria in identifying the effective SC actors (Ghodsypour and O'Brien, 1998).

In this section, we present and classify the most popular supply selection criteria and add novel criteria related to risk and disruption that make it possible to build disruption-resistant supply chain.

Dickson (1966) proposes a list of 23 performance criteria commonly used in the supplier performance measurement. Lehman et al. (1982) grouped the criteria used in purchasing decisions into 4 categories: performance criteria, economic criteria, integrative criteria, and adaptive criteria. These are explained respectively, as the ability to ensure the quality and quantity standards, the lowest price, willingness to cooperate, and the flexibility to adapt plans to uncertainties.

Deng and Wortzel (1995), Verma and Pullman (1998) carried out an empirical study to determine the criteria being used in practice for the purpose of supplier selection. The most important criteria were price, product quality, and on-time delivery. Mummalaneni et al. (1996) use six attributes to assess supplier performance: on-time delivery, quality, price/costs targets, professionalism, responsiveness to customer needs, and long-term relationships with the purchasing company.

Furthermore, the performance criteria proposed by Li et al. (1997) to calculate the Standardized Unit-less Rating (SUR), a performance measurement method, can be divided into two categories: qualitative criteria and quantitative criteria. (See table 2)

Cebi et al. (2003) presented a categorization as a set of criteria and sub-criteria for measuring supplier performance. Table 2 summarizes the main supplier performance criteria proposed by different authors.

Table 2 - Criteria of Supplier Performance

Author	Criteria used for measuring supplier performance
Dickson (1966)	The net price. The ability of each vendor to meet quality specifications. The repair service. The ability of each vendor to meet specified delivery schedules. The geographical location of each vendor. The financial position and credit rating of each vendor. The production facilities and capacity. The amount of past business that has been done with each vendor. The technical capability, i.e. research and development facilities. The management and organization of each vendor. The future purchases the vendor aspires to make from the firm. The communication system (with information on progress data of orders). The operational controls (including reporting, quality control and inventory control systems) of each vendor. The position in the industry (including product leadership and reputation) of each vendor. The labour relations record of each vendor. The attitude of each vendor towards the organization. The desire for business shown by each vendor. The warranties and claims policies of each vendor. The ability of each vendor to meet the packaging requirements for the product. The impression made by each vendor in personal contacts. The availability of training aids and educational courses in the use of each product of each vendor. Compliance or likelihood of compliance with procedures (both bidding and operating) by each vendor. The performance history of each vendor.
Lehman *et al.* (1982)	Performance criteria, economic criteria, integrative criteria and adaptive criteria.
Deng and Wortzel (1995)	Price. Product quality. On-time delivery.
Mummalaneni *et al.* (1996)	On-time delivery. Quality.

	Price/costs targets. Professionalism. Responsiveness to customer needs and long-term relationships with the purchasing company.
Li *et al.* (1997)	**Qualitative criteria :** Quality (% acceptable). Response to special orders (scale 1to100). Response to problems (scale 1to100). Stocking programs (scale 1to10). Financial stability (scale 1to10). Ease of ordering (scale 1to10). **Quantitative criteria:** Price ($). Delivery performance (% on time). Proximity to plants (average shipping days).
Veram and Pullman (1998)	Quality. Cost. Delivery performance.
Cebi and Bayraktar (2003)	**Logistics criterion:** Delivery lead time. Supply lots. Flexibility in changing the order. Delivery in good condition. **Technological criterion**: Capacity to meet the demand. Involvement in formulating a new product or developing current products. Efforts to improve their products and processes, etc. Problem solving capability. **Business criterion:** Reputation and position in the sector. Financial strength, management skills, and compatibility. **Relationship criterion:** Easy communication. Past experience Sales representative's competence.

As seen above, the existing criteria deal with normal conditions and none of the presented criteria tackles the aspect of risk. We need to propose new criteria which consider conditions of disruption. Accordingly, we find it necessary to examine definitions of Supply Chain Risk Management (SCRM). In the literature, few definitions are available for the SCRM. The rarity of these definitions is consistent with the novelty of SCRM, whether in the academic world or the industrial one. We present here the following definitions:

1-"the identification and management of risks within the supply chain and risks external to it through a coordinated approach amongst supply chain members in order to reduce supply chain vulnerability as a whole".(Artebrant et al., 2003)

Besides the internal and the external characteristics of risk, the main points that emerge from this definition as a fundamental aspect of SCRM is reducing the vulnerability of the chain, and considering the SCRM as a collective action led by all the actors of the chain and not an isolated action led by a single actor.

2- "Supply Chain Risk Management is to collaboratively with partners in a supply chain, apply risk management process tools to deal with risks and uncertainties caused by, or impacting on, logistics related activities or resources". (Norrman and Linroth, 2002)

This second definition emphasizes the importance of use of relevant methods and tools in Supply Chain Risk Management.

SCRM is a set of techniques aiming to better guide decision-making. The management of risk, according to these relevant definitions, is a collaborative approach that must involve the various actors in the supply chain and not an isolated action undertaken by a unique actor of the supply chain. We share with (Norrman and Linroth, 2002) and (Artebrant et al. 2003) belief that joint action between actors of the supply chain is necessary for the establishment of an effective SCRM. In addition, the development of appropriate tools and methods, the SCRM can better guide the decision-making.

Based on these two main definitions of SCRM, we propose two novel criteria dealing with disruption, what we call *self-handling criteria* and *supportive criteria*. These criteria are important for the proposed model to build disruption-resistant SC:

- *Self-handling criteria: the ability to handle disruption once occurred.* This criterion is assessed in terms of resistance level to disruption, i.e. the number of times that the supplier has resisted the disruption, divided by the occurrence number of disruptions.

- *Supportive criteria: the ability to give backup supply to disrupted suppliers*: ability of the supplier of absorbing the effect of disruptions that is incurred to another supplier, so that he remains able to provide the required order as planned, i.e. the ability to provide backup supply when needed to ensure timely delivery to facilities.

b. Facilities (plants and DCs) evaluation criteria

Long-term decisions like those involving facility locations are often difficult to reverse once implemented, consequently a DC location may remain fixed for years.

First, we start this section by explaining the functions of DCs. Warehouses and DCs are important nodes in a supply chain. They play valuable roles and perform valuable functions that support the movement of materials. However, it is important to notice that there are some distinctions between warehouses and DCs. A DC is, in fact, a specific type of warehouse. Coyle et al. (2003), for example, define a DC as "a post-production warehouse for finished goods held for distribution". Frazelle (2002) and Ballo (2004) refer to DCs as distribution warehouses. Frazelle (2002) defines them as "facilities that accumulate and consolidate products from various points of manufacture with a single firm or from several firms, for combined shipment to common customers."

In this thesis, we adopt the common definition of DCs to be a type of warehouse, which focuses not on storage but on product movement through operations of receiving and shipping.

With enhanced communication and transportation, DCs have mutated from simple DCs to large and modern DCs with centralized inventories, reduced activity times, and a greater range of services (packaging, labelling, and light assembly). Furthermore, the substantial improvement in delivery capabilities has made it possible for some distributors to reduce the number of DCs without compromising customer service.

After examination of the functions of DCs, we will summarize the key considerations in their site selection and building design. While some criteria have remained the same, such as cost and transportation access, other criteria and considerations have emerged as the mission and needs of warehouse and distribution centres have evolved.

Based on the literature review and some managerial research reports, the key considerations in site selection for DCs are:

- *Properties of the appropriate size*: The future DC needs (in terms of space for facilities, utilities, tenants, etc.) drive the size of the property required.

- *The ability to expand* is also a key consideration in site selection. Sufficient space must exist on the site for track-staging. Furthermore, area for expansion must exist on the property, either through expansion into additional segments of the building or through the construction of an addition to the structure.

- *Consolidation accessibility*.. Companies should not move their warehousing operations nor do they want to locate in several buildings in multiple locations.

- *The operating cost of a typical DC.* The cost of the property, including the cost of proposals (labour, land, facilities, utilities, taxes and transportation), permits and site preparation are a principal consideration.

- *Property conditions,* such as the existence of wetlands or environmental contamination, factor into site considerations. The primary concerns are the cost and time involved in the time involved in the mitigation of environmental contamination or the need of pilings.

- *The distance separating customers from DCs.* Nearly all of the shipments leaving warehouses and DCs depart in trucks. Access to the major highways is essential. Ease of access, including the conditions of the local roads connecting to the highways, is a key consideration in site selection.

- *The ability to provide the best service* to all points connected to it.

- *Availability and access to labour.* Warehouses undertaking several value-added activities require a greater number of workers. The tight labour market could make labour availability a critical issue.

Similarly with suppliers, for an effective evaluation and selection of plants and DCs, we propose the novel criteria that deal with disruption:

- *Self-handling criteria: the ability to handle disruption.*
- *Supportive criteria: the ability to give backup supply to disrupted facilities.*

2. Performance measurements

Performance may be evaluated using a combination of multiple performance criteria. Those criteria may be aggregated into one single measurement of overall performance, by assigning "weighted" values to each key element performed by the actor and calculating a weighted score that can be used to track the performance. (Li et al., 1997)

Several propositions for performance evaluation have appeared in the literature. Although each of these approaches offers advantages under specific conditions, few provide a general methodology for combining multiple criteria or attributes into a single measure of performance.

SC actor selection can be greatly complicated by the fact that some of the criteria are quantitative (price, lead time) and some are qualitative (quality, flexibility, cooperation, service). Thus, a technique is needed that can adjust for the decision-maker's attitude toward the importance of each criterion for each item, as well as capture both the subjective and the objective criteria.

Choy et al. (2004) presents four traditional methods for evaluating the performance of suppliers.

In this paragraph, we review the most popular performance measures presented in the literature and based on multiple criteria. Some of these methods are applied to supplier only; the others can be applied to any SC actor having inputs and outputs which describe its operational functions.

- Standardized Unitless Rating (SUR)

Li et *al.* (1997) proposes a general and consistent technique of performance measurement known as Standardized Unitless Rating (SUR). It is based on several performance criteria and gives a comparison between many suppliers in terms of performance.
The parameters used for computing the (SUR) are the following:
i represents the supplier index, j the criterion index, a_{ij} and r_{ij} and w_j are respectively the value of performance criterion j for supplier i, human psychological blindness and the relative importance of criterion j. $\sum_j w_j = 1$ and $w_j \geq 0$.
For each supplier i the SUR is given by:

$$SUR_i = \sum_j \frac{(a_{ij} - \overline{a_j})}{(a_{\max,j} - a_{\min,j})} \times (1 - r_{ij}) \times \frac{w_j}{\sum_j |w_j|}$$

Where $\overline{a_j}, a_{\max,j}, a_{\min,j}$ are the mean, the maximum, and the minimum of the a_{ij}, respectively.

SUR_i is represented as the sum of a weighted average over performance criteria.
The first part $\frac{(a_{ij} - \overline{a_j})}{(a_{\max,j} - a_{\min,j})}$ is a standardized average satisfaction score or standardized actual measurement for the i^{th} supplier with respect to the j^{th} performance criterion.
The second part $(1 - r_{ij})$ is a measure of human psychological blindness.

The third part $\frac{w_j}{\sum_j |w_j|}$ is the relative importance of criterion j.

Even though SUR is an interesting measure of performance, in terms of considering the priorities and preferences of decision maker through the relative importance of criteria, it remains difficult to use due to the human psychological blindness which is a factor difficult to estimate. For strengths and limitations of SUR see table 2.

Data Envelopment Analysis (DEA)

The principle of DEA consists in assessing the relative performance of a set of decision making units (DMU) that use a variety of identical inputs. DEA assesses the performance of DMUs by measuring the ratio of total outputs to total inputs. Also, the performance estimated is relative to the best performing DMU_s. The best performing DMU_s have a score of 100% and the performance of other DMU_s varies between 0 and 100%.

According to Braglia and Petroni (2000), DEA is a non-parametric method that allows for efficiency to be measured without the need to specify the weights for the different inputs and outputs chosen. This methodology defines a non-parametric best-practice frontier that can be used as a reference for efficiency measures.

The mathematical program used by DEA which was proposed by Trick (www.deazone.com) is the following:

Let X_i be the vector of inputs used by DMU_i, Y_i the corresponding vector of outputs produced by the same DMU. Let X_0 be the inputs into a DMU_0 for which we want to determine its efficiency and Y_0 be its outputs.

Note that an input, in the DEA context, represents an element which should be decreased to make the DMU performs better, like price, lead time, etc. On the other hand, the output is an element which should be increased to make the DMU performs better like quality, flexibility, etc. The objective of the method is to find the best combination of reference DMU_s that dominates inefficient DMU_0, if DMU_0 is an inefficient one. In other words, the method aims to finding the best combination of DMU_s that uses reduced inputs and augmented outputs relatively to DMU_0.

The performance for DMU_0 is obtained by solving the following dual linear programming model:

$$\begin{cases} Min\ \theta \\ s.t. \\ \sum \lambda_i X_i \leq \theta X_0 \\ \sum \lambda_i Y_i \leq Y_0 \end{cases}$$

where λ_i represents the weight associated with each pair (X_i, Y_i) of reference DMU_i to dominate DMU_0 and θ is the performance of DMU_0.

In general, we should include DMU_0 on the left- hand side of the inequalities. Thus, the optimal θ cannot possibly be greater than 1. When we solve this linear program, we get the following requests:

1. The performance of $DMU_0(\theta)$, with $\theta = 1$, meaning that the supplier is efficient.
2. The ``goal" inputs is the difference between X_0 and $\sum \lambda_i X_i$.
3. Alternatively, we can keep inputs fixed and get goal outputs ($1/\theta \times \sum \lambda_i Y_i$).

Weber and Desai (1996) proposed data envelopment analysis (DEA) for evaluation of suppliers that have already been selected. Weber et al. (2000) combined MOP (Multiple Objective Programming) and DEA methods to develop supplier-order quantity solutions using MOP and then evaluating the efficiency of these suppliers based on multiple criteria using DEA.

Seydel (2006) provides decision-makers (DMs) an option for addressing problems involving finite alternative sets and multiple criteria, where criterion-weighting is difficult or impossible.

Way Wong and Coan Wong (2007) illustrate the use of data envelopment analysis (DEA) in measuring internal supply chain performance. The authors developed two DEA models– the technical efficiency model and the cost efficiency model. The information obtained from the DEA models helps managers to identify inefficient operations and take the right remedial actions for continual improvement.

This technique has some limitations, which make it difficult to apply in some conditions. DEA is good when estimating the "relative" performance of a DMU, but it converges very slowly to "absolute" performance. It gives an evaluation compared to peers but not compared to a "theoretical maximum". Besides, it does not consider the priorities and the preferences of decision maker. Table 2 presents both the strengths and limitations of DEA.

- Analytic Hierarchy Process (AHP)

- AHP concepts

The Analytic Hierarchy Process (AHP) provides a framework to cope with multiple criteria situations, involving intuitive, rational, qualitative, and quantitative aspects (Khurrum *et* al.2002).

The AHP is a decision-making method developed by Saaty (1980) for prioritizing alternatives when multiple criteria are considered, which allows decision-makers to structure complex problems in the form of hierarchical levels. Generally, these levels consist of the goal, the criteria, and the alternatives.

According to Saaty (1980) managerial judgments are used to drive the AHP approach. The AHP is a methodology that makes it possible to rank alternatives based on the decision-makers judgement in terms of the importance of the criteria to use, and their rating according to each alternative to integrate the perceptions and purposes into a synthesis. The first step of the AHP consists of determining the relative criteria to meet the goal. The second step consists of evaluating each alternative achievement with respect to each criterion. The final step gives the rating of each alternative based on the chosen criteria and the set goal.

For the supplier selection problem, the goal is to select the best overall suppliers (Nydick and Hill 1992). Similarly, the goals of plant selection and DC selection are respectively, to choose the most reliable plants and DCs.

In turn, criteria are chosen according to the organization's needs and the specific actor's characteristics. For plants, these criteria might be operating cost, reliability, and lead-time. For DCs, the criteria might be distance separating customers from DCs, ease of access, and access to labour.

Since these decisions are not to be reversible, at least in the short term, a wise choice of criteria is needed to select effective actors to keep in the network.

One of the important advantages is the simplicity of AHP. The AHP can also accommodate uncertain and subjective information, and allows the application of experience and intuition in a logical manner. Perhaps the most important advantage, however, is how the hierarchy itself is developed.

- **Using AHP for deriving the weights**

Expert judgments concern the pairwise comparisons of criteria and alternatives. They express the relative importance of one criterion versus another regarding the fixed objective, and express also the relative importance of one alternative versus another regarding each criterion.

Since expert judgements are used as a scale, the alternative ratios reflect the relative importance of the criteria in achieving the goal.

The AHP consists of the following steps:

1- Specify the set of criteria for evaluating the alternatives

2- Get the pairwise comparisons of the relative importance of the criteria in achieving the goal, and infer the priorities or ratios of each criteria

3- For each criteria we obtain the degree of achievement of each alternative

4- Obtain the pairwise comparison between alternatives of relative importance with respect to each criteria

5- Infer from 2 and 4 the ratios of each supplier to achieve the goal.

- Illustration example inferred from (Nydick and Hill, 1992)

We assume we have 3 criteria: quality, delivery-time and service. Furthermore, we have 4 suppliers; and we must compute the importance of their ratios for the selection process.

The high level in the hierarchy graph concerns with the effective selection of SC actors; the following level with the selection criteria that correspond to the company objectives; and the last level with the selection of the alternative actors.

Table 3 presents the evaluation scale used to make pairwise comparisons between criteria importance according to objective achievement (Table 4). This scale is issued from expert judgements.

Table 3 - Evaluation scale

Preference signification	Rating of preference
Equally preferred	1
Moderately preferred	3
strongly preferred	5
Very strongly preferred	7
Extremely preferred	9

The table 3 presents the scale of importance, increasing from 1 to 9:

- 9 is reserved to rate criteria that are extremely preferred,
- 5 is reserved to rate strongly preferred criteria,
- 1 is reserved to rate equally preferred criteria,

The intermediate values present additional levels of preference.

Table 4 - Comparison between criteria

Preference signification	Price	Service	Delivery
Price	1	3	5
Service	0.33	1	2
Delivery	0.2	0.5	1
Total	**1.53**	**4.5**	**8**

Table 4 is read as follows:

- (Line 1, column 2) = 3, indicates that price is moderately more important than service
- (Line 1, column 3) = 5, indicate that price is strongly more important than delivery
- (Line 2, column 3) = 2, indicate that the service is somewhat moderately important than delivery

The total values in the last line will be used in the next table.

Starting from table 4 we can build the normal matrix (Table 5), which includes relative importance ratios of each criterion.

The relative importance ratios are obtained through these following steps:

1- Sum of the elements in each column

2- Divide each value by its column sum

3- Compute raw averages

Table 5 - Relative importance ratios

Preference signification	Price	Service	Delivery	**Raw average**
Price	0.65	0.66	0.63	0.64
Service	0.22	0.22	0.25	0.23
Delivery	0.13	0.12	0.12	0.13
Total	**1**	**1**	**1**	**1**

We use the same process to evaluate suppliers. We chose a given criterion and compare suppliers accordingly, using the expert judgements based on the preference scale presented above, and derive the weights for each supplier. We do so for all the criteria.

Since the processes of evaluation are similar, we show in table 6 only the normalized matrices for each criterion.

Tables 6 - Deriving weights for each supplier

Price	Supplier 1	Supplier 2	Supplier 3	**Weights**
Supplier 1	0.25	0.26	0.23	0.24
Supplier 2	0.42	0.42	0.45	0.43
Supplier 3	0.33	0.32	0.32	0.13
Total	**1**	**1**	**1**	**1**

Service	Supplier 1	Supplier 2	Supplier 3	**Weights**
Supplier 1	0.55	0.56	0.53	0.54
Supplier 2	0.32	0.32	0.35	0.33
Supplier 3	0.13	0.12	0.12	0.13
Total	**1**	**1**	**1**	**1**

Delivery	Supplier 1	Supplier 2	Supplier 3	**Weights**
Supplier 1	0.45	0.46	0.43	0.44
Supplier 2	0.32	0.32	0.35	0.33
Supplier 3	0.23	0.22	0.22	0.23
Total	**1**	**1**	**1**	**1**

The final step of the AHP analysis consists of combining three previous tables 6 to derive overall weights for each supplier in order to select the best one. In the context of this thesis, to build the proposed multi-objective model we use the relative weights derived from AHP for each required criterion.

Triantaphyllou and Mann (1995) define the Analytic Hierarchy Process (AHP) as a multi-criteria decision-making approach which uses a multi-level hierarchical structure of objectives, criteria, sub-criteria, and alternatives.

The AHP is one of the better known decision-making processes that make it possible to make the best decision out of a set of possible options. Therefore, the AHP is considered a multi-criteria decision making process that balances both quantitative and qualitative aspects. The AHP process is summarized in four main steps: 1-identify final objectives, 2-identify alternatives, 3-evaluate key trade-offs among objectives, and 4-suggest alternative solutions and agree on final solutions.

According to Labib *et al.* (1998), the AHP is a method of breaking down a complex situation into its component parts. It arranges these parts into a hierarchical order, assigns numerical values to subjective judgments on the relative importance of each part, and then synthesizes the judgments to determine the overall priorities of the parts.

Karsten (1996) describes the AHP process via a three-level hierarchy problem. On the highest level, there is the overall goal of the decision. The decision criteria are situated on the next lower level, and the alternatives are placed under each criterion at the lowest levels of the hierarchy. At the next step, the decision maker brings out pair-wise preferences about alternatives and criteria. At the last step the within-criterion weights are mathematically merged with the between-criteria weights to yield an overall prioritization of the alternatives in light of the decision-maker's suggested preferences.

Due to its combination of flexibility and ease of use, the AHP has been successfully applied to a large variety of practical multi-criteria decision-making problems.

The table 7 summarizes the main advantages and limitations related to different tools of performance measurement:

Table 7 - Advantages and limitations of performance measures

Performance measures	Author	The limitations	The advantages
Data Envelopment Analysis (DEA)	Weber (1996) Liu et al. (2000) Braglia and Petroni (2000) Weber et al. (2000) Oral et al. (1991,1992) Seiford, (1990) Banker et al. (1984) Charnes et al. (1978)	• Noise such as measurement error can cause significant problems. • DEA is good at estimating "relative" performance of a DMU but it converges very slowly to "absolute" performance. It gives an evaluation compared to your peers but not compared to a "theoretical maximum." • The formulation of DEA creates a separate linear program for each DMU, large problems can be computationally intensive.	• DEA can handle multiple input and multiple output models. • DMUs are directly compared against a peer or combination of peers. • Inputs and outputs can have very different units. For example, X1 could be in units of lives and X2 could be in units of money without requiring an a priori trade-off between the two.
Standardized Unitless Rating (SUR)	Li *et al. (1997)*	• The human psychological blindness is measured arbitrary.	• Taking human psychological blindness into account. • Able to combines multiple criteria or attributes into a single measure of supplier performance. • considering the priorities and preferences of decision maker
Analytic Hierarchy Process (AHP)	Perçin (2006) Bayazit (2006) Narasimhan (1983) Lambert and Stock (1993).	• The AHP may reverse the ranking of the alternatives when an alternative identical	• AHP deal with Multi-criteria decision-making problems using criteria expressed in different dimensions.

	Choi and Hartley (1996). Ghodsypour and O'Brien (1998). Verma and Pullman (1998). Vonderembse and Tracey (1999). Yahya and Kingsman (1999). Masella and Rangone (2000) Akbari Jokar *et al.* (2001) Humphreys *et al.* (2001). Triantaphyllou and Mann (1995) Cebi and Bayraktar (2003) Karsten (1996) Labib *et al.* (1998)	to one of the already existing alternatives is introduced.	• AHP required input data are easy to obtain. • AHP deals with intangible factors, along with intuitive, qualitative, and quantitative aspects. • AHP can be applied in situations that require numerous factors to be considered with conflicting goals. • AHP is a decision support tool which can be used to solve complex decision problems. • The AHP permits the incorporation of priorities and preferences of decision maker.

Other interesting articles dealing with DEA are presented in the literature, for example, Oral et al. (1991 and 1992), Seiford, (1990), Banker *et al.* (1984), Charnes *et al.* (1978).

Other methods of computing performance exist in the literature. We mention briefly here, VPI, CRM and CM.

- VPI (Vendor performance index)

Willis *et al.* (1993) propose a technique of suppliers' performance measurement named vendor performance index (VPI) which compares between two suppliers. This method is defined as follows:

$$VPI = w \times \sqrt{\prod_{i=1}^{n} \left(X_i / Y_i \right)^{W_i}}$$

Where:

X_i = criterion *i* performance score for supplier X; i= 1, 2,..., n^{th} criterion;

Y_i = criterion *i* performance score for supplier Y; i= 1, 2,..., n^{th} criterion;

w_i = weight (relative importance) assigned to criterion i.

$$W = \sum_{i=1}^{n} w_i \qquad / 0 \le w_i \le 1 \text{ for i= 1, 2,..., } n^{th}$$

Willis *et al.* (1993) explains that a standard performance score can reflect either average levels of accomplishment for suppliers that have met JIT requirements, goal-oriented standards that JIT suppliers ultimately aspire to achieve, or a combination of these two requisites.

- CRM (Cost Ratio Method)

According to Vokurka et al. (1996) the cost-ratio method evaluates supplier performance using the tools of standard cost analysis. Vokurka et al. (1996) refers to Timmerman (1986) to affirm that the internal costs associated with quality, delivery and service are converted to a cost ratio which expresses the cost as a percentage of the total value of the purchase. Then this cost ratio is applied to the supplier's quoted price to obtain a net adjusted cost figure or total cost of each purchase to be evaluated.

- CM (Categorical Method)

The categorical method classifies each supplier's performance, or expected performance, in specific areas defined by a list of relevant performance criteria (Timmerman 1986). This approach helps structure the evaluation process in a clear and systematic way. However, Vokurka et al. (1996) explains that a drawback of this technique is that it does not clearly define the relative importance of each criterion. Another drawback is the fact that decisions made using this method may be subjective (Nydick and Hill 1996).

III. Selection model of efficient SC actors

The Multi-objective actor selection model considers an integrated, multi-product, multi-echelon, procurement-production-distribution design problem. A multi-objective mathematical programming model is formulated to design efficient SCs and to tackle both operational performance criteria and disruption-related criteria. For suppliers, it consists of minimizing cost, maximizing quality, maximizing delivery score, maximizing the ability to handle disruption, and minimizing cost of backup supply. For facilities, the model consists of maximizing the ability to expand, minimizing operating costs, maximizing the ability to handle disruption, and minimizing the cost of backup supply, subject to customer demand requirements, procurement limits, production and shipping capacities, and area constraints. Total costs include production, distribution, transport variable costs, and fixed capacity costs.

To develop the actor selection model, the AHP method is used because it allows for both the evaluation of SC actors and their incorporation into a mathematical programming model. Furthermore, the AHP captures both qualitative and quantitative criteria and accommodates uncertain and subjective information in a logical manner. The weights of qualitative and quantitative criteria cited above, are derived from the AHP for each actor.

Before developing the model, the way the SC network operates and the assumed hypotheses are specified. The following assumptions are made:

1. Facilities can ship either to distribution centers (Make to stock) or to demand zones (Make to order). They can also transship sub-assembled products to each other and transshipments can occur between any of the facilities (Figure 3).
2. Distribution centers can ship either to the facilities or demand zones. Figure 1 shows all possible flows in the network.
3. The number of internal, external (outsourcing) and potential facilities, as well as their locations, are already specified.
4. The model optimizes material flows throughout the supply chain, gives the optimal number and locations for suppliers, chooses the best sites for facilities and distribution centers, and provides the best assignment of suppliers to facilities, facilities to DCs, and the best assignment of DCs to customer zones.
5. A site can have several configurations. The configuration of the network is assumed to be flexible in order to adjust to variation in demand. This is identified below by *capacity*

options (Kissani and Martel, 2003). Several capacity options can be considered for each site *s*.

6. Parameters related to weights of the criteria considered in modeling are obtained from the AHP method. The weights provide a measure of the relative importance of each SC actor relatively to the chosen criteria.

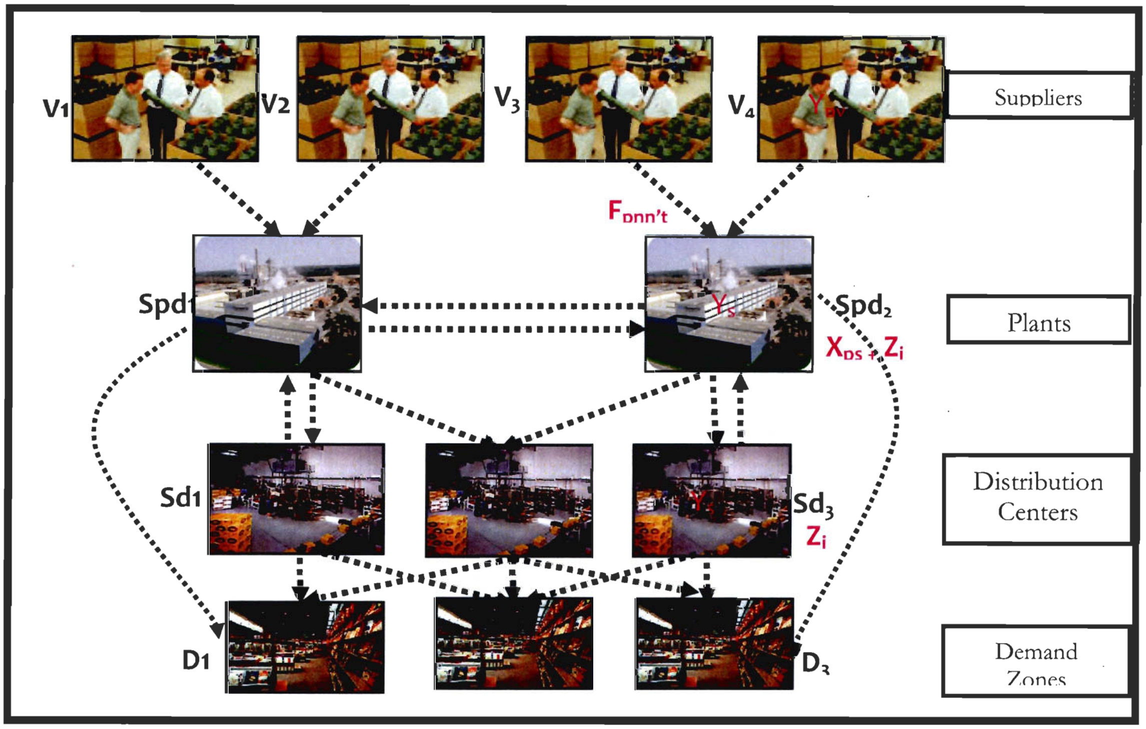

Figure 3 - A visual representation of the network

Costs and parameters

- S = Potential network sites (s ∈ S).
- Sp = Potential production sites.
- Sd = Potential distribution center sites.
- D_p = Set of demand zones of product p.

- RM = Raw material families.
- MP = Manufactured product families, i.e. sub-assemblies and finished products.
- SA = Sub-assemblies families (SA⊂ *MP*).
- FP = finished products (FP⊂ *MP*).

- S^o_{ps} = Set of potential sites (output destinations) which can receive product p from site s.
- S^i_{ps} = Set of potential sites (input sources) which can ship product p to site s.
- V_p = Suppliers of raw material p ∈ RM or of manufactured product p ∈ MP.

- KW_s = Receiving/shipping/handling technologies used in the site *s*.
- KM_{ps} = Production technologies used in the site s in order to manufacture product p.
- KM_s = Production technologies used in site *s*.
- P_s = Products which can be manufactured/stocked on site s.
- P_k = Products which can be manufactured/stocked with technology k.
- P_{ks} = Products which can be manufactured/stocked with technology k on site s.

- J = Potential capacity options.
- J_s = Potential capacity options which can be installed on site s.
- J_{ks} = Potential technology k capacity options which can be installed on site s.
- L_s = Sub-set of mutually exclusive options in Js (e.g: equipment and new version of this equipment after its reconditioning). ($l \in L_s \subset J_s$)
- J^l_s = l-th sub-set of mutually exclusive options J_s ($l \in L_s$).

- b_j = Capacity provided by option j.
- b_{pv} = Upper bound on the quantity of raw material p which can be supplied by supplier v.
- $g^k_{pp'}$ = Quantity of product p needed to make one product p' with technology *k*.
- e_j = Area required to install capacity option j.
- E_s = Total area of the site s.
- x_{pd} = Demand of product p by demand zone d.
- c_{pks} = Production variable cost of product *p* in site *s* with technology *k*.
- f_{psn} = Unit cost of the flow of product p between node n and site s.
- A_s = Fixed cost of using site s for the planning horizon.
- a_j = Fixed cost of using capacity option j for the planning horizon.
- w_p = The maximum number of suppliers for product p.
- L_{pv} = Rate of time delivery of raw material p from supplier v.
- P_{pv} = Purchasing cost (acquisition, transportation, etc.) of raw material p from supplier v
- A_{pv} = Rate of quality of raw material p provided by supplier v.
- D_s = Rate of ability of expansion of site s.
- H_s / H_v= Rate of ability to handle disruption of site s / supplier v.
- B_s/ B_v = Rate of ability to give backup supply of site s / supplier v.

Decision Variables

- X_{pks} = Quantity of product p produced in plant s with technology $k \in KM_{ps}$.
- F_{pns} = Flow of product p between node n and site s.
- Y_s = Binary variable equal to 1 if site s is used and to 0 otherwise.
- Z_j = Binary variable equal to 1 if capacity option j is installed and 0 otherwise.
- Y_{pv} = Binary variable equal to 1, if supplier v is selected for supplying product p and 0 otherwise.

Within the planning horizon we can renew supplier contracts, plan the capacity and plan the production.

Since we will have conflicting objectives, the design of logistic network problem with selection of reliable actors can be solved with a Multi-objective Programming model with binary variables.

The objective functions of the Multi-objective Programming proposed model are as follows:

- minimization of Z_1 which represents the sum of costs incurred along the logistic network, including supply and transportation costs associated with flows, production costs, costs of using sites or not and capacity options costs,
- maximization of Z_2 which represents quality objective function (for suppliers),
- maximization of Z_3 which represents delivery objective function (for suppliers),
- maximization of Z_4 representing the expansion ability (for facilities),
- maximization of Z_5 representing the ability to handle disruption (for suppliers and facilities),
- maximization of Z_6 representing the ability to give backup supply (for suppliers and facilities).

The proposed model

$$Min \quad Z1 \ ; \ Max \quad Z2 \ ; \ Max \quad Z3 \ ; \ Max \quad Z4 \ ; \ Max \quad Z5 \ ; \ Max \quad Z6$$

$$Z1 = \sum_{p\in P}\sum_{(n,n')} f_{pnn'}F_{pnn'} + \sum_{s\in Sd}\sum_{p\in MP}\sum_{k\in KM_{ps}} c_{pks}X_{pks}$$

$$+\sum_{s\in S}\left[A_sY_s + \sum_{j\in J_s} a_jZ_j\right] + \sum_{p\in RM}\sum_{v\in V_p}\sum_{s\in S_{pv}^{o}} P_{pv}F_{pvs}$$

$$Z2 = \sum_{p\in RM}\sum_{v\in V_p}\sum_{s\in S_{pv}^{o}} A_{pv}F_{pvs}$$

$$Z3 = \sum_{p\in RM}\sum_{v\in V_p}\sum_{s\in S_{pv}^{o}} L_{pv}F_{pvs}$$

$$Z4 = \sum_{s\in S_p} D_sY_s$$

$$Z5 = \sum_{v\in V_p}\sum_{p\in RM} H_vY_{pv} + \sum_{s\in S_p} Y_sH_s$$

$$Z6 = \sum_{v\in V_p}\sum_{p\in RM} B_vY_{pv} + \sum_{s\in S_p} Y_s$$

Subject to

- *Demand constraints*

$$\sum_{s \in S^i_{pd}} F_{psd} = x_{pd}, \qquad p \in MP, d \in D_p \tag{1}$$

- *Supplier selection constraints*

$$\sum_{s \in S^o_{pv}} F_{pvs} \le b_{pv} \times Y_{pv}, \qquad p \in RM, v \in V_p \tag{2}$$

$$1 \le \sum_{v \in V_p} Y_{pv} \le w_p \qquad p \in RM \tag{3}$$

- *Constraints of flow equilibrium of raw materials*

$$\sum_{n \in V_p} F_{pns} - \sum_{p' > p} \sum_{k \in KM_{p's}} g^k_{pp'} X_{p'ks} \ge 0 \qquad p \in RM, s \in Sp \tag{4}$$

- *Constraints of flow equilibrium of sub-assemblies products*

$$\sum_{k \in KM_{ps}} X_{pks} + \sum_{n \in S^i_{ps}} F_{pns} - \sum_{n \in D_p \cup S^o_{ps}} F_{psn} - \sum_{p' > p} \sum_{k \in KM_{p's}} g^k_{pp'} X_{p'k\,s} = 0 \qquad p \in SA, s \in Sp \tag{5}$$

$$\sum_{n \in S^i_{ps}} F_{pns} - \sum_{n \in D_p \cup S^o_{ps}} F_{psn} = 0 \qquad p \in SA, s \in Sd \tag{6}$$

- *Constraints of flow equilibrium of finished products*

$$\sum_{n \in D_p} F_{psn} - \sum_{k \in KM_{ps}} X_{pks} = 0 \qquad p \in FP, s \in Sp \tag{7}$$

$$\sum_{n \in S^i_{ps}} F_{pns} - \sum_{n \in D_p} F_{psn} = 0 \qquad p \in FP, s \in Sd \tag{8}$$

- *Constraints of production capacity*

$$\sum_{p \in P_{ks}} X_{pks} - \sum_{j \in J_{ks}} b_j Z_j \le 0 \qquad s \in Sp, k \in KM_s \tag{9}$$

- *Constraints of reception-shipping capacity*

$$\sum_{n \in D_p \cup S^o_{ps}} \sum_{p \in P_{ks}} F_{psn} - \sum_{j \in J_{ks}} b_j Z_j - \le 0 \qquad s \in S, k \in KW_s \tag{10}$$

- *Area constraints*

$$\sum_{j \in J_s} e_j Z_j - E_s Y_s \le 0, \quad s \in S \tag{11}$$

- *Constraints of capacity options selection*

$$\sum_{j \in JR^l_s} Z_j \le 1, \qquad s \in S, l \in L_s \tag{12}$$

$Y_{pv} \in \{0, 1\}\ \forall p \in RM, \forall v \in V_p$; $Y_s \in \{0, 1\}\ \forall s \in S$; $Z_j \in \{0, 1\}\ \forall j \in J$; $X_{pks} \ge 0\ \forall (p,k,s)$; $F_{pnn'} \ge 0\ \forall (p,n,n')$.

Equation (1) represents the demand constraint for each product.

Constraints (2 and 3) represent the capacity of supply for each supplier and the maximum of suppliers for each product (i.e., the limit of suppliers to not to exceed for each product). They require, also, that all products should be supplied.

Constraints (4-8) correspond to flow equilibrium of different product categories. "p'>p" means that the product p is a component of product p'.

Constraints (9 and 10) correspond to limits of production and reception-shipping capacities.

Inequality (11) corresponds to area constraints for the capacity options to be implanted in each site.

Expression (12) indicates the constraints of capacity options selection for each site.

IV. Discussion

In this section, we analyze the computational results obtained from the resolution of the proposed model considering disruption-related criteria and the variant of the model which considers normal conditions criteria only. Note that, besides strategic decisions, the proposed model allows also for some tactical decision-making. For example, decisions must be made about order quantities for selected suppliers as well as the quantity to produce at each plant. In the presented results, we focus on the efficient suppliers and facilities selected to be kept in the supply chain network.

In this work, we use sensitive analysis to see how the results change if we consider disruption-related criteria. We see how the cost increases if we increase the ability of the SC to handle disruption. We compare the two models, the deterministic model (the Statu-quo option of risk treatment) and the disruption-resistant model (Optimize option of risk treatment) (Figure 4).

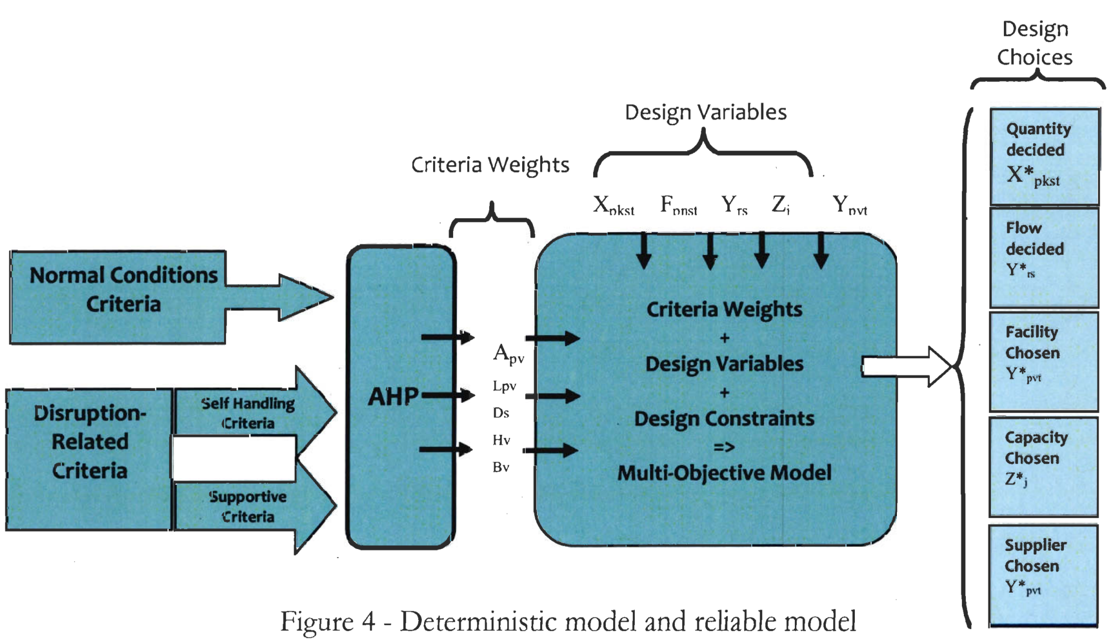

Figure 4 - Deterministic model and reliable model

We first compute and compare the cost objective functions in both cases to evaluate how much the cost increases when we consider reliability[2] criteria for SC actors; next we assess the percentage of reliability increase versus the percentage of cost increase.

- To apply the models we assume that the network is composed of 7 suppliers. Three normal conditions criteria are used to evaluate these suppliers: quality, price and delivery; furthermore, disruption-related criteria are considered: the ability to handle disruption and the ability to give backup supply.

- Moreover, we assume that the same network includes 18 facilities and 23 distribution centers. The criteria used for their performance evaluation are the ability to expand (normal conditions criteria); furthermore, the disruption-related criteria which are considered are: the ability to handle disruption and the ability to give backup supply.

- A large variety of products is also used for the model application.

- To simplify, we suppose that we have one period in planning horizon. If we have more periods, the same work will be done for the other periods.

- The resolution of the models is done with CPLEX 9.0 solver of ILOG. The results of actor selection are summarized below.

1 – Application of Deterministic model (Statu-quo option of risk treatment)

-Supplier selection

Table 8 - Supplier selection of deterministic model

Var name	Lw bound	Up bound	VarType	Opt.var.
Y_1_7	0	1	Bin	1
Y_2_8	0	1	Bin	1
Y _3_9	0	1	Bin	1
Y_4_9	0	1	Bin	1
Y_5_10	0	1	Bin	1
Y_1_11	0	1	Bin	1
Y _2_11	0	1	Bin	1
Y_3_12	0	1	Bin	0
Y 4_12	0	1	Bin	1
Y_5_13	0	1	Bin	0

[2] Reliability means in this chapter the ability to handle disruption.

We recall that in table 8, the first index refers to product and the second indicates the supplier. The table shows that supplier 12 was not chosen to supply the product 3. Further, the supplier 13 was not chosen to supply the product 5.

Table 9 - Sites' selection of deterministic model

Var name	Lw bound	Up bound	VarType	Opt.var.		Var name	Lw bound	Up bound	VarType	Opt.var.
Y_0_1	0	1	Bin	0		Y_0_33	0	1	Bin	1
Y_1_1	0	1	Bin	1		Y_1_33	0	1	Bin	0
Y_0_2	0	1	Bin	0		Y_0_34	0	1	Bin	1
Y_1_2	0	1	Bin	1		Y_1_34	0	1	Bin	0
Y_0_3	0	1	Bin	0		Y_0_39	0	1	Bin	1
Y_1_3	0	1	Bin	1		Y_1_39	0	1	Bin	0
Y_0_4	0	1	Bin	0		Y_0_40	0	1	Bin	1
Y_1_4	0	1	Bin	1		Y_1_40	0	1	Bin	0
Y_0_5	0	1	Bin	0		Y_0_41	0	1	Bin	1
Y_1_5	0	1	Bin	1		Y_1_41	0	1	Bin	0
Y_0_6	0	1	Bin	0		Y_0_42	0	1	Bin	1
Y_1_6	0	1	Bin	1		Y_1_42	0	1	Bin	0
Y_0_15	0	1	Bin	1		Y_0_43	0	1	Bin	1
Y_1_15	0	1	Bin	0		Y_1_43	0	1	Bin	0
Y_0_16	0	1	Bin	1		Y_0_44	0	1	Bin	1
Y_1_16	0	1	Bin	0		Y_1_44	0	1	Bin	0
Y_0_17	0	1	Bin	0		Y_0_49	0	1	Bin	0
Y_1_17	0	1	Bin	1		Y_1_49	0	1	Bin	1
Y_0_18	0	1	Bin	0		Y_0_50	0	1	Bin	1
Y_1_18	0	1	Bin	1		Y_1_50	0	1	Bin	0
Y_0_20	0	1	Bin	1		Y_0_52	0	1	Bin	1
Y_1_20	0	1	Bin	0		Y_1_52	0	1	Bin	0
Y_0_21	0	1	Bin	1		Y_0_54	0	1	Bin	1
Y_1_21	0	1	Bin	0		Y_1_54	0	1	Bin	0
Y_0_22	0	1	Bin	0		Y_0_55	0	1	Bin	1
Y_1_22	0	1	Bin	1		Y_1_55	0	1	Bin	0
Y_0_23	0	1	Bin	1		Y_0_57	0	1	Bin	1
Y_1_23	0	1	Bin	0		Y_1_57	0	1	Bin	0
Y_0_24	0	1	Bin	1		Y_0_65	0	1	Bin	1
Y_1_24	0	1	Bin	0		Y_1_65	0	1	Bin	0
Y_0_25	0	1	Bin	1		Y_0_66	0	1	Bin	0
Y_1_25	0	1	Bin	0		Y_1_66	0	1	Bin	1
Y_0_26	0	1	Bin	1		Y_0_68	0	1	Bin	0
Y_1_26	0	1	Bin	0		Y_1_68	0	1	Bin	1
Y_0_27	0	1	Bin	1		Y_0_70	0	1	Bin	1
Y_1_27	0	1	Bin	0		Y_1_70	0	1	Bin	0
Y_0_30	0	1	Bin	1		Y_0_71	0	1	Bin	1
Y_1_30	0	1	Bin	0		Y_1_71	0	1	Bin	0
Y_0_31	0	1	Bin	0		Y_0_74	0	1	Bin	0
Y_1_31	0	1	Bin	1		Y_1_74	0	1	Bin	1
Y_0_32	0	1	Bin	1						
Y_1_32	0	1	Bin	0						

The table 9 illustrates the selected sites for each plant and each distribution center. The 0 indicates the close of the site and value 1 represents the opening of the site. For example, the decision to make concerning site 1 is opening (Y_0_1=0; Y_1_1=1).

2- Application of Disruption-resistant model (Optimize option of risk treatment)

Table 10 - Supplier selection of reliable model

Var name	Lw bound	Up bound	VarType	Opt.var.
Y_1_7	0	1	Bin	1
Y_2_8	0	1	Bin	1
Y _3_9	0	1	Bin	**0**
Y_4_9	0	1	Bin	1
Y_5_10	0	1	Bin	1
Y_1_11	0	1	Bin	1
Y _2_11	0	1	Bin	1
Y_3_12	0	1	Bin	**1**
Y 4_12	0	1	Bin	1
Y_5_13	0	1	Bin	0

The results of running the disruption-resistant model (Table 10) show that supplier 12 is chosen to supply the product 3. Furthermore, the supplier 9 is not chosen to supply the product 3.

Table 11 - Sites' selection of reliable model

Var name	Lw bound	Up bound	VarType	Opt.var.		Var name	Lw bound	Up bound	VarType	Opt.var.
Y_0_1	0	1	Bin	0		Y_0_33	0	1	Bin	1
Y_1_1	0	1	Bin	1		Y_1_33	0	1	Bin	0
Y_0_2	0	1	Bin	0		Y_0_34	0	1	Bin	1
Y_1_2	0	1	Bin	1		Y_1_34	0	1	Bin	0
Y_0_3	0	1	Bin	0		Y_0_39	0	1	Bin	1
Y_1_3	0	1	Bin	1		Y_1_39	0	1	Bin	0
Y_0_4	0	1	Bin	0		Y_0_40	0	1	Bin	1
Y_1_4	0	1	Bin	1		Y_1_40	0	1	Bin	0
Y_0_5	0	1	Bin	0		Y_0_41	0	1	Bin	1
Y_1_5	0	1	Bin	1		Y_1_41	0	1	Bin	0
Y_0_6	0	1	Bin	0		Y_0_42	0	1	Bin	1
Y_1_6	0	1	Bin	1		Y_1_42	0	1	Bin	0
Y_0_15	0	1	Bin	0		Y_0_43	0	1	Bin	1
Y_1_15	0	1	Bin	1		Y_1_43	0	1	Bin	0
Y_0_16	0	1	Bin	0		Y_0_44	0	1	Bin	1
Y_1_16	0	1	Bin	1		Y_1_44	0	1	Bin	0
Y_0_17	0	1	Bin	0		Y_0_49	0	1	Bin	0
Y_1_17	0	1	Bin	1		Y_1_49	0	1	Bin	1
Y_0_18	0	1	Bin	0		Y_0_50	0	1	Bin	1
Y_1_18	0	1	Bin	1		Y_1_50	0	1	Bin	0
Y_0_20	0	1	Bin	0		Y_0_52	0	1	Bin	1
Y_1_20	0	1	Bin	1		Y_1_52	0	1	Bin	0
Y_0_21	0	1	Bin	1		Y_0_54	0	1	Bin	1
Y_1_21	0	1	Bin	0		Y_1_54	0	1	Bin	0
Y_0_22	0	1	Bin	0		Y_0_55	0	1	Bin	1
Y_1_22	0	1	Bin	1		Y_1_55	0	1	Bin	0
Y_0_23	0	1	Bin	1		Y_0_57	0	1	Bin	1
Y_1_23	0	1	Bin	0		Y_1_57	0	1	Bin	0
Y_0_24	0	1	Bin	1		Y_0_65	0	1	Bin	1
Y_1_24	0	1	Bin	0		Y_1_65	0	1	Bin	0
Y_0_25	0	1	Bin	1		Y_0_66	0	1	Bin	0
Y_1_25	0	1	Bin	0		Y_1_66	0	1	Bin	1
Y_0_26	0	1	Bin	1		Y_0_68	0	1	Bin	0
Y_1_26	0	1	Bin	0		Y_1_68	0	1	Bin	1
Y_0_27	0	1	Bin	1		Y_0_70	0	1	Bin	1
Y_1_27	0	1	Bin	0		Y_1_70	0	1	Bin	0
Y_0_30	0	1	Bin	1		Y_0_71	0	1	Bin	1
Y_1_30	0	1	Bin	0		Y_1_71	0	1	Bin	0
Y_0_31	0	1	Bin	0		Y_0_74	0	1	Bin	0
Y_1_31	0	1	Bin	1		Y_1_74	0	1	Bin	1
Y_0_32	0	1	Bin	0						
Y_1_32	0	1	Bin	1						

The results in table 11 indicate some changes due to disruption-related criteria considered in the disruption-resistant model.

Sites 15, 16, 20, and 32 are open because they give a good trade-off between reliability and cost.

✓ We now compare the cost-objective function for both models to evaluate how much the cost increases when we consider reliability criteria for SC actors. We run both models 5 times, each time changing certain parameters' data (Table 12).

Table 12 - Comparison between deterministic model and disruption-resistant model

Models	(Cost, reliability)	(Cost, reliability)	(Cost, reliability)	(Cost, reliability)	(Cost, reliability)
Deterministic model	(3012; 0.5)	(2158; 0.3)	(2500; 0.4)	(2900; 0.5)	(2430; 0.4)
Disruption-resistant model	(3500; 0.7)	(2500; 0.45)	(3500; 0.7)	(3170; 0.7)	(2800; 0.7)

- We now examine the cost of the objective function that accounts for reliability and the cost of the deterministic function, and examine the trade-off between these two objective functions to bring out the effect of introducing reliability into the model. This trade-off allows us to determine how significant a cost increase is required to add reliability to a system.

- For the first scenario, for example, when we run the deterministic model we get a cost of 3012 and reliability equals to 0.5, if we consider disruption criteria the model generates a cost of 3500 for a reliability of 0.7.

- The resulting trade-off curves obtained from the results of running models for the 5 times described earlier are depicted in the figure below. The cost is plotted on the x-axis and the reliability is plotted on the y-axis. Each point on a curve represents a different value of cost and reliability improvement corresponding to a different solution. The blue curve relates to the deterministic model and the red curve relates to the reliability model.

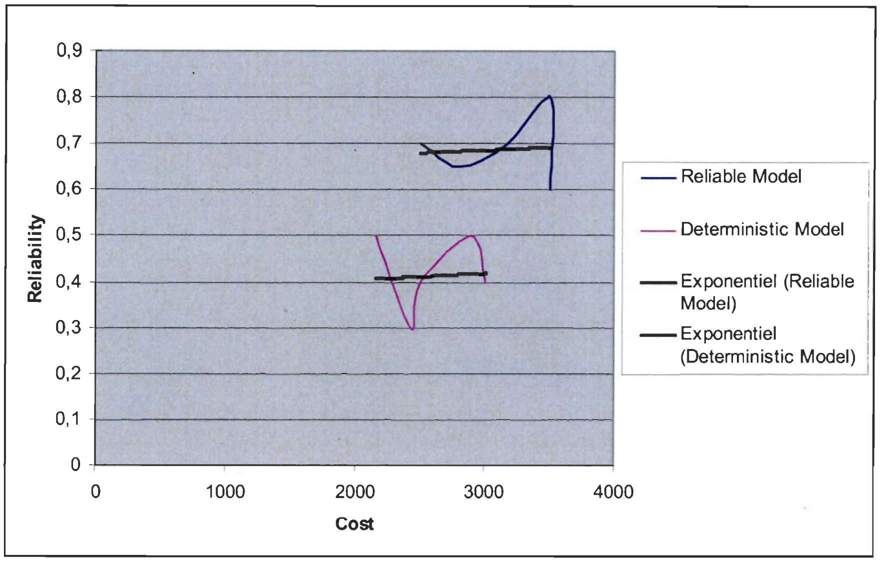

Figure 5 - Comparison between deterministic model and disruption-resistant model

- As we see in figure 5, the blue curve is steeper than the red one. This means that firms do not need to make huge investments when selecting reliable actors to improve the system's reliability. We believe that developing such trade-off curves is an important step in convincing firms to change their optimization objectives to include reliability.

- The steepness of the blue curve suggests that the reliable model solutions that are much better than the deterministic model solutions in terms of reliability but not much worse in terms of cost. For example, consider the second point from the left of this curve, which represents a solution that is 50% better than the traditional solution in terms of reliability improvement, but only 16% worse with respect to the traditional objective. Similarly, the fourth point is 40% better in terms of reliability improvement but only 9% worse with respect to the traditional objective.

- The shape of the trade-off curves with shows that large improvements in reliability can often be attained with only small increases in cost.

- We argue that the second model yields better solutions. Accordingly, it is preferable to the first model because its superiority in the reliability ratio even though the cost has increased sensitively. We can demonstrate that large improvements in reliability can be attained with small increases in cost.

Conclusion

This work highlighted the combination of the AHP approach and multi-objective programming to assist decision-makers to make effective decisions regarding SC actor selection. The AHP approach is flexible in accommodating conflicting criteria and relatively simple to apply. However, AHP can help evaluate and compare actors with respect to different evaluation criteria and cost data, AHP provides a more robust tool to decision-makers to select the most reliable actors making a trade-off between cost and reliability.

In this chapter, we reviewed the most frequently used criteria for measuring SC actor performance while proposing novel criteria dealing with risk and disruption. Next, we examined the existing methods of assessing performance.

Multi-objective actor selection model considers an integrated, multi-product, multi-echelon, and procurement-production-distribution design problem. A multi-objective mathematical programming model is formulated to design efficient SC and tackle both normal conditions and disruption-related criteria. For suppliers, it consists to minimize cost, maximize the quality, maximize the delivery score, maximize the ability to handle disruption, and minimize the cost of backup supply. For facilities, the model enables to maximize the ability to expand, to minimize the operating cost, to maximize the ability to handle disruption, and minimize the cost of backup supply, subject to customer demand requirements, procurement limits, production and shipping capacities, and area constraints. Total costs include production, distribution, transport variable costs, and capacity costs. The model uses the weighted sum method, a technique of Multi-objective Programming.

In this work, we use sensitive analysis to see how results would change if we consider disruption-related criteria. With comparing the two models: the deterministic model (Statu-quo option of risk treatment) and the disruption-resistant model (Optimize option of risk treatment), we see how the cost would increase if we increase the ability of the SC to handle disruption.

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CHAPTER II

QUANTIFYING RISKS USING BAYESIAN APPROACH

Effective risk analysis lies at the core of major organisations' current perspectives. Several methods and approaches, in various fields, have been proposed in the literature in order to analyse and mitigate risk that may threaten industrial organisations. To mitigate risk optimally, the first crucial step is to define and quantify it.

The purpose of this chapter is to clarify the notion of risk, and categorize the types of risks. The chapter then seeks to model and quantify risks occurring in industrial organisations by using Bayesian approach, which assign the appropriate probability distribution to uncertain parameters.

I. Introduction- The context of risk

The future is considered uncertain, regardless of any plan deployed to predict it and control it. There is no plan that can guarantee a certain outcome. The real value of predictable parameters can differ largely from the forecasted one. For this reason, the uncertainty of future events can create a wide range of disruptions for industrial organisations.

Uncertainties may affect the internal aspects of industrial organisations as much as external ones. Uncertainties may therefore concern raw material sourcing, uncertain lead times, uncertain demand, breakdown of production facilities, etc. On the other hand, uncertainties may concern regulations in foreign countries, labour union decisions, employee strikes, etc. (Husdal 2004).

In this chapter, we try to analyse the main types of risks occurring in industrial organisations in order to model decision-making problems using Bayesian approach. This method will make it possible to find the suitable probability distributions of complex and uncertain events.

We first explain and classify the main risks that threaten industrial organisations. We then present the Bayesian analysis as it has been presented in the literature for assessing the posterior probability of uncertain events. Lastly, we identify some limits of the Bayesian method. We conclude with a list of software used to compute posterior probability.

II. The main risks in industrial organisations

A number of trends during the last decade, such as globalisation, fierce competition, and outsourcing, have made the supply chain shift increasingly from simple to complex activities, from the first supplier to the end customer, in attempts to adjust to changes. These dynamics have made the supply chain more vulnerable to various disruptions.

Other drivers may be at the source of these disruptions, such as unpredictable partner behaviour, natural disasters, failure, obsolescence, machine breakdowns, strikes, government intervention, government regulation, recession, etc.

According to Husdal (2004), the common risk facing any company is the randomness of the real world.

Here, it is important to distinguish between the notions of risk and uncertainty. "Risk" and "uncertainty" are two tightly correlated terms, which are both related to the notion of randomness.

Risk can be defined as imperfect knowledge when the probabilities of the possible outcomes are known, and *uncertainty* exists when these probabilities are not known (Hardaker 2004).

When uncertainty is related to the lack of knowledge of a specific event, the risk concerns the possible occurrences of this event represented by its probability. In other words, uncertainty could be defined as imperfect knowledge about a specific event or parameter, and risk as uncertain occurrence.

Risk was defined by the experts of the Royal Society as "the probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge. As a probability in the sense of statistical theory, risk obeys all formal laws of combining probabilities" (Royal Society 1983).

The starting point for many discussions of risk is as it is presented in classical decision theory (March and Shapira 1987, Borge 2001). Here risk is the possible upside and downside of a single rational and quantifiable (financial) decision.

March and Shapira (1987) defined risk—from a decision theory perspective—as "variation in the distribution of possible outcomes, their likelihoods and their subjective values".

Elsewhere in the literature, Zsidisin (2003) acknowledges that risk is a multidimensional construct, interpreted by practitioners and academics alike in numerous ways.

Kisperska-Moron and Klosa (2003) and Andersson and Norman (2003) are among the many writers who present risk as: Risk= Probability (of a given event) ×Severity (negative business impact).

Furthermore, besides risk and uncertainty, disruption and vulnerability are terms related to randomness but frequently used for different things (Table 13):

Table 13 - Related notions to risk

Notions related to randomness	Definition
Disruption	Disturbance or failure that affects the continuity of an activity
Vulnerability	Intrinsic parameter related to degree of exposure to serious disturbance arising from supply chain risks and affecting the operational performance of the supply chain
Risk	Degree of knowledge of randomness= randomness with known probability
Uncertainty	Degree of knowledge of randomness =randomness without known probability

1. Risk in SC context

In this section, we explain some concepts related to the supply chain risk:

- ***Risk***

Juttner *et al.* (2003) defined supply chain risk as "the variation in the distribution of possible *supply chain* outcomes, their likelihood and subjective values". The authors discussed risk in a supply chain context and specified that uncertain "variations" or disruptions include those affecting the flow of information, materials or products across organizational boundaries. Supply chain risk thereby becomes anything that presents a risk to information, material, and product flows from the suppliers to the delivery of the product to the final customer. The author reiterated this definition in terms of "the possibility and effect of a mismatch between supply and demand" (an outcome).

The authors proceeded to suggest that risk "consequences" are supply chain variables such as cost or quality.

Compared with external, environmental risk sources, demand and supply risk sources are internal to the supply chain. Supply risk is defined as uncertainty associated with supplier activities and in general supplier relationships, i.e. "the transpiration of significant and/or disappointing failures with inbound goods and services" (Zsidisin et al., 2002, Zsidisin 1999).

Risk, vulnerability, and uncertainty are terms that in practice are often used interchangeably, but in the technical sense, they are different concepts.

- ***Vulnerability***

A valuable paper, Peck (2005), reviews the main literature on supply chain risk and vulnerability.

Svensson (2000), the first and most widely cited author in the supply chain risk field, placed vulnerability and related concepts, such as risk, uncertainty, and reliability, within the context of the wider concept of contingency planning. He defined vulnerability both as an "exposure to serious disturbance, arising from risks within the supply chain as well as risks external to the supply chain" and as "a condition that is caused by time and relationship dependencies in a company's activities in a supply chain."

Based on his study of inbound and outbound flows of an automotive assembler, Svensson (2002) presented supply chain vulnerability as a two-part construct, incorporating supply chain disturbances (unexpected deviations from the norm) and their negative consequences.

Similarly, in the cross-industry practitioner research by Peck and co-workers (2002, 2003, 2006), supply chain vulnerability is taken to be related to risk, in the sense that something is "at risk or vulnerable, is likely to be lost or damaged".

According to Uta Jüttner (2005), a supply chains' risk exposure determines its vulnerability. Thus, supply chain vulnerability is defined as "an exposure to serious disturbance arising from supply chain risks and affecting the supply chain's ability to effectively serve the end customer market".

Before quantifying risk, it is very important to show how to delimit or at least classify the types of risks that can threaten industrial organisations and to present their main drivers. This may help to provide a better grasp of each, and make it possible to achieve more efficient control.

2. A classification of risks

Everyday we talk about inflation, budget cuts, interest rate fluctuations, unemployment, war, the high cost of living, catastrophes caused by bad weather and so on. All these phenomena can have disparate levels of economic effects on organisations.

Risk management must constitute a key element of strategic planning, more especially as it takes increasing importance in the context of globalisation. Risk can take various forms and have various degrees of severity depending on the financial standing of the company and also of its risk aversion. Traditional insurance cannot protect from all types of risk. That's why organisations should deploy the appropriate measures and methods to avoid the most current risks. Paying attention to risk management is in fact a condition of the survival of organisations.

According to (Elkins 2003) part of the challenge in classifying and managing the portfolio of enterprise risks requires a very broad, cross-functional perspective of a company.

"Formally defined, enterprise risk management is the process of systematically identifying, quantifying, and managing all risks and opportunities that can affect achievement of a corporation's strategic and financial objectives" (Elkins 2003).

There are various categories of risks, in this section we give an overview of the main classifications presented in the literature.

- Repeatable risks versus non repeatable risks

One can describe repeatable risks as events that are frequent and recurrent. We can for example talk about demand variation, which generates a common repeatable risk related to a shortage in meeting customer demand when demand exceeds production.

According to Elkins (2003), repeatable risks are those that can be modeled using statistical distribution, as there is plenty of past statistical data relevant to the problem.

The name for that type of risk comes from the assumption based on expert opinion that supposes that past risk experience may be similar to future risk experiences.

The opposite of repeatable risks, non-repeatable ones, concern events that occur infrequently. Hence, they concern those that we cannot model directly using statistical approaches, because of the lack of data (unavailable, expensive, or difficult to gather). In this case, probabilistic models are built by combining available data and expert opinion, which make them subjective (Elkins 2003).

For instance, non-repeatable risks may concern new regulations in foreign countries, new labour union decisions, etc.

-Internally driven risks versus externally driven risks

The risk portfolio may also be divided into internally or externally driven risks. Note that internally driven risks are usually caused by the internal entities, either due to hazard or due to poor scheduling or controlling methods. On the other hand, externally driven risks, as their name suggests, are influenced by external entities, such as shortages in raw materials in case of unreliable suppliers.

-Dynamic risks versus static risks

Dynamic risks have been separated from static risks. Dynamic risks can be also described as commercial risks, and include decisions which can lead to profit as well as to negative output. As opposite to dynamic risks, there are static risks or non-commercial risks that concern the operational decisional level within the production processes and can only lead to losses (Artebrant 2003).

3. A wide variety of risks

According to Dormer et *al.* (2003) any enterprise faces essentially three main kinds of risks:

- *Financial risks* which include excessive consumption, excess inventory costs, lost sales, etc. The impact of financial risks may be both short-term and long-term. These dramatically change the allocation of resources for production of goods and services, and jeopardize the organization's credibility.
- *Chaos risks* are those whose impacts are related to availability, such as fluctuations in customer demand and variability in supply of raw materials. The volatility of supply and demand influences strategic, tactical, and operational decisions of an organization. Situations such as breakdowns, cancelled orders, and late deliveries can significantly affect the dynamics of the supply chain and threaten the availability of final products causing damage to business purposes.
- The third type is *market risk*; which involves inflation, rate change, etc.

We should note that most available risks could be transferred to the supplier. This risk represents the acceptance of responsibility for uninterrupted delivery of service. The supplier can thus assume the risk of absorbing the cost and supply consequences of making the service available when required and appropriate to the agreed levels of performance. Nevertheless, only the supplier usually assumes some elements, while others may be unpredictable, such as changes in government regulation, or they may be beyond the supplier's complete control. This type of risk can also have an effect on the normal course of the supply chain, but unfortunately cannot be assumed by any supply chain partner, so it should be mitigated by other means.

Furthermore, some extreme scenarios such as natural disasters, political instability, and regulations may exist, although they are rare. Should they occur, they can severely disrupt the supply chain network. Managers must therefore be careful to not pay so much attention to exceptional events than then neglect smaller risks. These risks can cause huge damage and be very severe if they are too numerous, and can lead to breakdowns and loss of credibility and performance.

According to (Elkins 2003), four main risk areas may divide the portfolio of enterprise risks:

- *Financial risk* concerns the management of capital, including external factors that affect the variability and predictability of revenue and cash flow (e.g., general economic conditions or foreign exchange rates).
- *Strategic risk* concerns events which may impact on the strategic level of the organisation. It may concern new competitors, demand variability, supply shortage, etc.
- *Operational risk* arises from aspects of running the business day-to-day, such as scheduling, accounting and information systems.
- *Hazard risk* includes natural disasters and catastrophes.

According to (Artebrant 2003), other types of risk are crucial in terms of threat caused to organisations, to which we should pay more attention.

- *Employee risk* includes problems such incompetence due to work injuries, lack of motivation, stress, and discrimination among colleagues. A company with an inferior working environment produces discomfort and work injuries, which results in an increased absence and unwanted high employee cost.
- *Property risk* concerns damage caused by fire, water, storms, and other natural disasters.
- *Criminal acts* represent sabotage, industrial espionage, and fraud. During the last decade, there has been a significant shift from outside criminal acts to inside operations.
- *Liability risks* may include responsibility of environment and product and risks with contracts. Product liability means that a company must pay damage when their product has caused personal injury or property damage. Artebrant (2003) explains that damage claims may be substantial if the amounts demanded for compensation are very high. To avoid risks associated with product liability it is important to have a quality securing system in the company to ensure adequate quality of the products and services corresponding to market norms.
- *Political risk* concerns new laws, nationalization, social revolution, etc. The most obvious political risk pointed out by Artebrant (2003) is confiscation or nationalization of

property. The economic situation of countries with political instability is quite volatile. This may affect the financial performance of firms located in such countries.

Artebrant (2003) speaks also of risk previously mentioned by other authors, such as market risk and environmental risk.

- *Market risk.* Financial transactions generate greater risk in current markets. Market risk concerns inflation, trade agreements, changed terms of competition, and risks with exchange and interest rate changes. Speculation with currency has lead to most big companies having some form of financial policy to limit associated risks.
- *Environmental risk* includes pollution and disasters. Artebrant (2003) explains that environmental problems are getting more and more difficult to monitor since sources are diffuse and hard to localise. Recently governments have made substantial efforts to support the reduction of pollution all around the world and to thereby reduce environmental risks. Table 14 summarises the main risks mentioned in reviewed literature and their classification.

Table 14 - Risks classification

Risk	Definition	Static	Dynamic	Internally driven	Externally driven
Financial risk	It concerns the management of capital, including external factors that affect the variability and predictability of revenue and cash flow (e.g., general economic conditions or foreign exchange rates). ▪ Dormer et *al.* (2003); Elkins (2003);		√		√
Market risk	Financial transactions generate more and more considerable risk in the actual markets. Market risks concerns inflation, trade agreements, changed terms of competition, risks with rate change. Speculation with currency has lead to most big companies having some form of finance policy to limit the associated risks. ▪ Artebrant (2003) ; Dormer et *al.* (2003)		√		√
Strategic risk	▪ Artebrant (2003) ; Dormer et *al.* (2003); Elkins (2003)	√			√
Operational risk	▪ Artebrant (2003) ; Dormer et *al.* (2003); Elkins (2003)	√		√	
Property or environmental risk	▪ They include pollutions and disasters. ▪ Artebrant (2003) ; Dormer et *al.* (2003); Elkins (2003)	√			√
Employee risk	Those risks include problems such incompetence due to working injuries, lack of motivation, stress and discrimination among colleagues. A company with inferior working environment produces discomfort and working injuries which results in an increased absence and unwanted employee turnover.	√		√	
Criminal act	Represents sabotage, industrial espionage, theft and fraud. During the last decade there has been a significant shift from outside criminal acts to inside operations. Artebrant (2003)	√		√	
Liability risk	Includes responsibility of environment and product and also risks with contracts. Product liability means that a company has a liability to pay damage when their product has caused injury to another property or person. Artebrant (2003) explains that the damage claims may be substantial if the amounts demanded for compensation are very high. To		√		√

	avoid risks associated with product liability it is important to have a quality securing system in the company to assure an adequate quality of products and services which corresponds best to the markets' norms.				
Political risk	Those risks concern new laws, terrorism, nationalization and social revolution etc. The most obvious political risk pointed out by Artebrant (2003) is considered to be confiscation or nationalization of property. The economic situation of countries with political instability is very changing. That may impact a lot on the financial performance of firms located in those countries.		√		√

As mentioned, the severity of disruptions depends on the financial standing of the company as well as its risk aversion. In the next paragraph, we highlight some drivers of these disruptions.

4. Primary drivers of supply chain disruptions

An important question emerges when we speak of supply chain disruptions; this concerns their primary drivers. Hendricks and Ivey (2005) have pointed out some of these primary drivers in order to give some insights into the factors that crease the chances of disruption:

- **Competitive environment:**

Hendricks and Ivey (2005) explains that in the current context of intense competition on the world market, changing customer behaviour, volatile demand, increased product variety, and short product life cycles create considerable supply-demand divergences.

- **Increased complexity:**

Global sourcing, managing large numbers of supply chain partners, innovations and using convoluted industrial technologies have increased the complexity of supply chains.

- **Efficiency**:

Hendricks and Ivey (2005) points out that improving operational efficiency by reducing costs is among the top-priorities in SC management for most companies, while for only few of them the top priority concerns making supply chain more flexible to manage risk. In other words, this means that firms seem to ignore that supply chain disruptions may be very costly, and consequently discount the impact on their efficiency.

- **Over-concentration of operations:**

Usually firms restrain their objectives to taking advantage of economies of scale, volume discounts, and lower transaction cost. Through this, they over-concentrate their operations at a particular side, than more valuable locations such as building relationships with reliable suppliers and concentrating effort to control changing customer's behaviour.

- Hendricks and Ivey (2005) explains that over- concentration of operations may reduce the flexibility of the supply chain to react to changes in the environment and leads to a fragile supply chain which is vulnerable to disruptions.

• Poor planning and execution:

Among the most drivers of breakdowns and failures, we find poor supply chain planning and supply chain execution. Furthermore, plans are too aggregate, lack details, and often based on inaccurate information. Lack of good information systems obstructs the ability of the organization to anticipate future problems and be pro-active in dealing with these problems. Hendricks and Ivey (2005) point that poor planning and execution capabilities result in more incidents of demand-supply divergences.

5. Some measures to minimize disruptions effect

According to Hendricks and Ivey (2005) many practices and trends have contributed to supply chains vulnerability. Some of the approaches exist and can help to deal with supply chains disruptions. Hendricks and Ivey (2005) briefly outline them below:

• Improving the accuracy of demand forecasts

To improve the accuracy and reliability of forecasts, firms should consider not only the expected demand forecast but also the demand forecast error (variance) in developing plans. This would allow planners to be aware what deviation may happen from the mean value.

• Synchronize planning and execution

When managers responsible for execution adjust plans to reflect current operating changes, they should imperatively communicate those adjustments to the planners to assure the synchronization between development and execution of plans.

• Collaborate with supply chain partners

For reducing information distortion and lack of synchronization that currently contribute to disruptions, supply chain partners must be implicated in both decision making and problem solving, as well as share information about strategies, plans, and performance with each others.

• Invest in Visibility

For developing visibility, some steps shall be followed. Those consist on identifying and selecting important indicators of supply chain performance; collecting data about those indicators; monitoring those indicators against a predetermined benchmark level to disclose possible deviations; at the end implementing processes for dealing with deviations.

- **Building sourcing flexibility**

This can be achieved by using flexible contracts as well as use of spot markets for supply needs.

- **Building manufacturing flexibility:**

This can be accomplished by acquiring flexible capacity to prevent demand volatility. Hence, firms should consider segmenting their capacity into basic and reactive capacity. The basic capacity is dedicated earlier to orders that can be accurately forecasted, and reactive capacity is dedicated later to orders that can be inaccurately forecasted.

- **Invest in technology:**

Investment in appropriate technology can contribute in reducing the chances of disruptions. Developing and linking databases across supply chain partners provide visibility of supply chains operations. This enables the firm to identify supply chain problems earlier rather than later and operate in a proactive rather than reactive mode.

III. Using the Bayesian method for assessing risk

Bayesian rules are used to determine probability distribution of uncertain parameters. The most important step in assessing risks is to assemble all the related data (subjective judgments, recorded data, etc) to help outlining the maximum knowledge. At the next step, forecasting methods will help to delimit the range of eventual values which would be taken by the parameters to estimate. Then, Bayes approach will be used to attribute a distribution probability to each estimated parameter.

Note that at the opposite of usual forecasting methods which need recorded data only, Bayes approach needs both recorded data and subjective opinion. Before checking the recorded data, we use subjective opinion to construct a prior distribution for the parameter to estimate. The recorded data is then used via Bayes formula to revise the prior probability distribution and get what is called posterior distribution probability.

The manager could consequently choose the high weighted values for the estimated parameter, in terms of the associated probability, to consider it into the risk analysis.

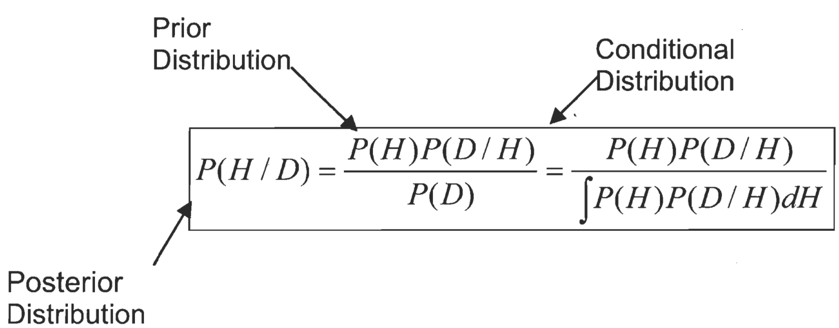
1. Bayesian method

Most firms cannot simply wait for the emergence of uncertain events and then react to it. Instead, they must anticipate and plan for future events so that they are prepared to react immediately to changes as they occur.

In general practice, accurate forecasts lead to efficient operations and high levels of performance, while inaccurate forecasts will inevitably lead to inefficient, high cost operations and poor levels of performance. In supply chains, the most important action which should be taken to improve the efficiency and effectiveness of the logistics process is to improve the quality of the forecasts.

However, there are several methods used to forecast the future. Each should be applied according to the context of its use and the data available. Some methods approximate a unique estimation for the predicated parameter; others give a distribution probability for the parameter to estimate.

Bayesian approach does not have the concept of a unique parameter. In other words, the method treats the parameters as random, not as fixed quantities. This method gives a probability distribution of the parameter to estimate. It uses the prior knowledge about the probability distribution of the given parameter, collect new data, and then update the available knowledge using Bayes rule to get the posterior probability distribution. (See figure 6)



$$P(H/D)=\frac{P(H)P(D/H)}{P(D)}=\frac{P(H)P(D/H)}{\int P(H)P(D/H)dH}$$

Figure 6 - **Bayes rule**

The Bayesian approach is based on the famous Bayes formula. As shown at figure 6, Bayes formula expresses the conditional probability of the event X occurring, given that the event D has occurred (P(H/D)), in terms of unconditional probabilities of H and D and the probability that the event D has occurred given that H has occurred (P(D/ H)).

The first step in the Bayesian approach consists of constructing subjective judgments in order to construct a prior distribution for the parameters to estimate. Note that the prior knowledge represents the person's belief about this parameter. After this, the data is taken from a sample survey; afterward it will be combined with prior knowledge to obtain a new probability distribution for the parameter to estimate. This probability distribution, which has been updated by the collected data, is called the posterior probability distribution. It is based on knowledge of the prior probability distribution and the sample survey data.

In other words, Bayesian estimation applies Bayes rule to combine a prior density and a conditional density obtained from the available data to obtain a posterior density.

If we want to get the best guess from the posterior distribution, the maximum of the posterior distribution, called Maximum a Posteriori (MAP), is used:

$$\theta_{MAP} = \arg\max_{\theta}\left\{p\left(\theta\middle|D\right)\right\} = \arg\max_{\theta}\left\{p\left(D\middle|\theta\right)p\left(\theta\right)\right\}$$

For more information about MAP see Godsill and Robert (2002).

Mockus (1993) presents a review of application of Bayesian approach to global and stochastic optimization. The author discusses the advantages and disadvantages of Bayesian approach and compares it with minimax approach.

Hill (1997) compares the Bayesian methodology and the classical approach which consists of deriving a point estimate for the unknown value of the parameter and using this to estimate the distribution of the variable. The author examines whether the Bayesian methodology with a uniform prior distribution probability provides a better framework than the classical approach when applied to a simple stochastic decision problem. For an exponential demand distribution Bayesian methodology provides a better framework. Also for Poisson and binomial demand distributions Bayesian methodology produces better results over a wide range of parameter values.

Sohn (1997) applied Bayesian dynamic forecasting approach to predict changes in reliability of an industrial product. The author assumes that a prior distribution of reliability follows a beta distribution where its mean is represented as a cumulative logistic function of age.

With a numerical example we illustrate the application of Bayes rule in case of supply uncertainty in supply chains.

With the objective of illustrating the application of the Bays' approach described previously in case of supply chains, this section presents a simple example to show how to assesses the probability distribution of uncertain supply, the same example may be applied to derive probability distributions of other parameters that could be relevant in real life (e.g. demand).

Assuming that a company J used to order 500 units of a given product P from the supplier S.

Assume that P(D): Probability of occurrence of {Order=500 units}

The statement of Bayes' theorem:

$$P(H_i / D) = \frac{P(H_i)P(D / H_i)}{\sum_i P(H_i)P(D / H_i)} = \frac{P(H_i)P(D / H_i)}{P(D)}$$

Figure 7 - Discrete-Probability example

In figure 7, H represents an underlying *hypothesis* and D represents observable *consequences* or *data*.

We assume this statement about the forward problem:

P(data | hypothesis): probability of obtaining observed data given certain *hypothesis* into statements about the corresponding inverse problem:

P(hypothesis | data): probability that certain model gave rise to observed data as long as we are willing to make some guesses about the probability of occurrence of that hypothesis, *P(hypothesis)*, prior to taking the data into account.

In our case:
D= Order of 500 units
H_1=On-time supply
H_2=Late supply

$P(H_1)$: prior probability for on-time supply based on overall frequency ≅ 60% (476 of 771 core samples)

$P(H_2)$: prior probability for late supply based on overall frequency ≅40% (295 of 771 core samples)

$P(D|H_1)$: probability of ordering 500 units guessing on-time supply= 7% (34 of 476 samples)

$P(D|H_2)$: probability of ordering 500 units guessing late supply = 95% (280 of 295 samples)

Then total probability of D, is given by:

$P(D) = P(D/H_1) \times P(H_1) + P(D/H_2) \times P(H_2)$ =0.07*0.60 +0.95*0.40= 0.422

If we make an order of 500 units, then the probability that the supply be on-time is:

$$P(H_1/D) = \frac{P(H_1)P(D/H_1)}{P(D)} = \frac{0.07 \times 0.6}{0.422} = 0.10$$

The probability that the supply be late is:

$$P(H_2/D) = \frac{P(H_2)P(D/H_2)}{P(D)} = \frac{0.95 \times 0.4}{0.422} = 0.90$$

Hence, Bayes rule allows for computing the probability of on-time and late delivery if we make an order of 500 units of the given product P.

2. Limits of Bayesian method- Monte Carlo approximation

Bayesian modeling and inference differs from classical inference in that it assumes a joint probability model for both the observed data and the unknown parameters. Bayesian inference is then made by examining the conditional distribution of the model parameters given the observed data.

One of the difficulties of Bayesian data analysis was the difficulty to determine the posterior distribution of the model parameters analytically. The integral in the denominator may not be mathematically solvable. In this case, we use simulation techniques to solve the equation and obtain an estimate of the posterior distribution.

For more complex models some posterior quantities could be approximated, but the list of models for which these approximations worked well is rather small.

The development and improvement of Monte Carlo techniques has recently made the posterior distributions of very complicated Bayesian models easy to approximate.

Monte Carlo is one of the many methods that have been used widely for Bayesian problems.

Classical Monte Carlo makes the approximation:

$$\int P(X)P(D/X)dX = \sum_i P(X_i)P(D/X_i)$$

Bayesian Monte Carlo Analysis simulates the prior distribution using a given number n of iterations of a Monte Carlo simulation. This simulation calculates the likelihood of the data for each of the number n simulated prior values. The prior values are generally considered equally likely, so have prior probabilities of p=1/n. These prior probabilities and calculated likelihoods are used in Bayes Rule to calculate posterior probabilities for each of the n simulated values.

These n posterior values and their calculated probabilities are used to simulate the posterior probabilities.

3. Some softwares for computing posterior probability

- Excel.
- BUGS: software to solve Bayesian posterior distribution. (Bugs = Bayesian inference Using Gibbs Sampling)
- WinBUGS is the successor to BUGS which includes CODA type diagnostics. Further, it includes Metropolis-Hastings Markov chain Monte Carlo (MCMC) in addition to Gibbs. It is for Windows operating systems only

  It's available at: http://www.mrcbsu.cam.ac.uk/bugs/welcome.shtml
- BEAST (Bayesian Evolutionary Analysis Sampling Trees): a Bayesian MCMC for phylogenetic analyses of molecular sequences.

  Available at: http://evolve.zoo.ox.ac.uk/software.html?id=tracer
- BOA (Bayesian Output Analysis) by Brian Smith, University of Iowa.

  Available at: http://www.public-health.uiowa.edu/boa/Home.html.
- CODA: a program for assessing output from BUGS (and WinBUGS).

IV. Main models dealing with uncertainty and risk

There is an increasing need for incorporation of various forms of uncertainty into decision making for supply chain problems.

We present here some *robust* and *reliable* models. Broadly defined, a supply chain is *robust* if it performs well with respect to uncertain future conditions; a supply chain is *reliable* if it performs well when parts of the system fail (Snyder 2003).

The goal of robust optimization in general is to find solutions that perform well under every realization of the uncertain parameters. Note that those solutions could not be necessarily optimal.

The two most widely considered models for robust optimization under uncertainty are stochastic models (minimizing expected cost) and minimizing worst-case cost or regret models.

Most of the stochastic models involve objective functions expressed in the form of minimizing the expected cost of the system. These models are solved using either special-purpose algorithms or more general stochastic programming techniques: classical recourse-based stochastic programming (cf. Birge & Louveaux, 1997; Kall & Wallace, 1994; Ahmed et *al.* (2003)), robust stochastic programming (Mulvey, Vanderbei, and Zenios (1995)), probabilistic (chance-constraint) programming (Sahinidis 2004)., and stochastic dynamic programming (Sahinidis 2004).

For models of worst-case cost or regret minimization, the formulation adds a constraint that restricts the regret in any scenario to be within a pre-specified limit (Snyder 2003).

Similarly, reliable optimization problems hedge against either expected cost of failure or worst-case cost due to failure. Generally, there is a trade-off between the operating cost of a system and the reliability of that system.

One set of models addresses the trade-off between operating cost and the maximum cost that might result when an entity fails, while another set addresses that between operating cost and the expected cost of failure when entities have a given probability of failing.

Reliable optimization may similarly concern models aiming to minimize total costs and restrict the maximum failure cost to be no greater than a pre-specified value. A failure costs might be defined as the increase in cost when a fail occur (e.g. the cost that results when a facility fails, sourcing fails, transportation fails, etc.) (Snyder 2003)

The figure 8 summarizes the main models which deal with uncertainty and risk.

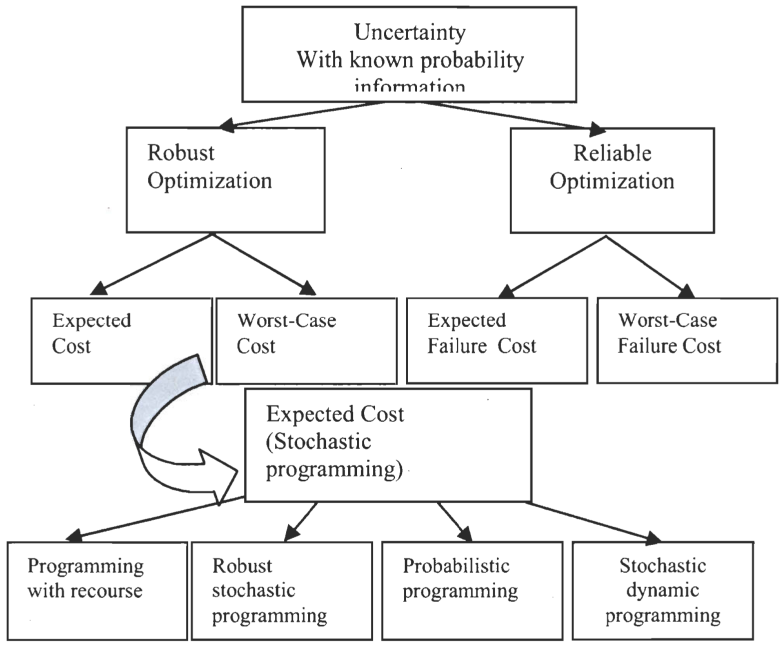


Figure 8 - Models dealing with uncertainty

Like stochastic programming, fuzzy programming also addresses optimization problems under uncertainty. A principal difference between the stochastic and fuzzy optimization approaches depends on the manner uncertainty is modeled. In the stochastic programming case, uncertainty is modeled through discrete or continuous probability functions. On the other hand, fuzzy programming considers random parameters as fuzzy numbers and constraints are treated as fuzzy sets (Sahinidis 2004).

Many of the developments in the area of fuzzy mathematical programming have been recently popularized by the work of Zimmermann (1991).

When no probability information is known, the two most common models are minimax cost and minimax regret.

Conclusion

This paper elucidates the notion of risk and uncertainty. It makes a classification of main risks that threaten industrial organisations and their common drivers. Next, the Bayesian theory is used as a method to quantify risks.

The methodology used for assessing risks consists of the main following steps:

- Identifying risks: we can identify risks through audits, brainstorming, expert judgement, surveys, examining the occurrence frequency of previous events, examining local and overseas experience, etc.
- Sorting and categorising risks through the main categories.
- Quantifying risks by assigning a weight to each risk that describes the probability of its occurrence using Bayesian approach.
- Prioritizing risks for each category of risks, we classify those through their priority. This priority can be evaluated by first that probability that the risk will occur, and by the enormity of the risk impact on the organisation objectives.
- Model decision-making problems of the organisation taking into account the main risks in modeling.

We also present some software used to compute posterior probability.

At the end we address taxonomy of the various models dealing with risk and uncertainty. It is beyond the scope of the paper to provide a detailed coverage of these models. Instead, we gave pointers to the literature that can be used as starting points for further study.

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CHAPTER III

RELIABILITY-BASED OPTIMIZATION FOR SUPPLY CHAIN DESIGN PROBLEM

SCRM has gained increasing importance at the same time as vulnerability of supply chains to disruptions has increased. While uncertainty of SC environment has been disregarded for a long time, it is now viewed, after recurrent incidents happened over the last years, as an inherent property of supply chain systems.

Several types of uncertainties exist in the SC environment. Even if the parameters are estimated accurately, a supply chain may face several uncertainties which differ in terms of severity of their impact and their mitigation. We agree that any type of uncertain and unexpected event might have an impact on supply chain performance, especially, supply-side and demand-side uncertainties.

Demand-side uncertainties concern all uncertainties which may impact on the demand coming from the customer such as uncertainty in demand, cost, etc.

In turn, supply-side uncertainties concern all uncertainties which may impact on the availability of the product coming from supplier, such as supplier service interruption, uncertainty in lead time, sourcing unavailability, etc., or other uncertainties which may impact on the availability of product coming from facilities (facility failure, machine breakdowns, etc). Note that the notion of supply-side uncertainty is larger than supply uncertainty or supply risk.

We will not examine here the main uncertainties nor present their definitions, because this exercise has been done in the previous chapter. Nor can we analyze all types of uncertainties, nor mitigate them. However, we focus on the main supply-side and demand-side uncertainties and try to mitigate the supply chain disruptions based on these uncertainties.

In the current context of enlarged logistics and uncertain environment, it is necessary to design reliable and disruption-resistant supply chains. In this thesis, we emphasize the design of reliable supply chains to mitigate supply chain disruptions. Unlike the other works of the literature, supply risk and disruptions here are not restricted to supplier only, but they cover all the other SC actors.

In the literature, the usual definition of reliability is the ability of a component to perform its role as expected or the ability to absorb or mitigate the impact of the disturbance.

The IEEE defines reliability as "the ability of a system or component to perform its required functions under stated conditions for a specified period of time."

For example, for a software product the reliability is usually defined as "the probability of execution without failure for some specified interval of natural units of time" (Musa 1998).

To guarantee reliable sourcing and avoid any supply risk, companies have to select reliable actors of the SC for the success and the continuity of logistic operations. Reliable SC models are likely to perform well when a supply chain disruption occurs. Since facility location and supplier selection decisions involve long term planning, which are costly to implement and difficult to reverse, these strategic decisions allow for very little recourse once a disruption occurs, other than backup suppliers and re-assignment of customers to non-disrupted facilities. The main motivation behind the supply chain design using reliability-based optimization is then to choose reliable suppliers and facilities proactively so that the supply chain performs well if disruptions occur.

To the best of our knowledge, we are among the few researchers to present a novel approach to assess the reliability of supply chain actors, and propose accordingly an analytical model for reliable supply chains design that incorporate trade-off between cost and reliability to mitigate supply chain disruptions.

I. Introduction

Supply chain disruptions have a variety of sources and may take various forms. Disruptions due to demand-side and supply-side uncertainties are at the core of this work.

Nowadays, many cases are present in the literature showing the inability of traditionally designed supply chains to deal with disruptions due to inefficient management of unanticipated events.

Traditional models for the strategic design of supply chains focus on the cost-efficiency of the system, thus not considering redundancies in the form of multiple supplier arrangements and developing long-term relationships with a smaller supplier base, Nahmias (2001).

Supply chain management based on the assumption that every actor in the supply chain will always operate as planned, increases exposure and vulnerability to the risk of disruption. Several shortages and failures can severely affect supply chain efficiency due to uncertainties and unexpected events. Furthermore, once a disruption occurs, there is very little recourse regarding changing strategic decisions since these decisions can not be reversed or changed rapidly.

How can managers use historical data and expert judgment to assess the probability of disruption of each actor and how can they use this probability to build a reliable supply chain capable of resisting supply chain disruption?

The topics of supply risk assessment and reliable supply chain design have been largely unexploited. Discussion about risk mitigation and reliability of supply chain networks are in progress after recurrent disruptions that occurred in the last decade, leading to an increased consideration of risk and vulnerability in today's production-distribution networks. However, to date, only a few research publications have appeared that present analytical models dealing with reliable supply chain design under uncertainty. Reliability in the present work refers to the opposite of the failure of the supply chain. Thus, reliable supply chain design relates to a design that may resist to disruptions, especially those arising from supply-side and demand side uncertainties.

Furthermore, to the best of our knowledge, it is assumed throughout the literature that the reliability of supply chains actors is known and uses it to either, assess the whole supply chain reliability (Chen 2003), or optimize the whole supply chain reliability (Snyder 2005).

The goal of this section is to fill the gap in the assessment of SC actor reliability, by exploring approaches to assess reliability under uncertainty, and consequently by building a reliability optimization-based model for strategic supply chains design.

In this regard, our contribution can be summarized in two novel concepts:

- We assess the reliability of supply chain actors assuming uncertainties of solicitation and supply related to each actor, using the load/strength concept and the interference theory.
- We design reliable supply chains to mitigate risk of failure, i.e. building supply chains with enhanced reliability by ensuring the selection of reliable actors.

Reliability is commonly defined as the probability that a system or a component carries out its functions as intended within a specified time horizon. A system including different components can perform as intended if every component fulfils its functions stated by the whole system. Kuo and Zuo (2003), Andrews and Moss (2002).

In the context of supply chain management, supplier refers to the component, and supply chain to the system. No broad definition in the literature is given for supply chain reliability; nevertheless, existing definitions of supply chain reliability are presented from specific perspectives (e.g. minimizing the cost of failure (Sydner 2005), finding solutions that perform well when parts of the system fail).

Note that reliability is different of robustness in the context of this work. Generally speaking, "a supply chain is *robust* if it performs well with respect to uncertain future conditions; a supply chain is *reliable* if it performs well when parts of the system fail". (Snyder 2003).

Accordingly, supply chain reliability is the ability to perform well when not all entities or suppliers are operational.

Thomas (2002) points out that supply chain reliability is defined as the probability of the chain meeting mission requirements to provide the required supplies to the critical transfer points within the system.

Tomlin (2006) explores Contingency strategies under uncertain supply. The author presents various strategies for coping with disruptions, including inventory, dual sourcing, and acceptance (that is, simply accepting the disruption risk and not protecting against it), and shows that the optimal strategy changes as the disruption "profile" changes.

Daskin and Snyder (2005) present facility location problems to minimize the total failure cost of a SC.

A qualitative discussion of global supply chain design is given by Vidal and Goetschalckx (1997, 2000); the latter paper also presents a large-scale MIP for choosing plant locations and suppliers that incorporates the suppliers' reliability into the constraints.

As seen in the general introduction to this dissertation, reliability-based optimization is concerned with finding solutions that perform well under uncertainty.

In this chapter, we present a formulation for the strategic design of reliable supply chains. The proposed model is based on traditional supply chain design models, with new constraints to ensure a minimum reliability value for the supply chain actors.

The few models that deal with reliability optimization assure that reliability is known. In this work, before modeling reliable supply chains, we assess supplier reliability using an approach based on the load/strength concept.

The concept of load/strength was originally developed to evaluate the reliability of mechanical components when subjected to randomly occurring requests under conditions of random strength. We adapt this very important concept in our research to assess the reliability of supply chain actors.

We will explain in this work the analogy between SC actors and mechanical components in order to apply the load/strength concept to reliability measurement, in a context where the components or Sc actors receive requests to which they must react. Note that both requests and strength are generated randomly; they are statistically distributed using collected data and expert opinion.

For the sake of explanation, in a consistent manner throughout this chapter, we will use the term "supplier" in a large sense to represent any actor for the supply chain; therefore, it may refer to a raw materials supplier, a plant or a public warehouse.

The basic notions of the concept load/strength are introduced in the second section. In this section, we emphasize the manner characterizing the requests and the strength related to SC actor in search for the load/strength concept application.

To adopt some corrective measures to reduce supplier failure, we examine various possible scenarios.

The third section addresses the strategic design model of reliable supply chains. The last section presents a numerical example to illustrate the application of the proposed methodology.

II. Reliability and failure assessment: Interference Theory and load / strength concept

1. The basis of the concept load / strength

We should point out from the start that the proposed approach will be presented to assess both reliability and failure probability, since one can be inferred from the other. The disruption of each actor related to its inability to perform as planned will be represented by the failure probability derived from this approach.

The bases of the load/strength approach were introduced by several works (O'Connor (2002), Rao (1992)). According to Ait-Kadi and EL Khaïr EL Idrissi (2006) this method has been also used by Shooman (1990), Lewis (1994), Marcovici and Ligeron (1974), Ireson et al. (1995), Villemeur (1992), Kapur et Lamberson (1997), Chuech (1970) and Carter (1986).

It is also referred to in the literature as load-capacity interference, stress-strength relationships, or order-supply interference.

The load/strength approach was used to assess the reliability of mechanical systems which are subject to requests with random occurrence and whose strength is random.

Usually mechanical systems undergo different kinds of load when they are in function. For that reason, they require some strength to support the load of the external factors. Strength here is defined as the ability to support the exerted load.

The reliability of a mechanical system depends on its level of strength. Whether or not it fails depends on whether its strength is lower or higher respectively than the experienced load.

We explain briefly the main idea of the load/strength approach and the interference theory by using an example of a load-strength system, the same that was introduced by Rao (1992).

The basis principle of this theory is to compute the probability of failure, when the load and the strength parameters are not fixed but uncertain, and are defined with probability distributions.

As failures occur when loads are higher than strengths, the reliability of a load-strength system can be determined as the probability of the load being less than the strength.

The work of O'Connor (2002) also uses the interference theory to measure the reliability of a load-strength system. The author explains that a common cause of failure results from the situation when the applied load exceeds the strength. Note that load and strength are considered in the broadest sense. "Load" might refer to mechanical stress, or to internally generated stress, such as temperature. "Strength", might refer to any resisting physical property, such as hardness. According to the author, usually the load and the strength are not fixed, but are distributed statistically.

Load and strength interference is represented in the overlap area as described in figure 9. The interference area represents analytically the conditions of failure or unreliability, in opposite the reliability is represented by the value (1-the interference area).

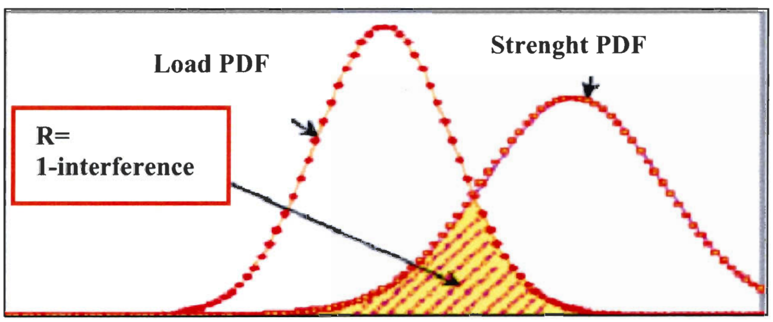


Figure 9 - The interference theory concept

The probability of failure of a load-strength system can be determined as the probability of the load being more than the strength. When loads vary on the lower side, everything is failure-free. When loads vary on the higher side, failures occur and reliability is lost. Similarly, when strength varies on the lower side, failures occur and thus reliability is lost. When strengths vary on the higher side, everything is failure-free.

O'Connor (2002) points out also that where loading irregularity is low (i.e. small standard deviation of loads) and strengths are well behaved (i.e., small standard deviations of strengths) and displaced widely to the right of the loads, we can achieve reliability since the overlap area, i.e. the probability of failure, will be low.

Assuming known probability distributions of load and strength, the reliability of the system is represented by the reliability that the strength exceeds the load. According to Rao (1992) the equation of reliability is:

$$R_s = \int_{-\infty}^{+\infty} f_s(s) \left[\int_{-\infty}^{s} f_L(l)dl \right] ds = \int_{-\infty}^{+\infty} f_s(s) F_L(s) ds$$

Where:

- $f_S(s)$ is the probability density function of the strength,
- $f_L(l)$ is the probability density function of the load, and
- $F_L(s)$ is the cumulative distribution function of the load in units of the strength.

The statement of unreliability 1- R is a statement of failure probability expressed by Rao as:

$$P_s = \int_{-\infty}^{+\infty} f_L(l) \left[\int_{-\infty}^{l} f_S(s)ds \right] dl = \int_{-\infty}^{+\infty} f_L(l) F_S(l) dl$$

Where: $F_S(l)$ is the cumulative distribution function of the strength in load units.

2. Assessing the reliability of Supply chain actors according to the load/strength concept

In this part of dissertation, we show the methodology to assess the reliability of SC actors using the load/ strength concept. We assume in this dissertation that all actors receive a solicitation and have a given strength to respond to this solicitation. In the next section we describe in details the assessment of the reliability of supplier, which we can easily extend to the other actors of the SC using the same concept. (Figure 10)

In figure 10, we recall the main sources of supply chain uncertainties, showing the position of load and strength according to each actor in the SC.

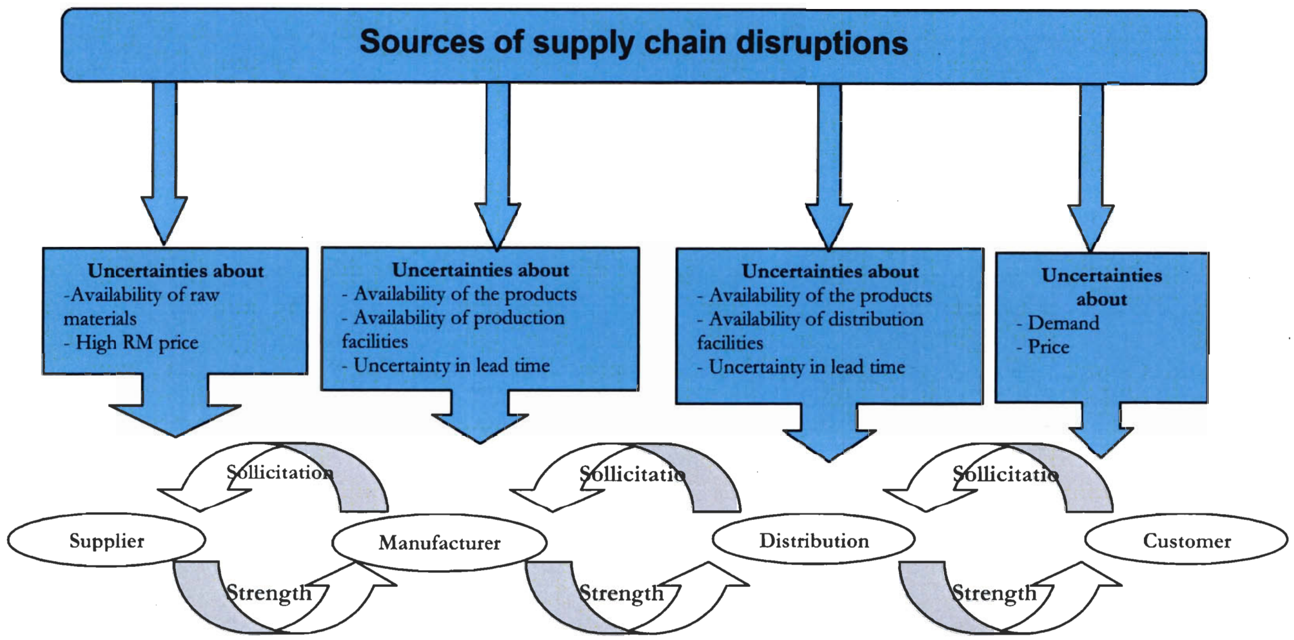


Figure 10 - Sources of supply chain disruptions

a. The concept load / strength applied to supplier

One way to consider supplier reliability is to use historical data to estimate the probability that a supplier will send timely and accurate shipments (Vidal and Goetschalckx, 2000). In this dissertation work, the proposed method for assessing the sourcing reliability of suppliers to satisfy the order makers' solicitation is based on the load/strength concept and the interference theory introduced by Rao (1992). This approach is usually applicable in the mechanical engineering field. Therefore this research work proposes an adaptation of the method of Rao (1992) to logistics, drawing an analogy between the mechanical system (the applied load and its strength) and the supplier (the solicitation and his strength or ability to respond to this solicitation).

"Solicitation" is characterized by the request of the company from its suppliers; it is represented in a broad sense and can cover several attributes (lead time, quality, quantity, etc).

"Strength" is characterized by the ability of the supplier to respond to the request of the company. The analysis of supplier strength must also be based on several criteria in order to be more representative. Thus, strength may also have different attributes (delivery time, quality, quantity, etc).

Thomas (2002) developed a method for quantifying the reliability of supply chains for contingency logistics systems based on the reliability inferred from the interference theory. However, the author assumes a very restricted case where we have a single supplier, and supply and solicitation are represented conventionally by sourcing and demand quantities (one attribute).

The interference theory will be used in this research work to compare the order maker solicitation and the supplier strength and to assess a ratio for each supplier expressing its sourcing reliability, i.e. its ability to respond to the order maker solicitation.

We focus on two key stages for the evaluation of the reliability of supply networks assuming uncertainty of solicitations and supply (strength). We generate a group of solicitations according to collected data and expert opinion, and then we check the strength of the suppliers to respond to these solicitations. Solicitations and strength are distributed statically since we assume their uncertainty. Accordingly, we attribute to each supplier a reliability measure based on the associated supply and solicitations, assessed by the interference theory.

Generally, we use the Bayesian approach to specify the distribution of random variables. In our case these variable are solicitation and strength. The approach consists in selecting the distribution (and its parameters) that best fits the collected and generated data using expert opinion.

- **Characterizing the suppliers' solicitation (load)**

The criteria for supplier evaluation are very numerous in the literature and are prioritized according to the strategic objectives of each company.

Several works present the various criteria of supplier evaluation (Barbarosoglu and Yazgac 1997, Cebi and Bayraktar (2003), Veram and Pullman (1998)).

An interesting work which is a reference cited among many papers dealing with supplier evaluation and selection problems, was due to Dickson (1966). Dickson in fact identifies 23 criteria for supplier evaluation.

According to Benyoucef et al. (2003), overall, the set of 23 criteria listed in the article of Dickson (1966) seems to cover most of the criteria presented in the literature until today. On the other hand, the evolution of the industrial environment has changed the relative importance of these criteria.

Therefore, to describe supplier solicitation, we can choose a variety of attributes among the cited criteria. It is up to the company to choose the most important criteria that match its objectives.

In addition, knowing that the competing strategy of the company is the way by which the company plans to reinforce its competitive position (to reduce lead times, to deliver products in time, etc), the evaluation and selection of the suppliers must be compatible with this strategy. Thus, the selected suppliers must be perfectly able to satisfy it. For example, a company with a strategy of differentiation by "delivery time" and which is in a market with unanticipated demand must choose a supplier who respects delivery times strictly.

On the other hand, if the strategy of the company is dominated by cost, it must seek suppliers who offer less expensive products which are not necessarily of good quality, or short delivery time. In conclusion, selecting the supplier who offers various advantages but who cannot reinforce the strategy of the company is not a judicious choice.

Therefore, suppliers must be evaluated according to the criteria which support the competitive strategy of the company.

Assume the solicitation attributes (or criteria) are:

- Type of product,
- lead time : the length of time the company is willing to wait until the order is shipped,
- quantity of the product ordered,
- price the company is willing to pay.

In this case, a new solicitation is a combination of different attribute values. For example the following perceived or intended order (company wants 110 units of the product in 12 days at 90$) is a kind of solicitation.

The solicitation is routed to the supplier and the proposed framework associates the fulfillment of the supplier to the solicitation according to the combination of attributes (price, lead-time, quantity, etc.).

- **Characterizing supplier strength**

"Strength" is characterized by the ability of the supplier to meet the request of the company. It is important to note that the reliability of suppliers should be based on strength evaluated according to several combined criteria.

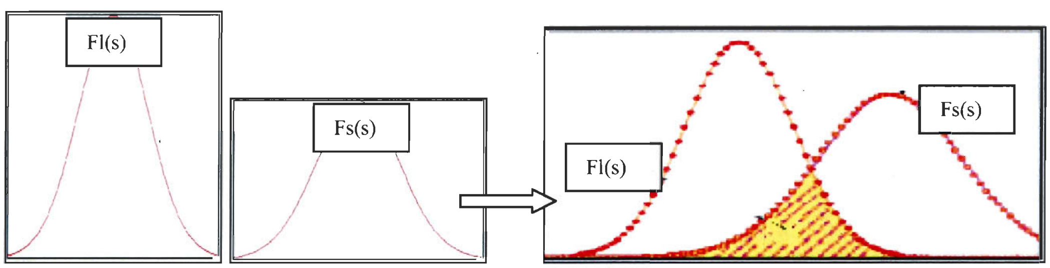
The proposed framework works as follows (see figure 11):

1) Collect historical data and expert opinion about possible attributes (e.g. lead time, quantity, price) for both sides: company solicitation and supplier strength.

2) Generate random samples from the data related to the company's solicitation and to supplier strength. The solicitation and strength are generated with a specific lead time, quantity, and price for a given product (attributes).

3) Compare the value of the combined solicitation attributes with the value of combined supplier strength attributes.

4) Evaluate the reliability of the supplier to respond to the company's order.



- $F_l\ (s)$ = the cumulative distribution function of solicitation (load) routed to supplier s
- $F_s\ (s)$ = the cumulative distribution function of the strength of supplier s
- P_s = failure probability of supplier s
- R_s = the sourcing reliability of supplier s

Figure 11- Using interference theory to assess suppliers sourcing reliability

Applying concepts of interference theory, we define a failure for supplier s as the event $\{S_S < L_s\}$; this is when the solicitation (load) exceeds the sourcing capability (strength) of supplier s. Failure is the inability of a supplier to respond to solicitation.

In contrast, the supplier's sourcing reliability refers to the probability of the event $\{L_S < S_s\}$. This represents his strength to respond to the solicitation.

In case of a continuous probability distribution, the reliability of supplier s (R_s) and the failure probability of supplier s (P_s) are, according to the interference theory, given by:

$$R_s = \int_0^{\infty} f_l(l)[\int_l^{+\infty} f_S(s)ds]dl$$

or

$$R_s = \int_0^{\infty} f_S(s)[\int_0^{s} f_l(l)dl]ds$$

Assuming that $f_l(.)$ indicates the function of density associated with the load, and $f_s(.)$ is associated to the strength.

In turn, as failure occurs as soon as load L exceeds strength S.The probability P of failure comes from the probability of all realizations when load L exceeds strength S:

$$P_s = \int_0^{\infty}[1 - F_l(s)]f_s(s)ds$$

and $F_l(s) = \int_0^{s} f_l(x)dx$.

According to Ait-kadi (2005) for a given component, the choice of the distribution $F_l(.)$ associated with load is deduced from an analysis of its mission profile. The distribution $F_s(.)$ of strength on the other hand, is obtained from test results carried out by simulation.

b. Corrective actions for the improvement of supplier reliability

To increase their efficiency and effectiveness, and thus their profitability, companies must cooperate with their suppliers. The result is that the efforts worked out to increase supplier reliability must be taken into consideration to better achieve the goals of the company. In this section, we will present some corrective actions to improve supplier reliability.

As seen above, probability of failure of a supplier can be determined as the probability of the load exceeding the strength.

The value of the standard deviation and the mean determine the area of interference and consequently the failure probability or the reliability of each supplier. If these parameters change, consequently the area of interference changes and so does the reliability and the failure probability.

We present here some economical and analytical phenomena that can impact on the shape and the position of the load or the strength curves, and consequently improve the reliability of the suppliers according to the firm's objectives.

Acting on standard deviation of loads and strength

O'Connor (2002) points out that where loading irregularity is low (i.e. small standard deviation of loads) and strengths are well-behaved (i.e., small standard deviations of strengths) and displaced widely to the right of the loads, we can achieve reliability since the overlap area, i.e. the probability of failure, will be low.

Here are some phenomena that can impact on the shape of the load or the strength curves in order to improve the reliability of the suppliers:

1. If the firm controls its processes well it can reduce the variance of the load such that the curves will be tighter. This can be achieved through various operations, such as:

   a. Having more accurate forecasts of demand. Accurate and timely demand plans are a vital component for effective supply chain management. Inaccurate demand forecasts typically result in supply chain disruptions. Accuracy of forecast is critical for resource allocation.

   b. Being proactive with respect to fluctuations in demand. Ultimately, to reduce costs and impacts of demand volatility, managers must shift from being reactive to being proactive decision makers in a market with unanticipated demand.

2. The supplier can control its processes to respond adequately to demand-side solicitation; consequently, its strength will have small standard deviations. This can be achieved through many operations (Barbarosoglu and Yazgac 1997), such as:

a. <u>Ensuring shipment quality</u>

   i. Reducing the percentage of defective incoming material detected by the incoming quality control, noticed during production, or returned from the customer;

ii. Encouraging lot certification: the practice of using reliable lot certification in all procurement transactions;

iii. Defective acceptance: reducing the percentage of defective material which can be tolerated in the final product;

b. Delivery

i. Conformity with quantity: the supplier should respect the predetermined order quantity within the tolerance limits;

ii. Conformity with due date: the supplier should respect the predetermined order due date within the tolerance limits;

iii. Conformity with packaging standards: the supplier's compliance with the packaging standards (dimension, labelling, etc.);

c. Cost analysis

Cost reduction activities: the actual cost reduction achieved by the supplier as a result of corrective actions and technological investments.

Acting on the position of the load and the strength curves

When loads vary on the lower side, everything is failure-free. When loads vary on the higher side, failures occur and reliability is lost. Similarly, when strength varies to the lower side, failures occur and thus reliability is lost. When strengths vary on the higher side, everything is failure-free.

In this paragraph, we present some phenomena that could have impact on the position of the load or strength curves in order to improve the reliability of the suppliers:

1 If the firm develops good partnerships with its suppliers it can reduce its expressed load for suppliers and so the load and strength curves will be separated making the load vary toward the lower side.

This can be achieved by enhancing manufacturing operations through the following adjustments (Barbarosoglu and Yazgac 1997):

i. Implementing effective production planning systems and developing improved communication with the supply level;

ii. Assigning the supplier reasonable lead-time;

iii. Extending preventive maintenance in order to ensure conformity between current and planned activities;

iv. Ensuring efficient plant layout from the material handling point of view;

v. Ensuring effective transportation, storage and packaging in order to reduce delivery time;

2 The supplier can control its process to respond adequately to demand side solicitation, so its strength will be enhanced and make the strength curve vary on the higher side. This can be achieved through many operations, such as (Barbarosoglu and Yazgac, 1997):

i. Process improvement and conformity with company specifications.

ii. Response to quality problems: the supplier's ability to solve quality problems detected by the company during audit, incoming quality control, production, or new product development;

iii. Design capability: the supplier's capability to develop a new design;

iii. Level of cooperation and information exchange: the supplier's cooperation and information exchange with the company about technical processes such as design, prototype building, die alterations, and other phases from design to production.

III. Modeling reliability optimization in the SCD context

1. Model assumptions

Once the reliability of each entity is assessed, we can formulate the reliability-based optimization model of supply chain design. Since any supplier failure or facility failure compromises supply chain reliability, the reliability of the whole supply chain is conditioned by each supplier's reliability.

The proposed model is based on known supplier reliability and reliability of facilities, and concerns reliable supply chain design through the selection of reliable suppliers and facilities.

The design of a reliable supply chain consists in enhancing supply chain reliability in order to perform well when disruption occurs by mean of the selection of reliable suppliers and facilities.

The term supply chain reliability is used to express the probability that a supply chain can completely fulfill the demand for a final product without any loss of supply resulting from failures of suppliers (Bundschuh 2003).

An extension to this definition we can define a reliable supply chain as one that is able to fulfill the demand for a final product without any loss of supply resulting from failures of suppliers and facilities.

a. The strategic design of reliable supply chains

The proposed model of the strategic design of reliable supply chains is based on common considerations of standard models of supply chain design related to supplier selection and facility location. Recall that the considerations of a standard supply design problem consist of minimizing the total of production and fixed costs subject to constraints on meeting the demand of the final product, flow equilibrium, supplier sourcing limitations and production capacity limitations. Besides these common considerations, the proposed model concerns the selection of reliable suppliers and facilities making a trade-off between reliability and incurred cost.

b. Objective function - Trade-off between reliability and cost

Assuming the negative correlation between cost and reliability, stipulating that the cheapest suppliers and lowest-cost facilities are not the most reliable ones, the aim of the proposed model is to guarantee a high level of reliability with the lowest possible cost. Hence, the proposed reliability-based optimization model of supply chain design consists in making a trade-off between the reliability of the set of suppliers and facilities which should be greater than a specific value and the costs of this reliability. This trade-off allows us to determine how significant a cost increase is required to add reliability to a system.

The extension of the standard model of SCD consists in assuming uncertainties of supply and solicitations, using the load/strength concept and the methodology of interference theory to measure the reliability of suppliers and facilities, and in proposing a model of reliable supply chain design, besides usual considerations, based on the reliable suppliers' selection problem by introducing redundancy (Figure 12).

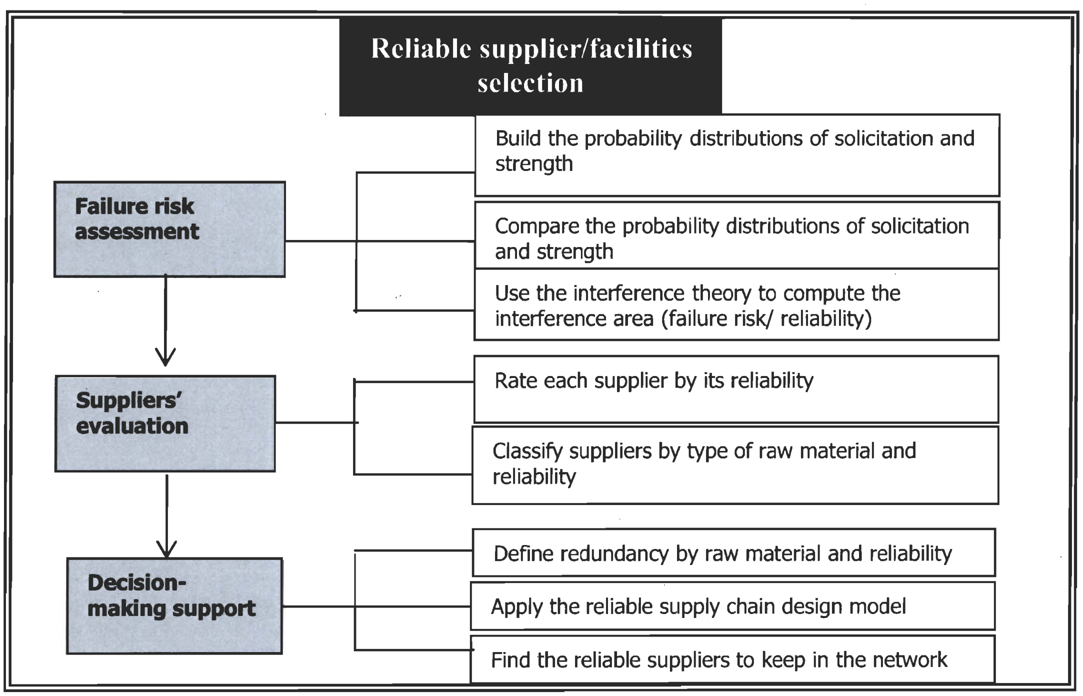


Figure 12 - Supplier selection process under uncertainty

The following subsections provide the relevant details of the proposed model. The features of the reliable supply chain design problem associated with the elements discussed above are explained.

c. Supplier assumptions

To mitigate supply chain disruptions coming from suppliers, companies develop various contingency strategies. These strategies accommodate or involve using alternative options of sourcing during disruptions. Of course, these options differ in terms of cost and the degree to which they protect from disruption, in other words of their ability to fulfill the demand.

Supplier redundancy

Snyder *et al.* (2006), explain that two main factors may be responsible for supply chain disruption or failure risk: demand uncertainty and supply uncertainty. According to the authors, disruptions induced by the supply-side uncertainties have more intense impact than disruptions coming from the demand-side ones. Backup suppliers and facilities play a vital role in mitigating supply chain disruption coming from supply-side uncertainties because they make it possible to cover the shortages produced by the primary supplier (or facility) to meet the demand.

Choosing a reliable actor who can play a backup role is an important decision for the company. For instance, in case of supplier failure or disruption, the manufacturer must reroute supply from the unreliable supplier to the reliable one. His decision is constrained by the cost of paying the reliable supplier and the degree to which the supplier hedges the disruption. Backup supply is assessed in terms of response time and volume provided. (Tomlin 2003)

For modeling requirements, backup suppliers are represented by a redundant system. A redundant system is shown in figure 13. For the system to succeed, one of its units at least must succeed. Redundant units are also referred to as parallel units. Redundancy is a very important aspect used to improve system reliability. It is used in many industries where reliability is expected.

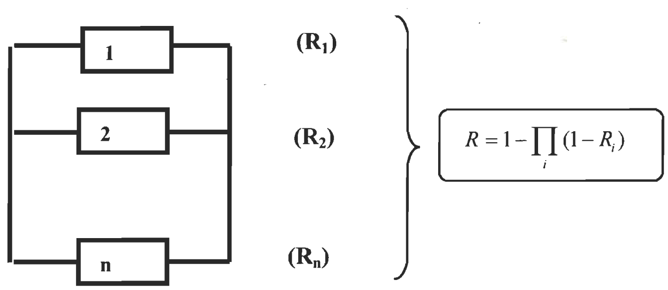


Figure 13 - A parallel system

Generally, redundancy aims to improve the reliability of systems. By multiplying the systems, we decrease the probability of failure through using the standby suppliers rather than relying completely on one of them. We apply this same principle of redundancy to the suppliers of a logistic network.

A very important point is to underline in this contribution. Usually, the duplicated elements are rigorously identical (e.g. suppliers of domestic markets), and sometimes deliberately different (domestic suppliers and international suppliers) to avoid the fact that, being sensitive to the same phenomena, they do not fail at the same time, to reduce the impact on the total reliability of the system.

Similarly, in case of supply chains, to counter the chance of some suppliers being unable to respond to the routed order, we multiply suppliers (for each raw material) in order to increase the overall reliability to meet the required demand. Drawing an analogy with mechanical systems, in order to increase the reliability of a sub-system, instead of increasing the strength of this sub-system, we multiply sub-systems having the same reliability to strengthen the overall reliability.

It is assumed that independence between suppliers is essential, each supplier have unlimited capacity and should be able to respond to the whole demand for a specific raw material.

In order to have enhanced reliability to satisfy the minimum level required, the company must base the selection of its suppliers on their individual reliability. Thus, we use a network made up of sub-networks of suppliers. The sub-networks are represented by the suppliers of the same raw material but with different levels of reliability to avoid simultaneous failure in the case of sensitivity to the same phenomena. Thus in the case of failure, if a primary supplier is not able to satisfy the standards of the order routed to him, the back up suppliers of the same sub-network are ready to support this order to absorb the arising risk. This is what motivates the use of a network of suppliers made up of sub-networks of backup suppliers.

Generally, companies must have contingency plans and alternative suppliers, alternative transportation modes and alternative warehouses to which they can resort when their supply chains are disrupted.

There are other contingency strategies for the compensation of supply in case of disruption. Sheffi (2001) proposes strategic emergency buffers which are used only in case of a supplier disruption. These buffers contain critical supply items needed for the production of additional components to compensate for a loss of supply. Unlike conventional safety stock, the author explains that strategic emergency buffers are not used to hedge against stochastic demand. The author points out that using strategic emergency buffers alone is a very expensive to guarantee sufficient loss compensation.

Redundancy is used to spread risk. Unless all suppliers on a stage fail simultaneously, the failure of one or more suppliers does not lead to a complete shortage of supply, but still reduces the total available supply. This supplier sourcing limitation can be eliminated by using emergency buffers proposed by Sheffi (2001), which further improves the mean output and the standard deviation of the output.

Navas (2003) gives an example of car manufacturers, which have started to build up pools of secondary suppliers to mitigate the risk of primary supplier failure.

Constraints of supplier selection

We present in this paragraph the group of constraints of suppliers' selection which is composed of many equations and inequalities. Note that for symbols explanation we refer the author to details in the proposed model.

$$\sum_{s \in S^{o}_{pv}} F_{pvs} \leq O_{pvt} \times y_{v} \qquad p \in RM, v \in V_{p}$$

- This set of inequalities assures limits of supply for each supplier and for raw material, and assures that the flows emanated from the supplier are conditioned by its selection.

$$1 \leq \sum_{v \in V_p} y_v \leq w_p \qquad p \in RM$$

- This constraint uses bounds to limit the number of suppliers for each type of raw materials.

$$1-\prod_{f\in F_p}(1-P_f)^{x_p^f} \geq R_{\min}^{pv} \qquad \forall p\in RM, v\in V_p$$

$$\Leftrightarrow\left[\sum_{f\in F_p} x_p^f \ln(1-P_f) \leq \ln(1-R_{\min}^{pv}) \qquad \forall p\in RM, v\in V_p\right]$$

• This constraint assumes that the reliability of the whole redundant network should be at least equal to the minimum required reliability.

$$\sum_{v\in V_p^f} y_v = x_p^f, \forall f\in F_p \qquad \forall p\in RM$$

• That equation assures that the number of selected suppliers is equal to the number of backup suppliers.

$$L_p^f \leq x_p^f \leq N_p^f \qquad \forall p\in RM, \forall f\in F_p$$

• These inequalities put bounds to limit the number of backup suppliers.

d. Facilities assumptions and reliability constraints

Facilities assumptions

In addition to reliable supplier selection, the model we attempt to build aims to locate reliable facilities. Facilities which are reliable and disruption-resistant are preferred and chosen over others according to their level of reliability.

Similarly with suppliers, facilities must be chosen through several criteria. We will summarize the key considerations in selecting facility sites. While some criteria have remained the same, such as cost and transportation access, other criteria and considerations have emerged as the mission and needs of warehouse and distribution centres have evolved.

Based on the review of the literature and some managerial research reports, the key considerations in site selection for warehouses and DCs are:

- Properties of the appropriate size: The future warehouse needs (in terms of space for facilities, utilities, tenants, etc.) drive the size of the property required.

- The ability to expand is also a key consideration in site selection. Sufficient space must exist on the site for track staging. Furthermore, room for expansion must exist on the property, either through expansion into additional segments of the building or through the construction of an addition to the structure.

- Consolidation accessibility. Companies should not move their warehousing operations nor should they be located in scattered sites.

- The operating cost of a typical DC. The cost of the property, including the cost of proposals (labour, land, facilities, utilities, taxes, and transportation), permits and site preparation are an overriding consideration.

- Property conditions, such as the existence of wetlands or environmental contamination, factor into site considerations. The primary concerns are the cost and time involved in the mitigation of environmental contamination, or the need for pilings.

- The distance separating customers from DCs. Nearly all of the shipments leaving warehouses and DCs depart in trucks. Access to the major highways is essential. Ease of access, including the conditions of local roads connecting to the highways, is a key consideration in site selection.

- The ability to provide the best service to all points connected to it.

- Availability and access to labour. Warehouses undertaking several value added activities require a greater number of workers. A tight labour market can make labour availability a critical issue. Among warehouses, ones use vans to transport workers from urban areas to their locations.

Constraints on facility reliability

When a facility is disrupted, the customers might be served by the backup facility that is not disrupted and still operational.

$$1-\prod_{f\in F_s}(1-P_f)^{\hat{x}_p^f} \geq R_{\min}^{ps} \qquad \forall p\in MP, \forall s\in S_p$$

$$\Leftrightarrow \left[\sum_{f\in F_p}\hat{x}_p^f \ln(1-P_f) \leq \ln(1-R_{\min}^{ps}) \qquad \forall p\in MP, \forall s\in S_p\right]$$

• This constraint assumes that the reliability of the whole redundant network compound of all facilities should be at least equal to the minimum required reliability).

$$1 \leq \sum_{s \in S_p} \hat{y}_s \leq \hat{w}_p \qquad p \in MP$$

$$\sum_{s \in S_p^f} \hat{y}_s = \hat{x}_p^f \qquad \forall p \in MP, \forall f \in F_p$$

$$\hat{L}_p^f \leq \hat{x}_p^f \leq \hat{N}_p^f \qquad \forall p \in MP, \forall f \in F_p$$

• These equations put limits for the number of selected facilities and assure that this number is equal to the number of backup facilities. The last one limits the number of backup facilities.

Note that for symbols explanation we refer the author to details in the proposed model.

2. An optimization reliability-based model for supply chain design

In this section, we outline a number of extensions to the base models of supply chain design dealing especially with facility locations and supplier selection. The proposed model will allow for selection of reliable suppliers among a set of backup (redundant) suppliers, besides allowing us to locate reliable facilities.

The problem of supply chain design concerns the strategic configuration of the supply chain; the related planning horizon is about five years or more, while the operational costs are typically determined on an annual basis.

The strategic variables concern the entire planning horizon, and the operational variable concerns the separated periods.

All customer requests must be fully satisfied. All costs are expressed in terms of a single currency. All transportation and production costs are linear functions of the quantities produced or transported.

To model the risky nature of the real-world data, we assume that suppliers are evaluated on the basis of uncertain demand and sourcing with continuous probability distributions.

After we compute the reliability of suppliers to respond to the variability in demand, we will solve the supplier redundancy allocation model and capacity options' selection.

We assume that we have a supply network composed of several categories of suppliers; each corresponds to a reliability level. These levels are computed from the interference theory and correspond to the sourcing reliability of suppliers. Hence, each supplier provides a specific raw material and belongs to a specific category (reliability level).

Moreover, we have the following additional basic assumptions and characteristics on which the model is to be based:

a. The Assumptions

- A category comprises a set of suppliers with the same reliability level and the same raw material. We assume that suppliers of the same raw material and the same category have the same reliability level.
- We can find the same supplier in several categories according to the raw materials provided. Each supplier can have a distinct reliability level for each raw material.
- Each supplier is identified by the combination (raw material, reliability level).
- A supplier may or may be chosen by the model; furthermore, it may be chosen by the model to supply one or more raw materials.
- If a given supplier is not chosen by the model, in other words if it does not satisfy the required level of reliability, it will not be considered in the supply network, and its supply should be assumed by other suppliers of the network belonging to the same category. Unless the other suppliers of the same category cannot cover its offer, the supplier will be kept in the network, even if its reliability is not sufficient, because no supplier can replace its offer.
- The proposed approach allows for tradeoffs between the cost of reliability of backup suppliers and the reliability level to be reached, assuming a supply network with a minimum level of reliability. Moreover, it allows for the best tradeoffs between the strategic investment, through implanting capacity options, and the incurred strategic and operational costs.
- We must therefore find a balance between minimizing the cost of improving reliability, operational and strategic costs, and choosing the most reliable suppliers and facilities to keep in the network and capacity options to implement.

- We define the model parameters and decision variables in the following subsections.

b. Model parameters and decisions variables

Model parameters

- S =Potential network sites (s ∈S)
- Sp =Potential production center sites
- Sd =Potential distribution center sites
- D_p =Set of demand zones of product p
- V =Set of all suppliers
- S^f_p = Set of sites producing or shipping product p, and having reliability f
- S_p = Set of suppliers of raw material p
- S^o_{ps} = Set of potential sites (output destinations) which can receive product p from site s
- S^i_{ps} =Set of potential sites (input sources) which can ship product p to site s
- V_p =Suppliers of raw material p ∈RM
- v^f_p =Suppliers of raw material p ∈RM having reliability f
- D_{pd} =Demand of product p by demand zone d
- M_{pv} =Maximum quantity of raw material p which can be supplied by supplier v
- N^f_p =Number of available standby (redundant) suppliers for reliability category f and raw material p
- L^f_p =Lower bound on the number of standby (redundant) suppliers for reliability category f and raw material p
- $\hat{N}^f_p$ = Number of available standby (redundant) facilities for reliability category f and product p
- $\hat{L}^f_p$ =Lower bound on the number of standby (redundant) suppliers facilities for reliability category f and product p
- $R^{ps}_{\min}$ = Minimum reliability required for site s and product p
- $R^{vs}_{\min}$ = Minimum reliability required for supplier v and product p
- P_f = Reliability of category f
- C_v = Capacity of supplier v
- P_{pv} / P_s = Cost of supply of raw material p by supplier v/Cost of opening site s
- c^f_p = Cost of adding reliability to the system for raw material p and for reliability category f
-
- $\hat{c}^f_p$ = Cost of adding reliability to the system for product p and for reliability category f
- RM =Raw material families.
- MP =Manufactured product families, i.e. sub-assemblies and finished products.
- SA = Sub-assemblies families (SA⊂ MP)
- FP =Finished products (FP⊂ MP)
- J =Potential capacity options

- J_s =Potential capacity options which can be installed on site s (e.g.: *statu quo*, purchase a new equipment, reconditioning an existent equipment, replacement of an equipment, *etc.*).
- c_j =Capacity provided by option j
- c_s =Capacity available in site s
- $g_{pp'}$ =Quantity of product p needed to make one product p'
- e_j =Area required to install capacity option j
- E_s =Total area of the site s
- c_{ps} =Production variable cost of product p in site *s*
- f_{psn} =Unit cost of the flow of product p between node n and site s
- A_s =Fixed cost of using site s for the planning horizon
- a_j =Fixed cost of using capacity option j for the planning horizon
- w_p =The maximum number of suppliers for product p

Decision variables

x_p^f = Number of standby (redundant) suppliers of raw material p and reliability f

y_v = Binary variable corresponding to supplier v selection

$\hat{x}_p^f$ = Number of standby (redundant) facilities of product p and reliability f

$\hat{y}_s$ = Binary variable corresponding to facility s selection

X_{ps} = Quantity of product p produced in plant s

$F_{pnn'}$ = Flow of product p between node n and node n'

Z_j = Binary variable equal to 1 if capacity option j is installed and to 0 otherwise.

c. The proposed model

$$Min \quad Z1$$

$$Z1 = \sum_{p \in P} \sum_{(n,n')} f_{pnn'} . F_{pnn'} + \sum_{s \in Sp} \sum_{p \in MP} c_{ps} X_{ps} + \sum_{s \in S} \sum_{j \in J_s} a_j Z_j + \sum_{p \in RM} \sum_{v \in V_p} p_{pv} y_v + \sum_{p \in MP} \sum_{s \in S_p} p_s y_s + \sum_{p \in RM} \sum_{f \in F_p} c_p^f x_p^f + \sum_{p \in MP} \sum_{f \in F_p} \hat{c}_p^f \hat{x}_p^f$$

- Demand constraints (1)

$$\sum_{s \in S_{pd}^i} F_{psd} = D_{pd}, \qquad p \in MP, d \in D_p$$

- *Constraints of suppliers' selection* (2)

$$\sum_{s \in S_{pv}^{o}} F_{pvs} \leq M_{pv} \times y_v \qquad p \in RM, v \in V_p$$

$$1 \leq \sum_{v \in V_p} y_v \leq w_p \qquad p \in RM$$

$$1 - \prod_{f \in F_p} (1 - P_f)^{x_p^f} \geq R_{\min}^{pv} \qquad \forall p \in RM, v \in V_p$$

$$\Leftrightarrow \left[\sum_{f \in F_p} x_p^f \ln(1 - P_f) \leq \ln(1 - R_{\min}^{pv}) \qquad \forall p \in RM, v \in V_p \right]$$

$$\sum_{v \in V_p^f} y_v = x_p^f \qquad \forall p \in RM, \forall f \in F_p$$

$$L_p^f \leq x_p^f \leq N_p^f \qquad \forall p \in RM, \forall f \in F_p$$

- Constraints of facilities' selection (3)

$$1 \leq \sum_{s \in S_p} \hat{y}_s \leq \hat{w}_p \qquad p \in MP$$

$$1 - \prod_{f \in F_s} (1 - P_f)^{\hat{x}_p^f} \geq R_{\min}^{ps} \qquad \forall p \in MP, \forall s \in S_p$$

$$\Leftrightarrow \left[\sum_{f \in F_p} \hat{x}_p^f \ln(1 - P_f) \leq \ln(1 - R_{\min}^{ps}) \qquad \forall p \in MP, \forall s \in S_p \right]$$

$$\sum_{s \in S_p^f} \hat{y}_s = \hat{x}_p^f \qquad \forall p \in MP, \forall f \in F_p$$

$$\hat{L}_p^f \leq \hat{x}_p^f \leq \hat{N}_p^f \qquad \forall p \in MP, \forall f \in F_p$$

- *Constraints of flow equilibrium of raw materials* (4)

$$\sum_{n\in V_p} F_{pns} - \sum_{p'>p} g_{pp'} X_{p's} = 0 \qquad s \in Sp, p \in RM$$

- *Constraints of flow equilibrium of sub-assemblies products*

$$X_{ps} + \sum_{n\in S^i_{ps}} F_{pns} - \sum_{n\in D_p \cup S^o_{ps}} F_{psn} - \sum_{p'>p} g_{pp'} X_{p'k\,s} = 0 \qquad s \in Sp, p \in SA$$

$$\sum_{n\in S^i_{ps}} F_{pns} - \sum_{n\in D_p \cup S^o_{ps}} F_{psn} = 0 \qquad s \in Sd, p \in SA$$

- *Constraints of flow equilibrium of finished products*

$$\sum_{n\in D_p} F_{psn} - X_{p\,s} = 0, \qquad s \in Sp, p \in FP$$

$$\sum_{n\in S^i_{ps}} F_{pns} - \sum_{n\in D_p} F_{psn} = 0 \qquad s \in Sd, p \in FP$$

- *Constraints of production capacity* (5)

$$\sum_{p\in P_s} X_{ps} - \sum_{j\in J_s} c_j Z_j \leq 0 \qquad s \in Sp$$

- *Constraints of capacity options* (6)

$$\sum_{j\in J_s} c_j Z_j - c_s Y_s \leq 0, \quad s \in S$$

$$\sum_{j\in J_s} e_j Z_j - E_s Y_s \leq 0, \quad s \in S$$

- *Constraints of capacity options selection* (7)

$$\sum_{j\in J_s} Z_j \leq 1, \qquad s \in S$$

$y_s \in \{0, 1\}\ \forall s \in S$; $x_p^f \in \{0,1\}\ \forall p \in P\ \forall_f \in F$; $\hat{y}_s \in \{0, 1\}\ \forall s \in S$, $\hat{x}_p^f \in \{0, 1\}\ \forall p \in P\ \forall_f \in F$;

$Z_j \in \{0, 1\}\ \forall j \in J$; $X_{ps} \geq 0\ \forall\ (p,s)$; $F_{pnn''} \geq 0\ \forall\ (p,n,n')$.

The objective function consists of the minimization of costs incurred along the logistic network. In particular, the minimization of reliability cost for redundant suppliers and redundant facilities. In addition, it incorporates costs of implanting capacity options, transportation costs associated with flows, and production costs.

- Equation (1) represents the demand constraint for each product.

- The group of constraints of suppliers' selection (2) is composed of many equations and inequalities:

  - The first set of inequalities assures limits of supply for each raw material and each supplier, and assures that the flows emanated from the supplier are conditioned by its selection.

  - The second constraint uses bounds to limit the number of suppliers for each type of raw material.

  - The third constraint assumes that the reliability of the redundant network should be at least equal to the minimum required reliability.

  - The fourth equation assures that the number of selected suppliers is equal to the number of backup suppliers.

  - The fifth equation limits the number of backup suppliers.

- The constraints set (3) correspond to "facility selection":

  - The first constraint uses bounds to limit the number of facilities for each product.

  - The second constraint assumes that the reliability of the standby (redundant) network compound of all facilities should be at least equal to the minimum required reliability.

  - The third equation assures that the number of selected facilities is equal to the number of backup facilities.

  - The fourth constraint limits the number of backup facilities.

- The constraints set (4) correspond to flow equilibrium of different product categories. "p'>p" means that the product p is a component of product p'.

- Equations (5-7) represent the capacity options to be implanted in each site in terms of quantity and area.

IV. Numerical example for reliability assessment

For the sake of simplicity and without loss of generality the example will cover the case of conventional suppliers, i.e. suppliers of raw materials and semi-finished products. Of course, with little change we can extend the example to the other SC actors (plants and DCs). We progressively explain the application of the proposed methodology of order-supply interference.

1) Collect data

We assume that the order attributes are:

- Type of product,
- lead time : the length of time the company is willing to wait until the order is shipped,
- quantity of the product ordered,
- price the company is willing to pay.

We first collect historical data and expert opinion about the attributes (lead time, quantity, price) for both sides: supply and order, and next generate random samples from these data.

In this case, a new order is a combination of different attributes' values. For example the combination: (manufacturer wants 110 units of the product in 12 days at 90$) is a kind of order.

We have the same thing for the supplier supply. For example the combination: (supplier can deliver 10 units of the product in 5 days at 87$) is a sort of supply.

Without loss of generality, the attributes are assumed to be lead time, quantity, and price. For most realistic cases, one needs to consider several other quantitative and qualitative attributes in addition to lead time, quantity, and price (e.g., quality, technology, etc).

We consider the case where there is only one product that is supplied by suppliers. We assume that the suppliers are capable of supplying different quantities of the product with different lead-times and prices. There can be similarity in price/quantity/lead-time combinations over several suppliers.

The data of this example is inspired from the work of Emerson and Piramuthu (2004).

Tables I5 provide the information for the ranges of attribute values for the order and the supply related to supplier1.

Tables 15 - Order and supply information for supplier 1

Order	Lead time	Quantity	Price
1	1-5	1-30	97$
2	6-10	1-70	95$
3	11-15	1-100	93$
4	16-20	1-150	90$

Supply	Lead time	Quantity	Price
1	1-5	1-30	97$
2	6-10	1-70	95$
3	11-15	1-100	93$
4	16-20	1-150	90$

The data in table 15 are read as follows:

- The first line of the second indicates that the supplier can supply up to 30 units of product with a lead-time of 1-5 days at a price of 97$.

- Similarly, the last line states that the supplier can supply up to 150 units of product with a lead-time of 16-20 days at a cost of 90 $.

We assume that the supplier 1 and the company have agreed on the same values, which leads to the fact that the two sub-tables above are identical.

The proposed framework picks several combinations of lead-time, quantity, and price. The solicitation and supplier strength generators generate the manufacturer's orders and the supply of supplier1, with a specified lead time, quantity and price for a given product (attributes).

We use the data in Tables 15 to generate examples for both orders and for the supply of supplier1. We generate examples by randomly sampling in the ranges 1-20 and 1-150 respectively for lead time and quantity values and choosing the appropriate price values.

The following are possible examples for either order or supplier strength:

(Lead Time = 3) & (Quantity = 30) & (Price = 97)

(Lead Time = 7) & (Quantity = 50) & (Price = 95)

(Lead Time = 12) & (Quantity = 70) & (Price = 93)

2) *Generating the probability distributions of order and supply*

In realistic situations, clearly the supplier may or may not respond to these circumstances. Although these circumstances are close to the real behaviour of the supplier, however, this combination of conditions is rarely met in most real-world situations. Therefore, it is necessary to be able to dynamically deal with variations due to mismatches in supply and demand. That is why we assume that the supplier's sourcing can not be realized with certainty.

We therefore build the distribution probabilities based on the picked combinations according to the data collected (table 16).

The distribution $F_o(.)$ of order is obtained from orders generated randomly. The probability distribution $F_s(.)$ of supply is obtained from test results carried out by simulation.

Table 16 - The order routed to the supplier

Order	Lead time	Quantity	Price	Probability
1	3	30	97$	0.7
2	7	50	95$	0.2
3	12	70	93$	0.8
4	19	120	90$	0.5

The order is routed to the supplier, and the proposed framework associates the fulfillment of the supplier to the order according to the combination of attributes (price, lead-time, quantity, etc.). We consider the respective distribution of probabilities.

Table 17 provides discrete probability occurrences for some values of solicitation and supplier strength.

Table 17 - Probability occurrences of order and supply

Supply	Lead time	Quantity	Price	Probability
1	2	30	97$	0.5
2	7	50	95$	0.6
3	13	70	93$	0.7
4	18	120	90$	0.5

The data in table 17 are read as follows:

- For example, the first lines of the two tables indicate that the manufacturer might order 30 products to be dispatched within 3 days at 97$, with probability 0.7. On the other hand, the supplier could respond to this intended demand with probability 0.5.

- Similarly, the last lines of the two tables state that the manufacturer might order 120 products to be dispatched within 19 days at 90$, with probability 0.5. On the other hand, the supplier could respond to this pattern combination with probability 0.5.

There are cases, however, where the company might want a large quantity of the product in a short time.

For example, at line 3 if a solicitation requires 70 products to be delivered in 12 days, it might not be feasible for the supplier. In such cases, the suppliers certainly cannot fulfill the order, consequently supply probability=0.

3) Assessing supplier reliability

We compare the probabilities of the same values of the combination order attributes to the supply attributes one.

Table 18 presents supplier capability compared to generated order according to the attributes (lead time, quantity, price) and the consequent state of failure or success.

Table 18 - supplier capability compared to order

Scenarios for the attributes (Lead time, quantity, Price)	Order values	Supply values	Failure/ success (-/+)
1	(3, 30, 97, 0.7)	(2, 30, 97,0.5)	+
2	(7, 50, 95, 0.2)	(7, 50, 95, 0.6)	+
3	(12, 70, 93, 0.8)	(13, 70, 93, 0.7)	-
4	(19, 120, 90, 0.5)	(18, 130, 90, 0.5)	+

An example of comparison between order values and supply values, using lead-time, quantity, and price information is as follows:

1. For scenario 1, the order values are (3, 30, 97):

As (LeadTime ≤ 3) <u>and</u> (Quantity ≥ 30) <u>and</u> (Price ≤ 97) <u>and</u> order probability po ≠ 0 <u>and</u> supply probability ps ≠ 0, THEN the combination value falls in the interference area, so related probabilities (order and supply) are considered for reliability assessment.

2. For scenario 3, the order values are (12, 70, 93):

Since (LeadTime > 12) <u>and</u> supply probability ps = 0, THEN the combination value does not fall in the interference area, so it is not considered for reliability assessment.

The multiplication of non-zero probabilities related to the same attribute values composes the area of interference.

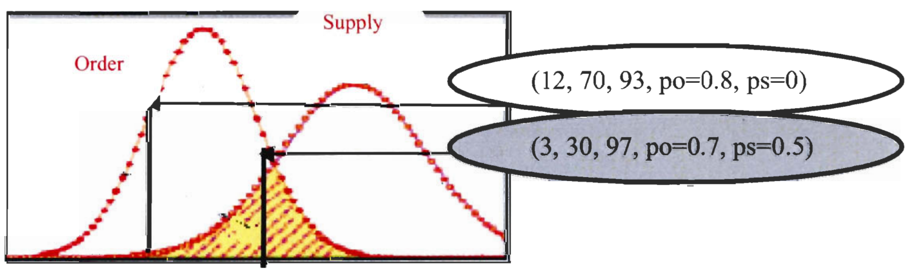


Figure 14 - Assessing supplier reliability

The area of interference in figure 14 gives the possibilities where order can exceed supply; it represents risk failure (1-reliability) of the supplier to respond to the routed order (solicitation).

From the occurrences of order and supplier probabilities examined in the example, we compute:

- Failure probability =0.7×0.5+0.2×0.6+0.5×0.5=0.089

- Supplier reliability =0.911

Conclusion

In this context of enlarged logistics, satisfying customers depends crucially on reliable sourcing. Thus, taking into account the reliability of the actors in supply chain design problems is an important factor for the competitive advantages of companies.

In this work, emphasis is placed on SC actor reliability assesment using the concept of load/strength. Note that solicitation is generated randomly; moreover, both solicitation and strength are statically distributed using collected data and expert opinion.

The basic notions of the concept load/strength are introduced and the manner characterizing the solicitation and the strength is investigated to assess the reliability using the interference theory.

After the assessment of supplier reliability using the load/strength concept, we formulate a model of reliable supply chain design (Figure 15).

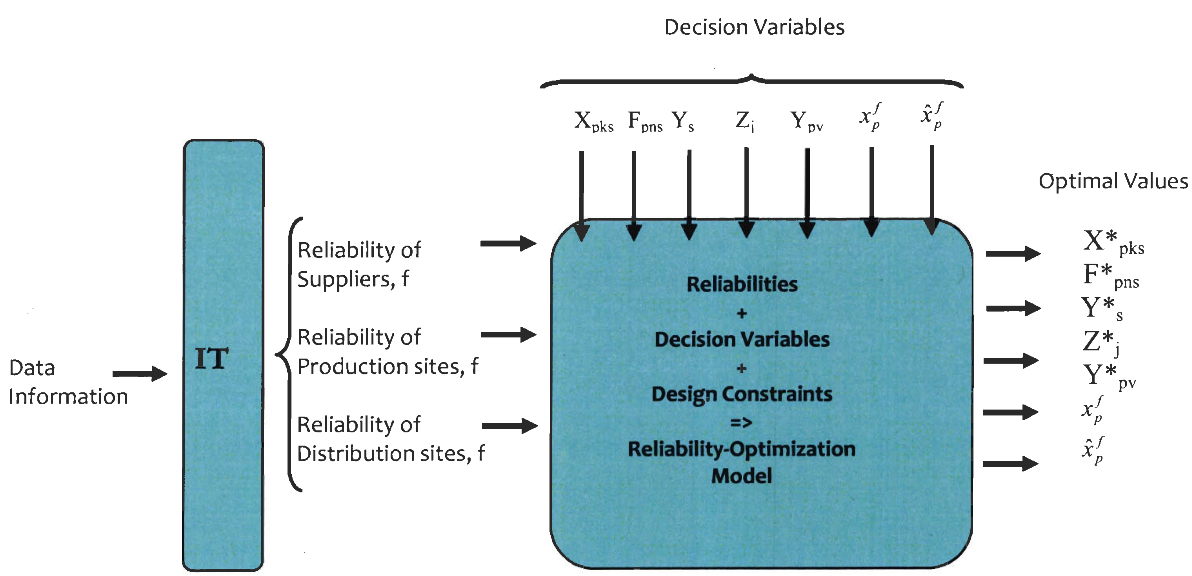


Figure 15- Model of reliability optimization in supply chain design

The approach based on the Interference Theory allows to assess the reliability R of a component subjected to constraints (load) L having random occurrence and intensity are and whose strength S is also a random variable.

The reliability of such a component is given by:

$$R = P\{\, l < s \,\} \qquad (1)$$

Failure will occur as soon as load L exceeds strength S of the component. The probability F that such an event is carried out is given by:

$$F = P\{l \geq s\} \qquad (2)$$

Assuming that $f_l(.)$ indicates the function of density associated with the load, and $f_s(.)$ is associated to the strength. Thus, the expression of reliability R is given by:

$$R = \int_0^{\infty} f_l(l)[\int_l^{+\infty} f_s(s)ds]dl \qquad (3)$$

or

$$R = \int_0^{\infty} f_s(s)[\int_0^{s} f_l(l)dl]ds \qquad (4)$$

The probability F of failure is given by:

$$F = \int_0^{\infty} [1 - F_l(s)] f_s(s)ds \qquad (5)$$

$$F_l(s) = \int_0^{s} f_l(x)dx \cdot$$

Since the component can be only in operation or out of use, one can write:

$$R + F = 1 \qquad (6)$$

Knowing the functions of density $F_s(.)$ and $f_l(.)$, it is possible to calculate the reliability R of the component using the relation (4) or (5) and (6). In the general case, one uses numerical procedures to calculate R and F. Numerical results were obtained by Kapur and Lamberson (1977), for various probability distributions generally used of reliability, such as: exponential, extreme Gamma, Weibull, Normal, and lognormale.

According to Ait-kadi (2005) for a given component, the choice of the distribution $F_l(.)$ associated with load is deduced from an analysis of its mission profile. The distribution $F_s(.)$ of strength on the other hand, is obtained from test results carried out by simulation.

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CONCLUSION
AND FUTURE RESEARCH FEATURES

I. General conclusion

1. The importance of improving supply chain performance and reliability

Much of the prior research concerning the measurement of supply chain performance has focused on the development of models which make emphasis on cost reduction or profit improvement. In the actual context of globalisation and markets competition, which make uncertain the operational environment, companies should not only focus on those two elements and ignore the importance of the eventual impacts of unpredictable events such supply shortage resulting from unreliable partners. Unreliable partners and suppliers (in terms of bad quality, long lead time, etc.) could affect more than high costs the long term objectives of the company.

Hence, an overall model that provides a global approach for improving and controlling the whole performance and reliability of the supply chain including all its entities, from suppliers through distribution centers to plants, should be a better alternative for improving supply chain performance.

The process of choosing appropriate supply chain performance measures is difficult due to the complexity of these systems. Furthermore, each performance measure depends on several and various types of performance criteria (cost, quality, lead time, etc). That's why, performance criteria selection becomes a crucial step in the process of evaluation of supply chain performance.

This research proposes a selection model of reliable supply chain entities to simultaneously achieve a high level of efficiency in terms of cost reduction and a high level of customer service by choosing reliable suppliers.

The research presented here goes beyond the previous work by allowing the development of a global framework for the selection of reliable supply chain entities. The research begins with the categorization of supply chain performance criteria and measures in order to choose the suitable ones to use for the proposed model.

Hence, the chapter presents an overview and an evaluation of the performance criteria and measures used in supply chain selection models. Therefore, we used AHP to compute delivery and quality rates and introduced them into the proposed model which is a selection model for robust supply chain entities.

Supply chains that utilize this framework can more completely improve the performance of their supply chain system.

2. Dealing with presence of risks in supply chain

A number of trends during the last decade, like globalisation, hard competition, and outsourcing, have made the supply chain activities from first supplier to end customer changing increasingly in order to be adjusted to the environment changes.

Consequently, the context of supply chain operations is gaining large scale, since it is operating with various partners and extending its entities over the world.

Those alterations make the supply chain more complex and more vulnerable. Unfortunately, in the actual business context, many accidents could affect the supply chain performance for a variety of reasons. Examples of possible accidents include equipment failures, supply shortage, unpredictable customer behaviour change, natural disasters (such as earthquakes), human errors, and failure of operating procedures.

As the business context becomes more diversified, the potential consequences of those accidents become more severe.

Those accidents can be extremely costly, not only to the owner of the specific facility where the accident occurred, but also to the entire industry and in some cases to society as a whole. The diversification of its processes and business relationships increases, unfortunately, the possibility of the supply chain exposure to various disruptions, compelling the companies to find alternative methods to deal with their vulnerability.

A number of trends were mentioned that make the supply chain more vulnerable. Besides internal drivers (increased complexity, over-concentration of operations, poor planning and execution, etc.) there are external drivers (competitive environment, disasters, etc.). With diversification of those external and internal drivers the supply chain becomes more exposed to risks and tends to become more vulnerable than before.

A necessary first step in dealing with vulnerability and risk reduction efforts is to identify the risks related to the system and get sufficient knowledge about them. We can identify risks through audits, brainstorming, expert judgement, surveys, examining the occurrence frequency of previous events, examining local and overseas experience, etc.

The following step consists of sorting and categorising risks through the main categories. After that, we quantify risks by assigning a weight to each risk which describes the probability of its occurrence using Bayesian approach. Next we prioritizing risks, for each category of risks we classify those through their priority. This priority can be evaluated by first that probability that the risk will occur, and also by the enormity of the risk impact on the organisation objectives. At the end the manager will be able to model decision making problems of the organisation taking into account the main risks in modeling.

Through those actions, while accidents can never be completely eliminated, it is often possible to reduce their frequency by preventing them via appropriate tools.

Some of the approaches that can help to deal with disruptions are briefly outlined below:

- Improving the accuracy of demand forecasts: with considering not only the expected demand forecast but also the demand forecast error (variance) in developing plans. This would allow to planners to be aware what deviation may happen from the mean value.
- Integrate and synchronize planning and execution:

When managers responsible for execution make adjustments to plans to reflect current operating changes, they should communicate those adjustments to the planners to assure the integration between development and execution of plans.

- Collaborate and cooperate with supply chain partners:

For reducing information distortion and lack of synchronization that currently contribute to disruptions, supply chain partners must be implicated in both decision making and problem solving, as well as share information about strategies, plans, and performance with each others.

- Invest in Visibility:

For developing visibility some steps shall be followed. Those consist on identifying and selecting important indicators of supply chain performance; collecting data about those indicators; monitoring those indicators against a predetermined benchmark level to disclose possible deviations; at the end implementing processes for dealing with deviations.

- Building flexibility on the product design side : Standardization by use of common parts and platforms can offer the capability to react to sudden shift in demand and disruptions in delivery in parts.

- Building sourcing flexibility: This can be achieved by using flexible contracts as well as use of spot markets for supply needs.

- Building manufacturing flexibility: This can be accomplished by acquiring flexible capacity that can used to switch quickly among different products as the demand dictates. Firms should also consider segmenting their capacity into base and reactive capacity, where the base capacity is committed earlier to products whose demand can be accurately forecasted and reactive capacity is committed later for products where forecasting is inherently complex. Such would be the case for products with short product life cycles as well as products with very volatile demand. Late differentiation of products can also be used as a strategy to increase manufacturing flexibility.

- Invest in technology:

Investment in appropriate technology can contribute in reducing the chances of disruptions.

3. A reliability-based optimization model for mitigating supply chain disruptions

Long term strategic decisions like those involving plant location, DC location and supplier selection remain settled for many years and are difficult to reverse once they are taken. Furthermore, they are always made in an uncertain environment.

Reliability-based optimization models of facility location and supplier selection presented in the literature are not only rare, they have one major flaw: they consider reliability of the supply chain actors as known.

Having presented the method for quantifying risk, we shall assume in the third chapter that the probability distributions of supply and solicitation are known, in order to assess reliability of suppliers, plants, and DCs. The purpose of the third chapter is first to assess the reliability of each SC actor (suppliers, plants, and DCs), and to formulate a reliability-based optimization model for supply chain design that mitigates disruptions due to uncertainty about solicitation and supply. The proposed model consists of selecting reliable actors. Reliable supplier selection is based on redundancy (standby system) as a relevant contingency technique to counter risks of supply failure.

II. Futures researches

Modern supply chains become very complex and also vulnerable, with many physical and information flows occurring in order to ensure that all products are delivered in the right quantities, to the right place with the least cost.

Furthermore, the effort done to shift towards robust supply chains during the past years has resulted in a greater vulnerability. Unfortunately in the literature little research has been undertaken about supply chain vulnerabilities.

Many drivers may contribute to the severity of any supply chain disruptions. Artbrant (2003) points out that these drivers may include:

• The globalisation of supply chains

• The trend of outsourcing

• The lack of visibility and control procedures

On the other hand, Artbrant (2003) explains that disruptions can concern a number of features:

• Natural disasters, like earthquakes hurricanes, etc.

• Terrorist incidents

• Industrial fluctuation, like unexpected drops of the fuel production

• Accidents, like a fire

• Operational difficulties, like production or supply problems

Till now we have covered only few types of those disruptions. As we can not cover all the types of risks in a unique analysis, we have therefore concentrated in this thesis on two types of strategic risks related to supply and demand uncertainties, because they are considered among the most leading of any company's financial performance.

Artbrant (2003) explains that as there is a close interrelationship between different actors in the supply chain, consequently any disruption in some given entity may have huge impacts on the other entities. This is similar to the domino effect which is a problem of falling systems. If one system fails, the others fail too as they are dependent on it. Like a series of enormous rows of dominoes, if one fails the subsequent dominoes fail resulting in huge effects.

So for future research one can examine methods to model other types of risks as well as there is a wide range of risks resulting in an increasing interest in supply chain risk management issues, both as a practical application and as a research area. Hence, as seen one can suppose the existence of dependency between those risks to allow to companies to have a clear plan of action in case of occurrence of interdependent disruptions moreover if they result from a domino's effect.