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Walid Klibi
Alain Martel
Adel Guitouni

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Bureaux de Montréal :
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
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The Design of Robust Value-Creating Supply Chain Networks: A Critical Review

Walid Klibi[1,2], Alain Martel[1,2,*], Adel Guitouni[2,3]

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)

[2] Département des opérations et systèmes de décision, Pavillon Palasis-Prince, 2325, rue de la Terrasse, Université Laval, Québec, Canada G1V 0A6

[3] Defense R&D Canada - Valcartier, 2459 Pie-XI Nord, Val-Bélair, Québec, Canada G3J 1X5

Abstract. This paper provides an analysis of Supply Chain Network (SCN) design problems under uncertainty, and it presents a critical review the optimization models proposed in the literature to help design robust value-creating SCN. It points out some drawbacks and missing links in the literature, and provides motivations for the development of a comprehensive SCN design methodology. The paper reviews key random environmental factors and discusses the nature of major disruptive events threatening SCN, through an analysis of supply chains uncertainty sources and risk exposures. It also discusses relevant strategic SCN design evaluation criteria, and it reviews their use in existing models. It argues that the assessment of SCN robustness is necessary to ensure sustainable value creation. Several definitions of robustness, responsiveness and resilience are reviewed, and the importance of these concepts for SCN design is discussed.

Keywords. Supply Chain Network (SCN) design, value creation, uncertainty, network disruptions, robustness, scenario planning, location models, capacity models, resilience strategies.

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* Corresponding author: Alain.Martel@cirrelt.ca

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Introduction

Supply Chain Network (SCN) design involves strategic decisions on the number, location, capacity and mission of the production-distribution facilities of a company, or of a set of collaborating companies, in order to provide goods to a predetermined, but possibly evolving, customer base. Decisions on the selection of suppliers, subcontractors and 3PLs, and on the offers to make to product-markets, may also be involved. These strategic decisions must be made here-and-now but, after an implementation period, the SCN will be used on a daily basis for a long planning horizon. Day-to-day procurement, production, warehousing, transportation and demand management decisions will generate product flows in the network, with associated costs, revenues and service levels. The adequate design of a SCN requires the anticipation of these future demands, flows, costs, revenues and service levels. Furthermore, SCN must be designed to last for several years, which mean that strategic design decisions are made under uncertainty. Another important issue is the performance measures used to evaluate the quality of the network designed. Return on investment measures, such as the *Economic Value Added* (EVA), are often used by strategic decision makers in this context, but the design robustness is also an important dimension to consider. Despite a long history of work on SCN design problems, the majority of the models currently available take only a subset of these issues into account.

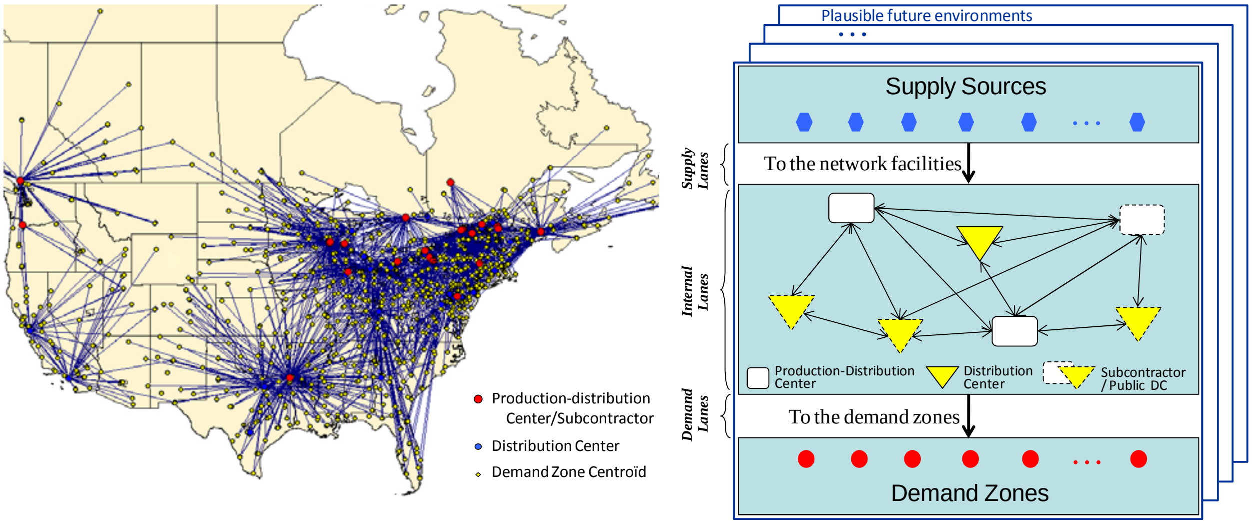
This paper is a critical review of the SCN design problem under uncertainty, and of the models available to support the design process. It points out some drawbacks and missing links in the literature, and provides motivations for the development of a comprehensive SCN design methodology. It reviews key random environmental factors and discusses the nature of major disruptive events threatening SCN, through an analysis of supply chains (SC) uncertainty sources and risk exposures. The paper also discusses relevant strategic SCN design evaluation criteria, and it reviews their use in existing models. It argues that the assessment of SCN robustness is necessary to ensure sustainable value creation. Several definitions of robustness, responsiveness and resilience are reviewed, and the importance of these concepts for SCN design is discussed.

The paper is organized as follows. The next section presents an overview of the SCN design problem. It discusses key issues to take into account when designing a SCN, and it proposes a value-based framework for SCN strategic performance evaluation. It also discusses the uncertain context under which design decisions are made, through an analysis of SCN uncertainty sources, risk exposures and available data sources. The next section provides a genesis of the literature on deterministic SCN design models, starting with classical location models. The following section discusses uncertainty modeling and risk assessment in the context of SCN. The work published on the design of SCN, using approaches such as stochastic programming and robust optimization, is reviewed. The next section discusses robustness considerations in SCN design, and explores the responsiveness and resilience strategies proposed in the literature. The paper concludes with a discussion on the need for a comprehensive SCN design methodology.

Overview of the SCN Design Problem

Strategic SCN Design Decisions

A typical SCN is represented in Figure 1a). In short, the SCN design problem is the reengineering of such networks to enhance value creation in the companies involved. In general, SC networks are composed of five main entity types: external suppliers, plants manufacturing intermediate and/or finished products, distribution centers (DC), demand zones, and transportation assets. Note that the production-distribution facilities can be subcontractors or public warehouses, and that for-hire transportation can be used. In order to reengineer an existing SCN, an alternative potential network including all possible supply, location, capacity, marketing and transportation options must be elaborated. This potential network can be partially represented by a directed graph such as the one illustrated schematically in Figure 1b). The nodes of this graph correspond to existing and potential supply sources, facilities and demand zones. The directed arcs are associated to the transportation lanes that could be used to move materials. Once the potential network has been elaborated, the SCN is reengineered by selecting a feasible sub-network that optimizes some predetermined value criterion.


a) SCN of a Pulp & Paper Company

b) Potential SCN under Uncertainty

Figure 1- Current and Potential Supply Chain Networks

The main type of strategic questions answered using this generic SCN design approach are the following: Which markets should we target? What delivery time should we provide in different product-markets and at what price? How many production and distribution centers should the network contain? Where should they be located? Which activities should be externalized? Which partners should we select? What production, storage and handling technologies should we adopt and how much capacity should we have? Which products should be produced/stocked in each location? Which factory/DC/demand zones should be supplied by each supplier/factory/DC? What means of transportation should we use (internal fleet, public carrier, 3PL…)? The activities of concern naturally include production and distribution, but recovery and revalorisation activities can also be considered. These strategic questions are rarely examined all together, but rather a few at a time when prompted by major events such as the launching of new products on existing or new markets, a merger, or an acquisition.

Many factors, in addition to the breath of the strategic questions raised and the number of potential internal and external entities involved, contribute to the complexity of SCN decision models. The first one is industry structure and decoupling points. For example, problems involving complex manufacturing processes in assemble-to-order or make-to-order industries are much more difficult than problems involving single-stage production and/or distribution in a make-to-stock context. A second dimension is the multinational or global coverage of a SCN. When several countries are involved, additional factors such as exchange rates, transfer prices, tariffs, tax regulations and trade barriers must be taken into account (Martel *et al.*, 2005, 2006). A third important aspect is the long-term impact of the design decisions. When the only decisions involved are the selection of public warehouses, it may be reasonable to use a static one-year model, as most of the literature does, but when supply agreements and manufacturing facilities last several decades, as in the forest product industry, this is far from sufficient. This leads to a fourth complexity factor: uncertainty. Most of the models proposed in the literature are not only static, but they are also deterministic. When long planning horizons are involved, the problem becomes dynamic and stochastic. In addition, to design robust networks, it is not sufficient to consider business-as-usual random variables such as demands, prices and exchange rates, but extreme events such as natural disasters or terrorist attacks that may seriously affect the capabilities of the network must also be considered.

Important investments may be required to implement the strategic design decisions discussed and, before they make such decisions, top-managers need to assess return on investments. This return comes from the net revenues generated by using a SCN during the planning horizon considered, that is from sales revenues less SCN operating expenditures associated to day-to-day procurement, production, warehousing, transportation and demand fulfilment decisions. In order to model the problem adequately, these operating revenues and expenditures must be anticipated in the SCN design model. This is usually done using aggregate production, inventory and flow variables. It must be realised however that such a modeling approach provides only a crude estimation of real operating revenues and costs. With this in mind, the rest of the paper will focus on uncertainty, performance evaluation and related issues in the context of SCN design.

Supply Chain Networks under Uncertainty

As illustrated in Figure 1b), when a SCN is designed, or reengineered, the business environment under which it will operate is not known. At best, several plausible future environments can be considered. These future environments are shaped by the random variables associated to business-as-usual factors such as raw material prices, energy costs, product-market demands, labour costs, finished product prices, exchange rates, etc. In addition a large spectrum of recent catastrophic events has make it clear that these environments are also shaped by the SCN vulnerability to extreme unforeseen events. Contrarily to random business-as-usual events, catastrophic events have been ignored by most businesses in the past, and it is only recently that a growing interest was observed (Martha and Vratimos, 2002; Semchi-Levi *et al.*, 2002; Helferich and Cook, 2002; Christopher and Lee, 2004; Chopra and Sodhi, 2004 and Sheffi, 2005). Several categorisations of SCN risk sources were recently proposed in the literature (Christopher and Peck, 2004; Kleindorfer and Saad, 2005; Wagner and Bode, 2006 and Tang, 2006b). They distinguish between environmental, demand side, supply side and internal SC risk exposures. An extended list of SC risk drivers is also provided in Chopra and Sodhi (2004). In what follows, we examine the sources of uncertainty shaping future business environments from the point of view of a firm or SCN, and not from the point of view of the entire economy. We are concerned with the impact of plausible future events on the firm, and not by the source of these events and the actions that could be taken by external agents to avoid them. Also, totally destructive events causing irreversible damages to the entire business are excluded from the analysis.

The suppliers, facilities and ship-to-points of SCN are typically dispersed across large geographical regions, possibly involving several countries, and adverse events may be associated directly to SCN assets/partners, or to the territory over which they are deployed. Figure 2 distinguishes three broad categories of SCN vulnerability sources: endogenous assets, SC partners and exogenous geographical factors. Endogenous assets include the equipments, vehicles, human resources and inventories of production, distribution, recovery, revalorisation and service centers. SC partners include customers, raw material and energy suppliers, subcontractors, and third-party logistics providers (3PLs). In addition to the random business-as-usual factors discussed previously, SC uncertainties are related to the fact that SCN assets and partners may fail: industrial accidents or fires may destroy or break equipments, vehicles and inventoried products, labour disputes may stop work during a period of time, partner bankruptcy, strikes or accidents may limit raw-material supply or decrease customer demand, etc. An interesting study of the potential impact of these uncertainty sources on SC is found in Helferich and Cook (2002).

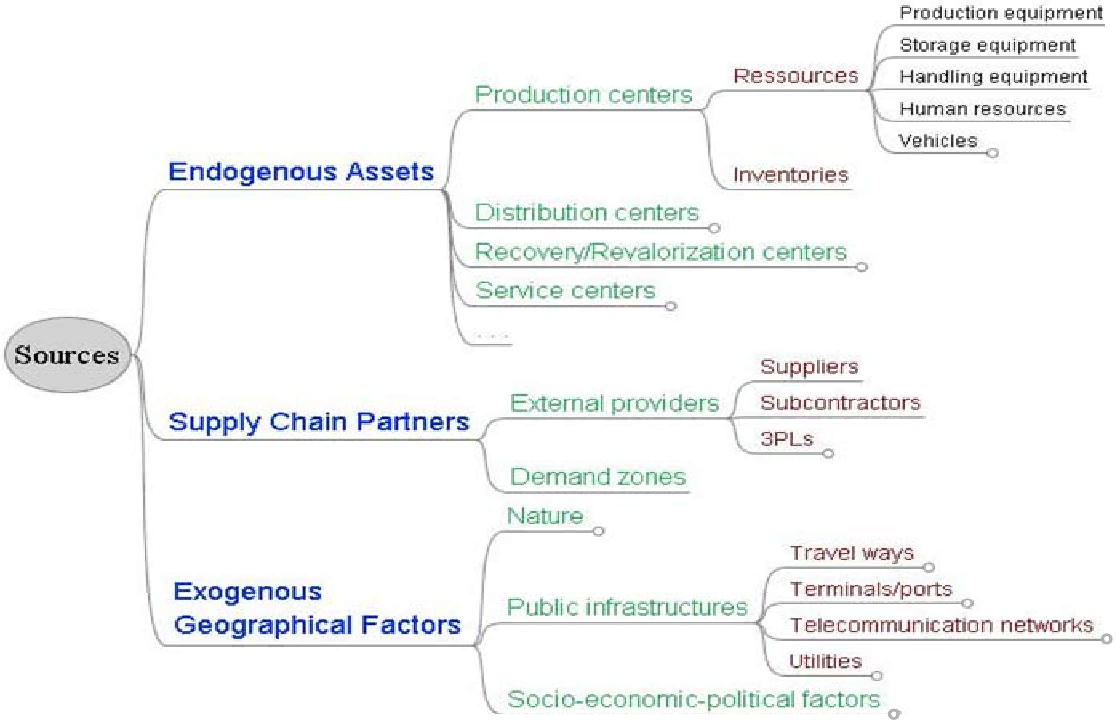


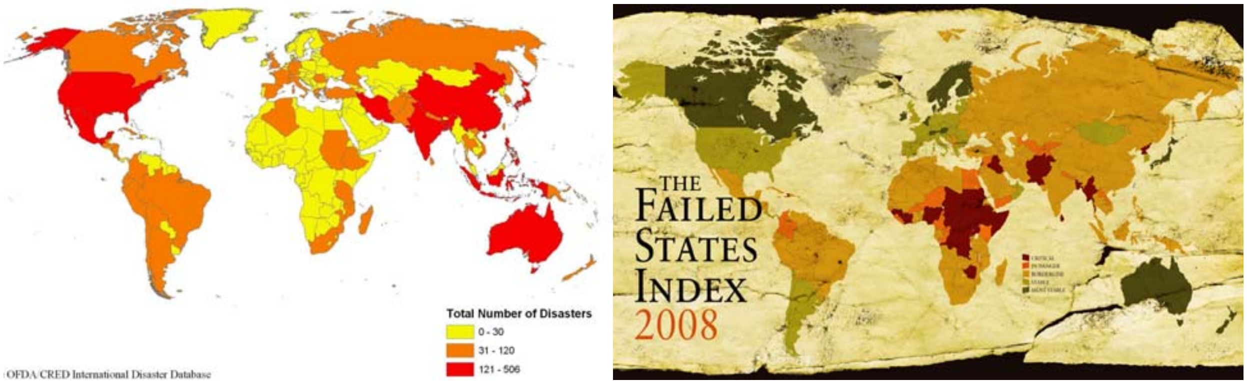
Figure 2- Supply Chain Network Vulnerability Sources

The assets/partners of a SC are all located in a specific geographical region. These regions and their associated public infrastructures (travel ways, terminals, ports, telecommunication networks, utilities…) are themselves vulnerable to natural (hurricanes, earthquakes, blizzards, floods, forest fires…), accidental (epidemics, chemical/nuclear spills…) or wilful (terrorist attacks, political coup…) disasters. All these possible extreme events are also important sources of SC uncertainty. A difficulty when considering these vulnerability sources is that little information is available to determine *what can go wrong*, and the *likelihood* of assets, partners or infrastructures failures. Based on recorded past events and/or professional expert opinions, for a given SCN design project, a portfolio of plausible extreme event types could be built, *hazard zones* differentiating *exposure levels* could be elaborated, and an event type arrival process per zone could be modeled (Banks, 2006, Gogu *et al.*, 2005). Moreover, in network design projects, only vulnerability sources having a serious impact on the strategic performance of the SCN should be considered. Sheffi (2005) proposed to build an enterprise vulnerability map to categorize and prioritize different possible disruptions, and Haimes (2004) suggest an *a priori* filtering, based on a qualitative assessment, to eliminate low consequence event types.

Another important aspect is the *consequence* of high impact disruptions on a SCN. Recently, Craighead *et al.*, (2007) argued that the *severity* of a supply chain disruption is related to SC density, SC complexity and SC nodes criticality. Several authors reported the impact of such catastrophic events on companies in terms of monetary losses, based on direct costs of repair and market share loss (Rice and Caniato, 2003; Lee, 2004; Sheffi, 2005, Hendricks and Singhal, 2005). However, rebuilding and repairing costs are generally insured, and thus they are not necessarily relevant for SCN design. On the other hand, the indirect losses related to business interruptions, and to temporary relocation and/or rerouting of materiel are crucial. In fact, the cost of any recourse used by the SC to continue operating during the crisis must be taken into account. Unfortunately, no work to date proposed a disruption severity modeling approach adequate for SCN design. The synthesis of available papers on SCN vulnerabilities (Helferich and Cook 2002; Kleindorfer and Saad, 2005; Sheffi, 2005) leads to the conclusion that specific severity dimensions are needed: damages caused to assets/partners should be estimated in term of design parameters such as capacity loss, supply loss or demand surge. Banks (2006) also suggested mapping severity with duration-impact curves, which seems adequate to model assets/partners availability in SCN design.

A maze of natural, accidental and wilful hazards data is available, but it is not always adequate for SCN design purposes. This data can be used relatively easily to compute exposure level indexes by geographical zones, for specific *multi-hazard* classes. Figure 3a) for example provides a natural catastrophes exposure index based on data provided by the *Centre for Research on the Epidemiology of Disasters* (www.cred.be). Other organizations such as the *Federal Emergency Management Agency* (www.fema.gov) and the *U.S. Geological Survey* (www.usgs.gov) provide similar information. The Failed States Index presented in Figure 3b) is a similar multi-hazard index designed to reflect the political stability of a country. It is compiled by *Foreign Policy* (www.foreignpolicy.com) and the *Fund for Peace* (www.fundforpeace.org) based on 12 economical, political, social and ethnic indicators. The Opacity Index published by the *Milken Institute* (www.milkeninstitute.org) is another political stability measure. Other relevant multi-hazard indexes include economic performance indexes such as the World Competitiveness Scores of the *International Institute for Management Development* (www.imd.ch) or the Global Competitiveness Index of the *World Economic Forum* (www.weforum.org), industrial accident indexes related to the claims made to insurance companies (www.munichre.com), and public infrastructure quality indexes calculated from databases such as the *CIA World Factbook* (www.cia.gov/cia/publications/factbook). An example of an empirical SC disruptions study involving multiple data sources is found in Craighead *et al.*, (2007).

The risk matrix (Norrman and Jansson, 2004) presented in Figure 4 summarizes key elements of our previous discussion. The impact on a SCN of business-as-usual random variables is relatively minor, and it can be modeled using standard probabilistic approaches. However, network threats are harder to consider in the SCN design process because they are difficult to predict and they may have serious or catastrophic consequences. Intuitively, many natural and man-made phenomena follow the Pareto law: a small fraction of the events cause most of the damage (Sheffi, 2005). This is why the risk exposure to such events is typically measured by its probability of occurrence multiplied by its business impact (or severity). Extreme events occurrences are predictable when they occur repeatedly, but they can also be sudden, unique and unpredictable. Little *a priori* information is typically available on non-repetitive extreme events such as sabotage, sudden currency devaluations or political coups (Banks, 2006). The occurrence of such events remains very difficult to predict (Sheffi, 2001; Kaplan, 2002; Lambert *et al.*, 2005).



a) Natural Disasters by Country (1974-2003)

b) The Failed States Index 2008

Source: www.emdat.be

Source: www.foreignpolicy.com

Figure 3– Example of Multi-hazard Indexes

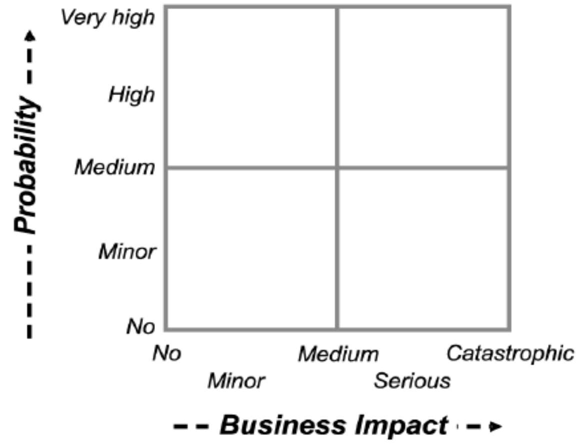


Figure 4– Risk Matrix (Norrman and Jansson, 2004**)**

Strategic Evaluation of SCN Designs and Optimization Criteria

It can be argued that the paramount goal of a business should be the sustainable creation of shareholder value, and that this goal implicitly provides a mechanism to reach a proper balance between the conflicting objectives of the various stakeholders of a firm (Yucesan, 2007). *Value* is defined as the sum of all the future *residual cash flows* (RCF) generated by a firm, discounted at the firm's weighted average cost of capital, where

RCF = (Revenues - Operating expenses)(1 - Tax rate) - Capital expenditures

In order to design value-creating supply chains, one should therefore select a SCN design maximizing the present value of all future RCF generated by the SCN, and discounted at the firm's cost of capital, which is easier said than done. In order to operationalize this definition, value-driven businesses use static strategic performance indicators such as the *economic profit* (EP), also referred to as the *economic value added* (EVA), and the *return on capital employed* (ROCE). They also break these strategic metrics into lower-level financial and operational performance indicators that are more appropriate for mid-level and operations managers (Yucesan, 2007). A comprehensive review of performance measures and metrics in SC management is found in Gunasekaran and Kobu (2007).

The definition of residual cash flows above implies that three broad categories of *value drivers* must be taken into account in SCN design, namely: revenue drivers, cost drivers and capital expenditures. Tax rates are an important consideration mainly for multinational SCN. Cost drivers can be associated to SCN procurement, production, warehousing, transportation and sale activities using *Activity-Based Costing* (ABC) concepts (Terrance, 2005; Shapiro, 2008). Revenue drivers are related to the notion of *order winners* introduced by Hill (1989). Order winners are value criteria enabling a firm to win orders in its product-markets, and thus to increase its market share and its revenues. These order winning criteria include product range, product prices, product quality and reliability, delivery speed and reliability, volume and design flexibility, agility (often defined as the combination of speed and flexibility), market coverage, ecological footprint, etc. (Lefrançois *et al.*, 1995; Vidal and Goetschalckx, 2000; Gunasekaran *et al*., 2004). Several of these criteria are directly related to the firm SC capabilities. Capital expenditures capture the investments required to develop the SCN as well as the market value of current assets. They may also be influenced by the financing mechanism used by the firm. They are associated to the various location/capacity options considered in the SCN design process. Recall finally that to evaluate the value of a SCN design, the net present value (NPV) of these revenues and costs over the life of the SCN must be calculated.

When designing a SCN, the value drivers discussed above are not necessarily all relevant. They are relevant only if they are affected by the various design options considered. Much of the SCN design literature considers simplified static and deterministic models for which the demand for a typical future period (usually a year) is assumed known. Under this assumption, the revenues are a constant and the objective reduces to the minimization of *total network costs* (relevant operating expenses and capital charges). The capital charges must then be expressed as a fixed yearly *rent* associated to binary facilities/technology selection variables. Some authors have proposed bi-criterion models aiming to minimize total network costs and an order winning criterion such as response time (Ballou, 1992) and volume flexibility (Sabri and Beamon, 2000). This is typically done by incorporating a constraint in the model imposing qualifying requirements on the order winner considered, and by parametrizing this requirement to construct an *efficient frontier*. This is illustrated in Figure 5a), where each point in the graph gives the total network cost and the maximum response time provided by a design such as the one in Figure 1a). One of the efficient designs on the efficient frontier can then be selected by management (Rosenfield *et al.*, 1985). If an explicit relationship can be established between demand, product prices and some order winners depending on the network structure (Ho and Perl, 1996; Vila *et al.*, 2007), or if sales in demand zones are considered as decisions variables bounded by penetration targets and potential market shares (Cohen *et al.*, 1989; Martel, 2005), then revenues depend on design variables and, as illustrated in Figure 5b), the objective must be to maximize residual cash flows.

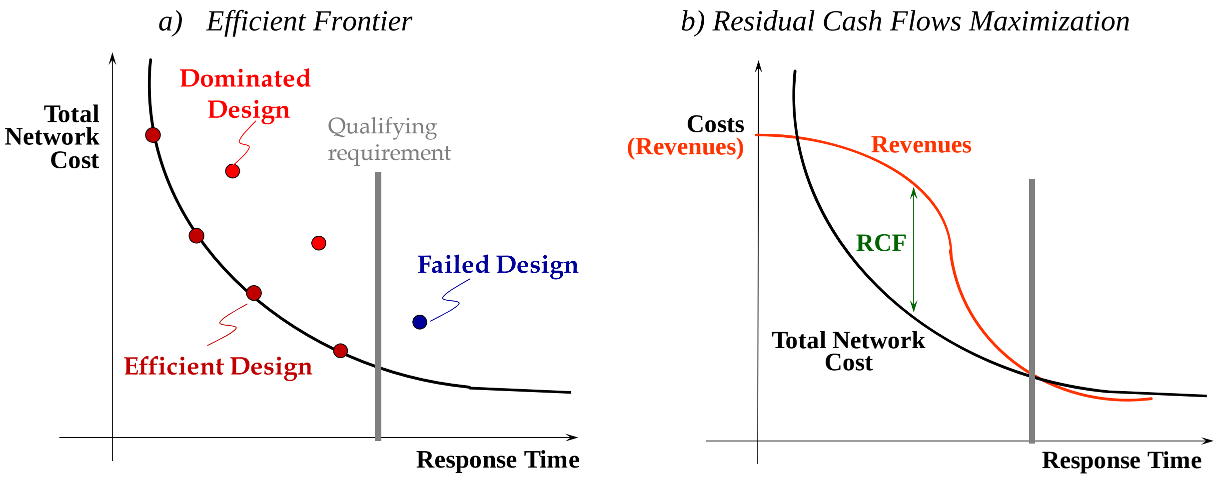


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Figure 5- Static Design Tradeoffs for a Domestic Supply Chain Network

When a finite planning horizon is considered, as opposed to a single planning period, the timing of structural SCN adaptations (opening/closing of facilities or of systems within facilities) and the consideration of real options (Trigeorgis, 1996) become important issues. The SCN design objective then becomes the maximization of the present value of the cash inflows and out-flows generated by the SCN during the planning horizon, and of the *residual value* of the SCN assets at the end of the horizon, i.e. of the RCF generated by the SCN assets after the planning horizon. Clearly, for any realistic planning horizon, these cash flows and residual values are not known with certainty at the time when SCN design decisions are made.

Static financial or operational performance indicators such as EVA, ROCE, assets turnover, resource utilization rates, market shares, service levels, etc. are easy to compute from historical data when looking at the past, but they are not of much use when looking at the future. Since future RCF are uncertain, the measures employed to evaluate future SCN performances depend on the approach used to model uncertainty. They normally involve a measure of central tendency, such as the expected value, and measures of dispersion, such as the variance or the maximum regret. The way in which these measures are combined to arrive at a global strategic valuation measure (or *return* measure) depends on the *attitude toward risk* of the decision-maker. A risk *neutral* decision-maker would base his decisions purely on a central tendency measure, but when considering strategic issues such as SCN design, most decision-makers are risk *averse*. Two types of aversion to risk must also be distinguished in SCN design, namely aversion to RCF variability and aversion to high-impact catastrophic events. Note that instead of trying to elaborate an adequate combined return measure, a multi-criteria decision approach may be used. Some authors have also advocated the elaboration of an efficient value-risk frontier, by incorporating maximum risk constraints in their model (Hodder and Jucker, 1985; Eppen *et al.*, 1989).

Several authors have proposed SCN performance measures or attributes to value sustainable returns in a perturbed business environment. These include downside risk (Eppen *et al.*, 1989), which is commonly used in finance to assess the risk of potential investments, operational flexibility (Dornier *et al.*, 1998), agility (Lee, 2004), reliability (Vidal and Goetschalckx, 2000; Snyder and Daskin, 2005; Berman *et al.*, 2007), robustness (Snyder and Daskin, 2006; Kouvelis and Yu, 1997; Dong, 2006), responsiveness (Bertrand, 2003; Graves and Willems, 2003) and resilience (Sheffi, 2005). There is a considerable overlap in these concepts, and the notions of *robustness, responsiveness* and *resilience* are sufficient to consider all the nuances they bring. Intuitively, in our context, robustness is a measure of the ability of a SCN design to remain effective under any plausible future, responsiveness is the ability of a SCN to respond to variations in business conditions, and resilience is the ability of a SCN to avoid or bounce back from unforeseen disruptions. These three concepts are discussed in detail at the end of the paper.

It is clear that the performance of a firm depends on its SCN design strategy: an adequate capacity deployment (network structure) provides valuable order winners and lowers costs; appropriate responsiveness and resilience strategies maintain value creation under uncertainty.

Given this, the challenge is to design SCN that are capable of providing sustainable shareholder value for any plausible future business environment, i.e. to design robust value-creating SCN. In order to do this in a practical way, the approach used to analyse SC vulnerabilities, and to model SCN structures, future business uncertainties and SCN responsiveness/resilience strategies, is a critical success factor. As far as we know, no comprehensive SCN design approach considering all these issues has been proposed in the SCN literature. The rest of this paper tries to make a first step in this direction through a representative review of the relevant literature. Note that although much of our discussion is cast in a business context, it is also directly relevant for non-business SCN such as military (Girard *et al*., 2008) or emergency relief (Tovia, 2007) logistics networks.

Deterministic SCN Design Models

Facility location models (Daskin, 1995; Drezner, 1995; Sule, 2001; Drezner *et al*., 2002; Daskin *et al.*, 2003; Revelle and Eiselt, 2005), and in particular *discrete* facility location models (Mirchandani and Francis, 1990), can be considered as the foundation of SCN design models. They deal with the location of facilities in some given geographical area. Basic facility location problems (FLP) consider a single product and a single production/distribution echelon with uncapacitated (UFLP) or capacitated (CFLP) facilities. Their original formulation goes back to Balinski (1961) and, despite their simplicity, they are still the subject of numerous publications (ReVelle *et al*., 2008). In the CFLP, demand can be supplied from more than one source. When it is required that each demand zone is supplied from a single source, the resulting CFLP with single sourcing (CFLPSS) is much more difficult to solve. In fact, the generalized assignment subproblem obtained for a given set of facilities is NP-hard (Fisher, 1986). Kaufman *et al*. (1977) studied an extended version of the UFLP incorporating a production and a distribution echelons. Several authors also studied multi-product extensions of the one or two echelon CFLP and CFLPSS. Geoffrion and Graves (1974) proposed a Benders decomposition approach to solve a path-based formulation of a multicommodity CFLPSS, with fixed production facilities and location-allocation decisions for the distribution echelon. Hindi and Basta (1994) solve an arc-based formulation of a similar problem with a Branch and Bound algorithm. Hindi *et al*. (1998), Klose (2000) and Pirkul and Jayaraman (1996, 1998) propose Lagrangian relaxation procedures to solve two-echelon CFLPSS's and CFLP's. Several heuristic were also proposed to solve these problems, based on interchange procedures (Kuenh and Hamberger, 1963; Zhang *et al*., 2005), tabu search (Al-Sultan and Al-Fawzan,1999; Michel and Van Hentenryck, 2004), genetic methods (Kratica *et al*., 2001), randomized rounding (Barahona and Chudak, 2005) and very large-scale neighborhood (VLSN) search (Ahuja *et al*., 2004). Owen and Daskin (1998) and Klose and Drexl (2005) present detailed reviews of the large literature available on these problems.

The static FLP models reviewed in the previous paragraph assume that the facilities capacity is predetermined, that there is at most one production stage, that the geographical area involved is within a single country, and that the fundamental tradeoffs are between facilities fixed capital/operating charges and variable linear production, warehousing and transportation expenditures, the later being crudely approximated via aggregate flow decisions. Several extensions were proposed to relax these assumptions. They can be classified in two categories: extensions to model SCN design decisions more closely, and extensions to anticipate operating decisions more closely.

The importance of capacity as a decision variable in location problems was recognized early (Elson, 1972), but the explicit incorporation of capacity decisions as SCN design variables is more recent. Some models consider capacity expansion as a continuous variable (Verter and Dincer, 1995) but, more realistically, others consider discrete facility capacity options (Paquet *et al.*, 2004; Amiri, 2006) or alternative facility configurations (Amrani *et al.*, 2008). The extended formulations proposed to model multi-stage production-distribution networks are based on the use of aggregate bill-of-material structures (Cohen and Moon, 1990; Arntzen *et al.*, 1995; Paquet *et al.*, 2004; Martel, 2005), or on the use of generic activity graphs with recipes (Brown *et al.*, 1987; Dogan and Goetschalckx, 1999; Lakhal *et al.*, 2001; Philpott and Everett, 2001; Vila *et al.*, 2006). Extensions covering product development and recycling (Fandel and Stammen, 2004), and alternative transportation modes were also considered (Cordeau *et al.*, 2006). Some authors have also proposed extensions to take into account economies of scale in production/handling (Soland, 1974; Kelly and Khumawala, 1982; Cohen and Moon, 1990), inventory (Martel and Vankatadri, 1999; Martel, 2005; Ballou, 2005) and transportation (Fleischmann, 1993) costs. Finally, several authors have proposed extensions to maximize residual cash flows in an international context (Cohen *et al.*, 1989; Arntzen *et al.*, 1995; Vidal and Goetschalckx, 2001; Goetschalckx *et al.*, 2002; Bhutta, 2004; Kouvelis *et al.*, 2004; Martel, 2005; Meixell *et al.*, 2005). The static-deterministic SCN models proposed by Arntzen *et al*. (1995), Fandel and Stammen (2004), Martel (2005), Cordeau *et al*. (2006) and Vila *et al*. (2006) are among the most comprehensive presented to date.

In the last few years major efforts have been devoted to the development of location models with a much more detailed anticipation of network users' transportation and inventory management decisions. These *integrated* location-routing, location-inventory and location-routing-inventory models are reviewed in Shen (2007). The first classification of location-routing problems is found in Laporte (1988) and several papers have studied different aspects of the problem (Nagy and Salhi, 1996; Prins *et al*., 2007; Berger *et al*., 2007). A comprehensive review of location-routing models and of their applications is provided in Nagy and Salhi (2007). Several authors also proposed location-inventory models taking into account the risk pooling effects of network cycle and safety stocks (Ho and Perl, 1996; Daskin *et al*., 2002; Shen *et al*., 2003; Ambrosino and Scutella, 2005; Shen, 2007). Recently, Romeijn *et al*. (2007) proposed a two echelon SCN design model integrating inventory and transportations decisions. Sabri and Beamon (2000) also proposed an interesting integrated approach to take strategic and operational planning decisions into account.

Several deterministic multi-period SCN design models were also proposed in the literature. Some of these models are static, in that they involve design decisions only at the beginning of the planning horizon, but they use several planning periods to anticipate operational decisions more closely (Cohen *et al*., 1989; Arntzen *et al*., 1995; Dogan and Goetschalckx, 1999; Martel, 2005; Vila *et al*., 2006). Some dynamic models allowing the revision of design decisions (number, location, technology and capacity of facilities; sourcing and marketing policies) at the beginning of each planning period were also proposed. Dynamic location problems were studied by Erlenkotter (1981), Shulman (1991) and Daskin *et al*. (1992). Capacity expansion problems are naturally multi-period (Julka *et al*., 2007). Dynamic SCN design models were proposed by Bhutta *et al*. (2003), Melo *et al*. (2005) and Paquet *et al*. (2008).

As indicated previously, several specialized exact and heuristic methods were proposed to solve basic location-allocation problems. For the more comprehensive SCN design models, some authors have suggested the use of decomposition methods, such as Benders decomposition (Geoffrion and Graves, 1974; Dogan and Goetschalckx, 1999; Paquet *et al.*, 2004, Cordeau *et al*., 2006), and/or the incorporation of valid inequalities in the model (Dogan and Goetschalckx, 1999; Paquet *et al.*, 2004). It should be noted however that most deterministic SCN design models can now be solved efficiently with the recent versions of commercial solvers such as CPLEX and Xpress-MP.

SCN Design Models under Uncertainty

The deterministic models discussed in the previous section provide a solid foundation for SCN design, but it should be clear from our previous discussion that there is no guarantee that the designs obtained will perform well for any plausible future. In order to obtain robust designs, these models must be extended to consider the uncertainty of their future business environment. Uncertainty modeling thus becomes an important challenge in SCN design. We therefore start this section with a relatively general discussion of the various approaches used to model uncertainty. We then look more specifically at the approaches which have been used in the literature to formulate and solve SCN design models under different types of uncertainty.

Rosenhead *et al*. (1972) proposed to distinguish between decision-making under *certainty*, *risk* and *uncertainty*, and this characterization was subsequently adopted by several authors (Kouvelis and Yu, 1997; Vose, 2000; Snyder, 2006). In this paradigm, certainty corresponds to the case where no element of chance intervenes between decisions and outcomes. Risky situations are those where the link between decisions and outcomes is governed by probability distributions. Uncertainty describes situations where it is impossible to attribute probabilities to the possible outcomes of a decision. This distinction between risk and uncertainty is however not universally accepted. In classical risk management, risk refers to the product of the probability and the severity of extreme events (Haimes, 2004; Grossi and Kunreuther, 2005), and probabilities are not the only way to model the likelihood of possible future events. Fuzzy sets (Zadeh, 1965) or possibilities (Zadeh, 1978), for example, could also be used. For these reasons, a characterization of uncertainty based on the information available is more useful in our context: decisions are made under *certainty* when perfect information is available and under *uncertainty* when one has only partial (or imperfect) information (French, 1995; Zimmerman, 2000; Roy, 2002; Stewart, 2005). The term *uncertain* under this paradigm is value neutral, i.e. it includes the chance of gain and, conversely, the chance of damage or loss. As explained by Stewart (2005), uncertainty leads to *risk* and this term refers to the possibility that undesirable outcomes could occur. The risk increases as the likelihood and the negative impact of possible outcomes increases, as illustrated by Normann's risk matrix in Figure 4.

Under uncertainty, different quality of information may be available. The worst case is *total uncertainty*, that is, complete ignorance. When some information is available, depending on the nature of this information and on the SC risk exposure, three types of uncertainties can be distinguished: randomness, hazard, and deep uncertainty. *Randomness* is characterized by random variables related to business-as-usual operations, *hazard* by low-probability high-impact unusual events, and *deep uncertainty* (Lempert *et al*., 2006) by the lack of any information to asses the likelihood of plausible future extreme events. For hazards, as indicated previously, it may be very difficult to obtain sufficient data to assess objective probabilities and subjective probabilities must often be used. Note that although these definitions of randomness and hazard are based on probabilistic notions, other formalisms such as fuzzy sets, possibilities or rough sets could be used to model outcome likelihood. However, since most of the literature on non-deterministic SCN models and on risk assessment is based on a probabilistic approach, we will pursue our discussion using a probabilistic language.

Randomness

Under randomness, some of the SCN design model parameters (demands, prices, exchange rates, raw material/energy costs…) are considered as random variables with known probability functions. The joint-events associated to the possible values of the random variables can be considered as plausible future scenarios, and each of these scenarios has a probability of occurrence. One approach often used to deal with these problems is to elaborate an average scenario, and then to solve the resulting deterministic model. It is well known that the solution thus obtained can be far from optimal for some scenarios and that it may even be unfeasible (Sen and Higle, 1999). An alternative is to select a few representative scenarios, to solve the resulting deterministic model for each of them, and to evaluate the designs obtained using Monte Carlo sensitivity analysis (Saltelli *et al*., 2004; Ridlehoover, 2004). The difficulty with this approach is to determine which among the solutions found is the best solution. A method to select a solution is presented in Lowe *et al*. (2002): they propose a screening procedure using a number of filtering criteria such as Pareto optimality, mean-variance efficiency and stochastic dominance. Good examples of how this approach works are found in Körksalan and Süral (1999), Mohamed (1999) and Vidal and Goetschalckx (2000). This is a reactive solution approach however in that it considers the random variables only in an *a posteriori* evaluation step. To consider the random variables explicitly in the SCN design model, a proactive stochastic programming (Birge and Louveaux, 1997; Ruszczynski and Shapiro, 2003, Shapiro, 2007) approach must be used.

Most of the static deterministic models reviewed previously can be transformed into two-stage stochastic programs with recourse relatively easily (Santoso *et al*., 2005). The models thus obtained typically consider that the design variables must be implemented before (first stage variables) the outcome of the random variables is observed, but that the network usage variables (second stage variables) provide the *recourses* necessary to make sure that the design obtained is feasible. The objective is to optimize the expected value of the design and recourse decisions. These models can also be extended to consider risk aversion through the use of risk measures such as mean-variance functions and conditional value at risk functions (Mulvey *et al*., 1995; Shapiro, 2007). Dynamic problems can also be modeled using multi-stage stochastic programs. A major difficulty of the stochastic programming approach is to deal with the possibly infinite number of possible scenarios. This difficulty can be removed by using a random sample of scenarios selected with Monte Carlo methods (Shapiro, 2003). Scenario generation techniques were also proposed for multi-stage programs (Ducapova *et al.*, 2000; Hoyland and Wallace, 2002).

Stochastic location models were proposed by Birge and Louveaux (1997) and Snyder and Daskin, (2006). A comprehensive review of simple location models under uncertainty is found in Snyder (2006). Fine and Freund (1990) develop a stochastic program for capacity planning. A review of recent relevant developments in the capacity management literature is found in Van Mieghem (2003). Two-stage stochastic SCN design models were proposed by Tsiakis *et al*. (2001), Santoso *et al*. (2005), Vila *et al*. (2007, 2008). Some models incorporating mean-variance objective functions to measure design robustness were also elaborated (Hodder and Jucker, 1985). Following the pioneering work of Pomper (1976), some authors have also proposed multi-stage SCN design models (Eppen *et al*., 1989; Huchzermeier and Cohen, 1996; Ahmed and Sahinidis, 2003).

Hazard

The difficulty when confronted with hazards comes from the fact that high-impact extreme events cannot be treated the same way as low-impact business-as-usual events. Moreover, the identification of potential threats and the assessment of the risk they represent is in itself a challenging task. Catastrophe models have been used to estimate the location, severity and frequency of potential future natural disasters (Grossi and Kunreuther, 2005). They are usually based on a catastrophe arrival process, and they provide tradeoffs between economic loss (a severity evaluation measure) and the probability that a certain level of loss will be exceeded on an annual basis (Haimes, 2004; Grossi and Kunreuther, 2005; Banks, 2006). This type of assessment is very useful for the insurance industry, but it is not very adequate for SCN design: considering each type of hazard separately is too cumbersome, and loss is not an adequate severity measure because it is not directly related to design variables. The first difficulty can be avoided by using multi-hazards, i.e. aggregate extreme events incorporating all types of recurrent natural, accidental and wilful hazards (Gogu *et al*. 2005; Scawthorn *et al*., 2006). However, adequate severity measures for SCN design would have to be related to key design variables/parameters such as facility/supplier capacity and customer demand. Qualitative SC disruptions risk identification and assessment approaches are proposed by Kleindorfer and Saad (2005) and Manuj and Mentzer (2008).

The relative importance of extreme events versus business-as-usual events is related to the issue of the aversion of decision-makers to extreme events discussed previously. Models using expected value objective functions completely miss this important problem dimension, because they give the same weight to these two types of events. A multi-objective partitioning approach was proposed by Haimes (2004) to avoid this pitfall. It uses a set of conditional expected value assessment functions taking the impact of various types of events into account. Despite the fact that the importance of extreme events in SCN design is now well documented (Helferich and Cook, 2002; Christopher and Lee, 2004; Sheffi, 2005; Craighead *et al*., 2007), to the best of our knowledge, no formal SCN design models currently take hazards into account.

Deep Uncertainty

Under deep uncertainty, it is possible to elaborate plausible future scenarios, but the information available is not sufficient to associate an objective or subjective probability to these scenarios. There is a large literature on the elaboration of narrative scenarios to support strategic decision-making (Godet, 2001; Van der Heijden, 2005). Lempert *et al.* (2006) suggests the use of narrative scenarios in deep uncertainty situations and shows how to use these scenarios to enhance solution robustness. Scenarios can be elaborated through structured brainstorming sessions and/or expert interviews related to SCN opportunities and threats. Qualitative forecasting approaches, such as the Delphi method, can be used to support the process (Boasson, 2005). Some companies, such as Shell, push this approach very far: they produce and regularly revise scenarios of what the world might look like over the next twenty years (Shell, 2005). This approach can be used to produce likely scenarios, but also worst case scenarios.

Narrative scenarios can be streamlined to obtain quantitative scenarios about the business future. When this is done, robust optimization methods (Mulvey *et al*., 1995; Kouvelis and Yu, 1997) can be used to find adequate SCN designs. The robust optimization approach proposed by Mulvey *et al*. (1995) can be seen as an extension of stochastic programming, but it can be used with a min-max regret criterion, which would be done in the case of deep uncertainty. With the approach proposed by Kouvelis and Yu (1997), the most common robustness criteria used are the minimization of the maximum cost and the minimization of the maximum regret across all possible scenarios. Robust optimization has been applied to different versions of the facility location problem under uncertainty (Gutierrez *et al.*, 1995; Kouvelis and Yu, 1997; Yu and Li, 2000; Snyder and Daskin, 2006), as well as to capacity expansion problems (Bok *et al.*, 1998).

To conclude this section on non-deterministic models, note that fuzzy sets were used by some authors to model facility location selection problems (Sule, 2001; Kahraman *et al*., 2003) and SCN design problems (Chen and Lee, 2006). A few papers based on the possibilistic approach were also published on SC problems (Wang and Shu, 2007; Torabi and Hassini, 2008). A relevant review of uncertainty models is found in Matos (2007). It should also be noted that all the location and SCN design papers reviewed in this section assume that the SC modelled is either in a randomness context or a deep uncertainty context. In real life, elements of plausible future business environments can fall under any of the three types of uncertainties discussed, namely: randomness, hazard and deep uncertainty. To the best of our knowledge, no comprehensive SCN design approach, dealing with all uncertainty types, has been proposed to date.

Fostering Robustness in SCN Design

Robustness

A lot of discussion on the notion of *robustness* in decision-making under uncertainty is found in the literature. As indicated by Roy (2002), the term *robust* can have different meanings depending on the decision-making context considered. A first distinction needs to be made between model robustness (Mulvey *et al*., 1995; Vincke, 1999), algorithm robustness (Sorensen, 2004) and solution (or decision) robustness (Rosenhead *et al*., 1972; Mulvey *et al*., 1995; Kouvelis and Yu, 1997; Wong and Rosenhead, 2000; Roy, 2002; Ullman, 2006, Hites *et al*., 2006). In our case, we are clearly concerned with solution robustness, or more specifically SCN design robustness. Rosenhead *et al*. (1972) and Wong and Rosenhead, (2000) state that robustness is a measure of the useful flexibility maintained by a decision so as to leave many options for the choices to be made in the future, which is representative of the generic definitions found in the literature. It is interesting to note that robustness is associated to the notion of solution flexibility, which is congruent with the recent emphasis on flexibility and agility in the SC literature (Bertrand, 2003; Lee, 2004). Several authors have discussed robustness in a supply chain context (Rosenblatt and Lee, 1987; Gutierrez *et al*., 1995; Mo and Harrison, 2005; Sheffi, 2005; Dong, 2006; Snyder and Daskin, 2006). They define robustness as the extent to which the SCN is able to carry its functions for a variety of plausible future scenarios.

Linking these definitions to our previous discussion on the evaluation of supply chain performances, it can be stated that a SCN design is robust, for the planning horizon considered, if it is capable of providing sustainable value creation under normal business conditions as well as major disruptions. To evaluate the sustainability of a design, one must work with the discounted sum of the residual cash flows generated over a multi-period planning horizon, and take the three types of uncertainties identified into account. When considering a set of plausible future scenarios, resulting partly from the random, hazard and deeply uncertain environmental elements considered, the revenues and costs of all the operational and contingency actions required to satisfy customers demands with a given network design must be evaluated. Under randomness and hazards, by maximizing the expected value of these discounted cash flows, one necessarily selects a robust design. This is the approach taken by stochastic programming through the modelling of recourses. To take aversion to value variability into account, one must use risk measures such as mean-variance or conditional value at risk functions (Mulvey *et al.*, 1995; Shapiro, 2007) instead of expected value. If scenario probabilities are not available (deep uncertainty) a robust optimization model can be used (Kouvelis and Yu, 1997). If probabilistic and non-probabilistic scenarios are considered, which is desirable in most practical situations, then the scenario set must be partitioned accordingly and, as suggested by Haimes (2004), a multi-criteria approach based on conditional expectations and min-max regrets could be used. Some authors have also suggested incorporating a regret constraint (*p*-robustness) in their model (Snyder and Daskin, 2006). This partitioning approach can also be used to take aversion to extreme events into account. Currently, no model available in the literature considers all these robustness criteria.

Our previous discussion provides means to evaluate the robustness of a SCN design. But, what kind of SCN structure is likely to be robust? More specifically, what kind of risk mitigation constructs should be incorporated in our optimization models to obtain robust SCN designs? To answer these questions we look more closely at the notions of SCN responsiveness and resilience. At the operational level, short-term mitigation actions are required to deal with the variability of low-impact, as well as high-impact, business events: these are the domain of responsiveness policies. However, to deal with network threat situations, mitigation postures related to the SCN structure, but going beyond the standard design decisions discussed previously, are required: these are the domain of resilience strategies. Currently, most supply networks are incapable of coping with emergencies (Lee, 2004). According to Chopra and Sodhi (2004) most companies develop plans to protect against recurrent low-impact events, but they neglect high-impact low-likelihood disruptions.

Responsiveness

The aim of responsiveness policies is to provide an adequate response to short-term variations in supply, capacity and demand. They provide a hedge against randomness and hazards to increase the SCN expected value. For a given network structure, they shape the means that can be used to satisfy demands with available internal resources and with preselected external resource providers. Responsiveness policies are typically associated to resource flexibility mechanism, such as capacity buffers (Sabri and Beamon, 2000 and Chopra and Sodhi, 2004), production shifting (Graves and Tomlin, 2003), overtime and subcontracting (Bertrand, 2003); safety stock pooling and placement strategies (Graves and Willems, 2003); flexible sourcing contracts (Kouvelis, 1998; Semchi-Levi *et al*., 2002; Lee, 2004; Sheffi, 2005; Tomlin, 2006); and shortage response actions, such as product substitution, lateral transfers, drawing products from insurance inventories, buying products from competitors, rerouting shipments or delaying shipments (Shen *et al*., 2003; Gunasekaran *et al*., 2004; Tomlin, 2006). In SCN design models, responsiveness policies are usually assumed to be elaborated beforehand and, when using stochastic programming, they are reflected in the recourse anticipation structure of the model. For example, if lateral transfers are permitted, then second stage flow variables between production-distribution centers would be defined; if overtime is permitted within certain bounds, then recourse variables and constraints would be added to reflect this policy; if dual sourcing is permitted then flow variables from suppliers would be defined accordingly.

Resilience

Resilience, on the other end, is directly related to the SCN structure and resources, and hence to first-stage design variables. It can be seen as a strategic posture of deployed resources (facilities, systems capacity and inventories), suppliers and product-markets, as a physical insurance against SC risk exposure, providing the means to avoid disruptions as much as possible, as well as the means to bounce back quickly when hit. More general discussions of enterprise resilience are found in Van Opstal (2007) and on the Web site of the Center for Resilience (www.resilience.osu.edu) who defines resilience as “the capacity of a system to survive, adapt, and grow in the face of unforeseen changes, even catastrophic incidents”. Rice and Caniato (2003), Christopher and Peck (2004) and Sheffi (2005) conclude from empirical studies that business is in need of resilience strategies to deal effectively with unexpected disruptions. The main challenge is to elaborate resilience strategies providing an adequate protection from disruptions without reducing the SCN effectiveness in business-as-usual situations.

The aim of resilience strategies is to obtain a SCN structure reducing risks and providing capabilities for the efficient implementation of the responsiveness policies previously discussed. This can be done by avoiding or transferring risks (Manuj and Mentzer, 2008), and/or by investing in flexible and redundant network structures (Rice and Caniato, 2003; Sheffi, 2007). Avoidance strategies are used when the risk associated to potential product-markets, suppliers or facility locations is considered unacceptable, due for example to the instability of the associated geographical area. This may involve closing some network facilities, delaying an implementation, or simply not selecting an opportunity. Another way to avoid risks may be through vertical integration, i.e. the internalisation of activities. This may reduce risk through an improved control, but it converts variable costs into fixed costs. This is an incitation to produce internally for low risk product-markets and to outsource production for higher risk product-markets, thus transferring risks to suppliers. These are important tradeoffs that must be captured in SCN design models.

Responsiveness capabilities development may be flexibility or redundancy based. Flexibility based capabilities are developed by investing in SCN structures and resources before they are needed. Examples of design decisions providing such capabilities include selecting production/warehousing systems that can support several product types and real-time changes, choosing suppliers that are partially interchangeable, and locating distribution centers to ensure that all customers can be supplied by a back-up center with a reasonable service level if its primary supplier fails. Redundancy based capabilities involve a duplication of network resources in order to continue serving customers while rebuilding after a disruption. An important distinction between flexibility and redundancy based capabilities is that the latter may not be used (Rice and Caniato, 2003). Examples of redundancy based capabilities include insurance capacity, that is maintaining production systems in excess of business-as-usual requirements, and insurance inventory dedicated to serve as buffers in critical situations (Sheffi, 2005). The consideration of such responsiveness capabilities complicates SCN design models considerably. Although a few reliability models for location decisions have investigated some of these concepts (Snyder *et al*., 2006; Murray and Grubesic, 2007), much remains to be done to address the problem adequately.

Conclusion

A large literature is available on SCN design modeling. However, most of the models proposed deal with static-deterministic sub-problems, with a cost minimization objective. This falls short of current business needs. We argued in this paper that, in order to be more relevant, the SCN design models developed must seek to provide sustainable shareholder value. To do this, multi-period models under uncertainty, with expected value and robustness maximization objectives, must be elaborated. Also, more emphasis must be put on the adequate anticipation of network user's revenues and expenditures. Furthermore, depending on the quality of the information available on the future business environment, different types of uncertainties must be taken into account, namely randomness, hazards and deep uncertainty. Some stochastic programming models were proposed to deal with randomness, a few deep uncertainty models based on robust optimization were also proposed but, to the best of our knowledge, no SCN design model currently deals with hazards, and no models deals with plausible future scenarios based on more than one type of uncertainty. The case of hazards and deep uncertainty also raises the necessity to cope better with responsiveness policies and resilience strategies in our models.

All this indicates that several missing links are present in the SCN design literature. A comprehensive methodology to deal with all the elements raised in the paper is in need. The detailed analysis provided in the preceding pages provides several useful research directions to arrive at a comprehensive methodology for SCN design under uncertainty.

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