European Journal of Operational Research 203 (2010) 283–293

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Invited Review

The design of robust value-creating supply chain networks: A critical review

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ARTICLE INFO

Article history:
Received 25 September 2008
Accepted 15 June 2009
Available online 23 June 2009

Keywords:
Supply chain network design
Value creation
Uncertainty
Network disruptions
Robustness
Scenario planning
Location models
Capacity models
Resilience strategies

ABSTRACT

This paper discusses Supply Chain Network (SCN) design problem under uncertainty, and presents a critical review of the optimization models proposed in the literature. Some drawbacks and missing aspects in the literature are pointed out, thus motivating the development of a comprehensive SCN design methodology. Through an analysis of supply chains uncertainty sources and risk exposures, the paper reviews key random environmental factors and discusses the nature of major disruptive events threatening SCN. It also discusses relevant strategic SCN design evaluation criteria, and it reviews their use in existing models. We argue for the assessment of SCN robustness as a necessary condition 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. This paper contributes to framing the foundations for a robust SCN design methodology.

1. 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. It also involves decisions related to the selection of suppliers, subcontractors and 3PLs, and to the offers to make to product-markets. 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, storage, transportation and demand management decisions 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 activity levels. Furthermore, SCN strategic design decisions are made under uncertainty. The choice of performance metrics to assess the quality of network designs is another important challenge. Return on investment measures are often used by strategic decision-makers, but the design robustness is also an important dimension to consider. Despite a rich literature on SCN design, most published models consider only a subset of these issues.

This paper presents a critical review of the SCN design problem under uncertainty, and of the available models proposed 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 argues that the assessment of SCN robustness is necessary to ensure sustainable value creation. The paper is organized as follows. Section 2 presents an overview of the SCN design problem. Key issues of SCN design under uncertainty are discussed, including uncertainty sources, risk exposures and available data sources. A value-based framework for SCN strategic performance evaluation is also proposed. Section 3 provides a genesis of the literature on deterministic SCN design models, starting with classical location models. Section 4 discusses uncertainty modeling and risk assessment in the context of SCN. The work published, using approaches such as stochastic programming and robust optimization, is reviewed. Section 5 discusses robustness considerations in SCN design, and explores the responsiveness and resilience strategies proposed in the literature. The paper is concluded in Section 6 with a discussion on the need for a comprehensive SCN design methodology.

2. Overview of the SCN design problem

2.1. Strategic SCN design decisions

A typical SCN is shown in Fig. 1a). In short, the SCN design problem is the reengineering of such networks to enhance value

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doi:10.1016/j.ejor.2009.06.011

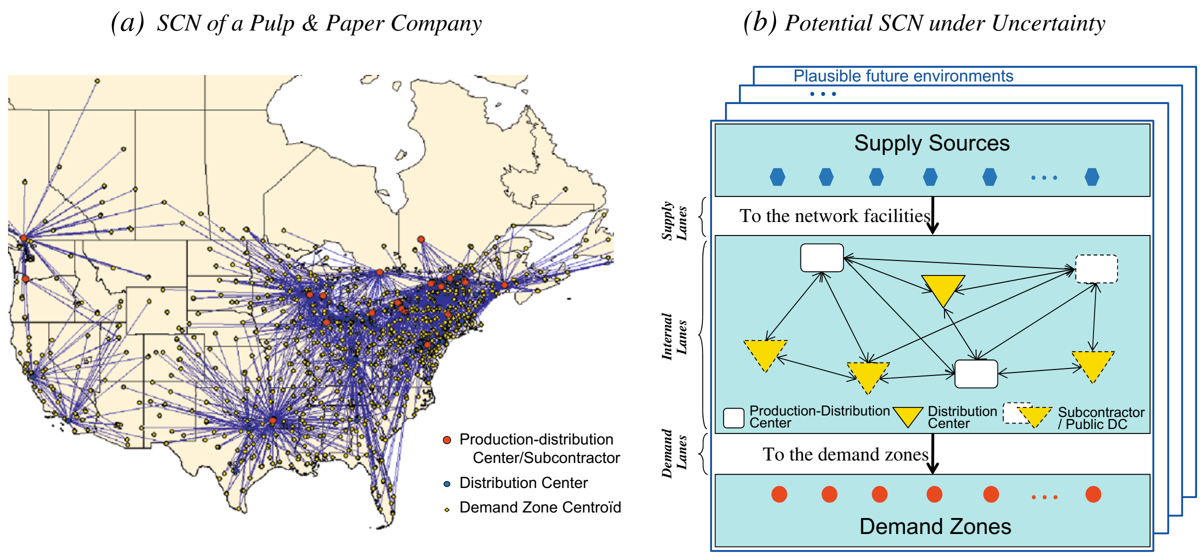

Fig. 1. Current and potential supply chain networks.

creation in the companies involved. In general, SC networks are composed of five main entity types: (i) external suppliers, (ii) plants manufacturing intermediate and/or finished products, (iii) distribution and/or sales centers (DC), (iv) demand zones, and (v) transportation assets. Note that the production–distribution facilities could be subcontractors or public warehouses, and that for-hire transportation could 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 as shown in Fig. 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. A SCN is reengineered by selecting a feasible sub-network of the potential network that optimizes some predetermined value criterion.

The main strategic questions addressed 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 be implemented? 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 be used (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.

On top of these strategic questions and of the number of potential internal and external entities involved, many factors 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. It may be reasonable to use a static one-year model when the decisions are limited to the selection of public warehouses, as most of the literature suggests. However, when supply agreements and manufacturing facilities last several decades, as in the forest product industry, static one-year models are far from suitable. This leads to a fourth complexity factor: uncertainty. Most models proposed in the literature are not only static, but deterministic. When long planning horizons are involved, the problem becomes dynamic and non-deterministic (e.g., stochastic). In addition, it is not sufficient to consider business-as-usual random variables such as demands, prices and exchange rates, but one should include extreme events such as natural disasters or terrorist attacks that may seriously affect the capabilities and the operations of the supply network.

Important investments are often required to implement strategic SCN decisions. Usually, executives and board members require an assessment of return on investments before making these decisions. The return comes from the net revenues generated by using a SCN during the planning horizon considered: sales revenues less SCN operating expenditures associated to day-to-day procurement, production, warehousing, inventory, transportation and demand fulfilment decisions. These operating revenues and expenditures must be anticipated in the SCN design model. This is usually done using aggregate production, inventory and flow variables, which provides only a raw estimation of real operating revenues and costs. With this in mind, the following sections focus on uncertainty, performance evaluation and related issues in the context of SCN design.

2.2. Supply chain networks under uncertainty

The future business environment under which a SCN will operate is generally unknown (see Fig. 1b). At best, several plausible future environments may be considered. Under stochastic assumptions, 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. Recent history has shown that a large spectrum of catastrophic events can be the source of major SCN deficiencies. Catastrophic events have been ignored by most businesses in the past, but a growing interest has been observed recently (Martha and Vratimos, 2002; Semchi-Levi et al., 2002; Helferich and Cook, 2002; Christopher and Lee, 2004; Chopra and Sodhi, 2004, Sheffi, 2005). Several categories of SCN risk sources were identified (Christopher and Peck, 2004; Kleindorfer and Saad, 2005; Wagner and Bode, 2006 and Tang, 2006b), and Chopra and Sodhi (2004) proposed an extended list of SC risk drivers. 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. 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. Three broad categories of SCN vulnerability sources are distinguished in Fig. 2: 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, 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. A review of potential impacts of these uncertainty sources on SC operations is found in Helferich and Cook (2002).

Assets and partners are located in specific geographical locations and regions. These regions and their associated public infrastructures (travel ways, terminals, ports, telecommunication networks, utilities…) are themselves exposed to natural disasters (hurricanes, earthquakes, blizzards, floods, forest fires…), major accidents (epidemics, chemical/nuclear spills…) and wilful attacks (terrorist attacks, political coup…). All these possible extreme events are important sources of SC uncertainty. Little or no information is usually available to determine *what could go wrong*, and the *likelihood* of asset, partner or infrastructure 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) suggested 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, facilities are generally insured. Thus, rebuilding and repairing costs 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, to our knowledge, no work to date has proposed a disruption severity modeling approach adequate for SCN design. The work done on SCN vulnerabilities (Helferich and Cook, 2002; Kleindorfer and Saad, 2005; Sheffi, 2005) suggest that 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.

Natural, accidental and wilful hazards data are generally available, but 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. Fig. 3a) for example provides a natural catastrophes exposure index based

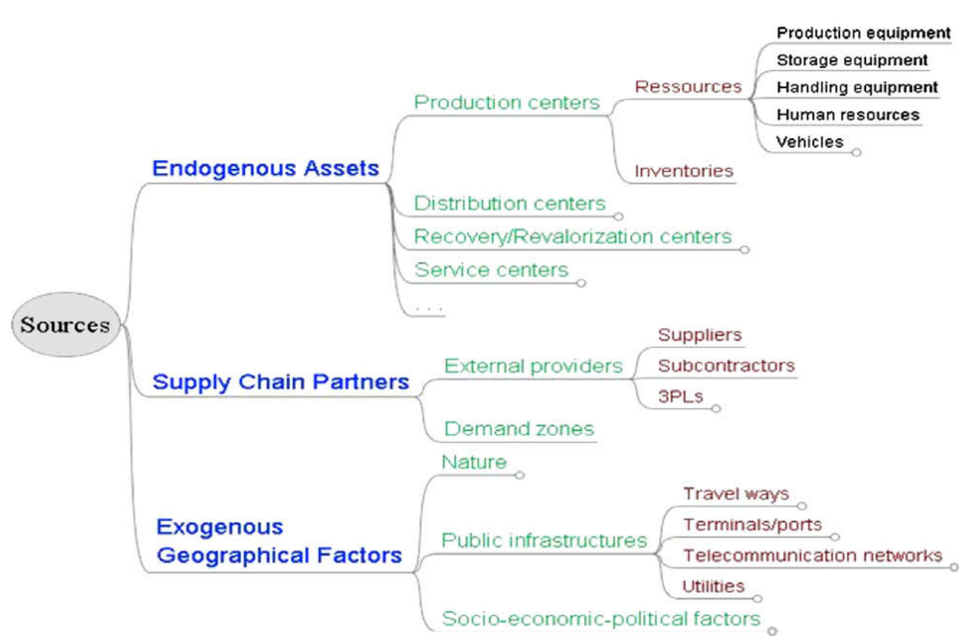

Fig. 2. Supply chain network vulnerability sources.

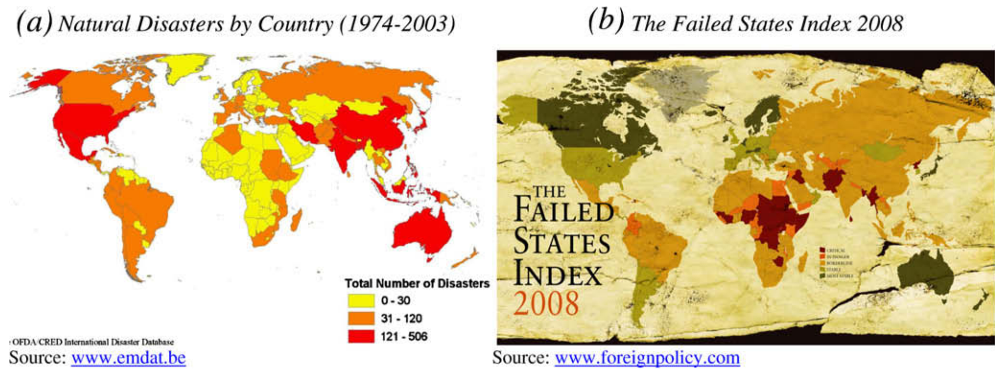

Fig. 3. Example of multi-hazard indexes.

on data provided by the *Centre for Research on the Epidemiology of Disasters*[1]. The Failed States Index presented in Fig. 3b) is a similar multi-hazard index designed to reflect the political stability of a country[2]. Other relevant multi-hazard indexes such as global competitiveness[3], industrial accident[4] and public infrastructure quality[5] scores may be relevant. An example of an empirical SC disruptions study involving multiple data sources is found in Craighead et al. (2007).

The risk matrix proposed by Norrman and Jansson (2004) summarizes key elements of the previous discussion (see Fig. 4). 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 difficult to predict and may have serious or catastrophic consequences, which makes them much harder to model in the SCN design process. 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).

2.3. 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

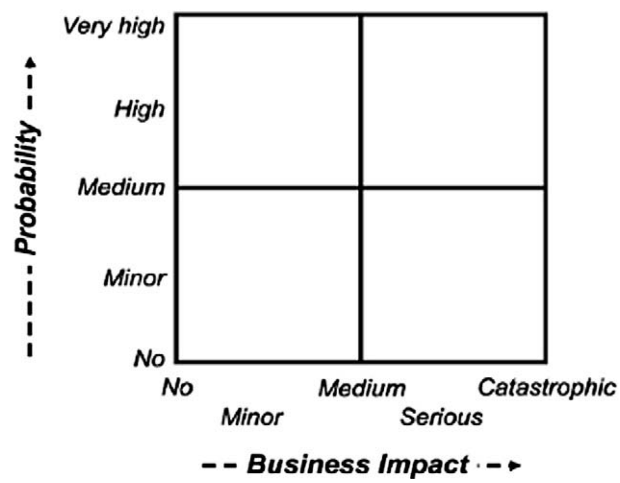

Fig. 4. Risk matrix (Norrman and Jansson, 2004).

$$\text{RCF} = (\text{Revenues} - \text{Operating expenses})(1 - \text{Tax rate}) \\ - \text{Capital expenditures}$$

In order to obtain 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. Often, 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)[6]. They also break these strategic metrics into 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 with SCN procurement, production, warehousing, storage, 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

[1] See www.cred.be. Other organizations such as the *Federal Emergency Management Agency* (www.fema.gov) and the *US Geological Survey* (www.usgs.gov) provide similar information.

[2] The Failed States Index 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.

[3] See 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).

[4] These indexes are based on the claims made to insurance companies (www.munichre.com).

[5] Calculated from databases such as the *CIA World Factbook* (www.cia.gov/cia/publications/factbook).

[6] Since ROCE = (Revenues – Operating expenses)/Capital employed, its use as an objective in a design model would however lead to a fractional program (Barros, 1995).

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. The net present value (NPV) of these revenues and costs over the life of the SCN must be calculated to evaluate the value of a SCN design.

The value drivers discussed above are not necessarily all relevant for SCN design. 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 Fig. 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 Fig. 1a). One of the 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 Fig. 5b), the objective must be to maximize residual cash flows.

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 outflows 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 values 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 way uncertainty is modeled and also 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. 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). Note that instead of trying to elaborate an adequate combined return measure, a multi-criteria decision approach may be used.

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, robustness is the quality of a SCN to remain effective for all plausible futures, responsiveness is the capability of a SCN to respond positively to variations in business conditions, and resilience is the capability of a SCN to avoid disruptions or quickly recover from failures. These three concepts are discussed in detail in what follows.

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

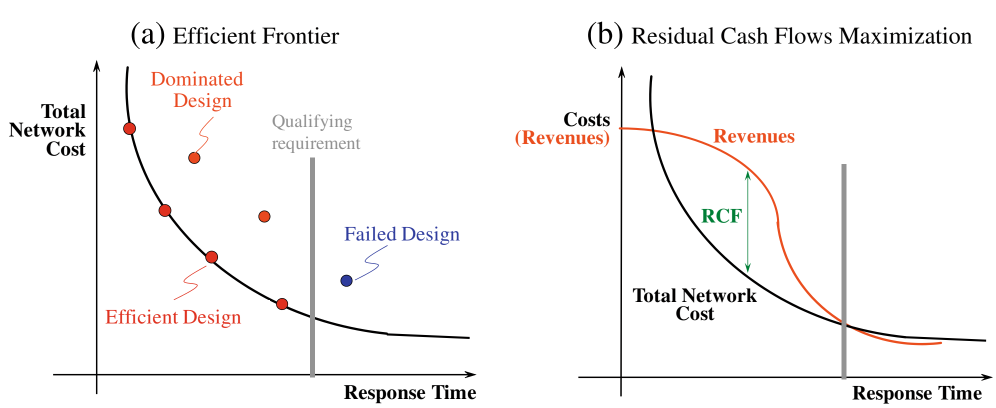

Fig. 5. Static design tradeoffs for a domestic supply chain network.

creation under uncertainty. So, 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. Therefore, the approach used to analyse SC vulnerabilities, and to model SCN structures, future business uncertainties and SCN responsiveness/resilience strategies is crucial. To the best of our knowledge, no comprehensive SCN design approach considering all these issues has been proposed in the literature. This paper charts directions for the development of a comprehensive SCN design approach through a representative review of the relevant literature. 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.

3. Deterministic SCN design models

Facility location models (Daskin, 1995; Drezner, 1995; Sule, 2001; Drezner and Hamacher, 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 are still being studied (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 (CFLPSS), the problem is much more difficult to solve. In fact, the generalized assignment sub-problem 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) solved 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) proposed Lagrangian relaxation procedures to solve two echelon CFLPSS's and CFLP's. Several heuristics were also proposed to solve these problems, based on interchange procedures (Kuehn and Hamburger, 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 are based on the following assumptions: (i) facilities capacity is predetermined, (ii) at most one production stage is considered, (iii) nodes and arcs of the network are within the same country, (iv) 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 precisely.

The importance of capacity as a decision variable in location problems was recognized early by Elson (1972). Nonetheless, explicitly integrating capacity decisions as SCN design variables is more recent. Some models consider capacity expansion as a continuous variable (Verter and Dincer, 1995) but, others more realistically 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 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. Shen (2007) has reviewed *integrated* location-routing, location-inventory and location-routing-inventory models. The first classification of location-routing problems is found in Laporte (1988). Several papers have studied different aspects of this problem (Nagy and Salhi, 1996; Prins et al., 2007; Berger et al., 2007). A comprehensive review of location-routing models and of their applications can be found in Nagy and Salhi (2007). Other contributions have considered the risk pooling effects of network cycle and safety stocks in location-inventory models (Ho and Perl, 1996; Daskin et al., 2002; Shen et al., 2003; Ambrosino and Scutella, 2005; Shen, 2007). Recently, Romeijn et al. (2007) has integrated inventory and transportations decisions into a two echelon SCN design model. Sabri and Beamon (2000) also proposed an 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 more closely operational decisions (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 by definition 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).

Several particular exact and heuristic methods were proposed to solve basic location–allocation problems. Decomposition methods have been proposed to solve more elaborated SCN design models (Geoffrion and Graves, 1974; Dogan and Goetschalckx, 1999; Paquet et al., 2004, Cordeau et al., 2006). Others have proposed to include valid inequalities in their model (Dogan and Goetschalckx, 1999; Paquet et al., 2004). In our opinion, most static deterministic SCN design models can now be solved efficiently with the recent versions of commercial solvers such as CPLEX and Xpress-MP. Melo et al. (2009) provide a recent review of the literature on the various extensions of location models discussed in this section.

4. SCN design models under uncertainty

The deterministic models discussed in the previous section provide a solid foundation for SCN design. Nonetheless, any design obtained based on these models has no guarantee of performance for any plausible futures. These models do not handle uncertainties and information imperfections about expected plausible future business environments. So, uncertainty modeling becomes an important challenge for more realistic SCN design. Uncertainty has different meaning and implications in a number of different fields. We therefore start this section with a relatively general discussion on various approaches used to model uncertainty. Then, we address SCN design models under different types of uncertainty.

The distinction between *uncertainty*, *risk* and *certainty* is an old issue of crucial importance (Knight, 1921). Rosenhead et al. (1972) proposed to distinguish between decision-making under certainty, risk and uncertainty. This characterization was subsequently adopted by several authors (Kouvelis and Yu, 1997; Snyder, 2006). According to these authors, 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), possibilities (Zadeh, 1978), belief functions (Shafer, 1990), rough sets (Pawlak, 1991) are example of other uncertainty modelling paradigms. Therefore, we suggest characterizing decision-making situations based on the quality of the information available: decisions are made under *certainty* when perfect information is available and under *uncertainty* when one has only partial (or imperfect) information (French, 1995; Zimmermann, 2000; Roy, 2005; 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 Fig. 4.

Under uncertainty, different quality of information may be available. The worst case is *total uncertainty* or complete ignorance. Three types of uncertainties may be distinguished when partial information is available: 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.

4.1. 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 distributions. 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 solve the resulting deterministic model. It is known though that the solution thus obtained is not necessarily optimal. Moreover, such solutions may be very bad or even unfeasible under specific scenarios (Sen and Higle, 1999). An alternative is to solve the resulting deterministic model for a subset of representative scenarios, 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. 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 because random variables are only considered during the *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. A random sample of scenarios selected with Monte Carlo methods may be used to overcome this difficulty (Shapiro, 2003). Scenario generation techniques were also proposed for multi-stage programs (Ducapova et al., 2000; Hoyland and Wallace, 2001).

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) developed 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), Vila et al., 2008 and Azaron et al. (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).

4.2. Hazard

High-impact extreme events should not be treated the same way as low-impact business-as-usual events. Moreover, identifying potential threats and assessing their risk are very challenging undertakings. 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 practical for the insurance industry, but it is not adequate for SCN design; considering each type of hazard separately is too cumbersome, and economic 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. 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.

4.3. Deep uncertainty

It is possible to elaborate plausible future scenarios under deep uncertainty. However, the information available is not sufficient to estimate an objective or subjective probability for 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 to imagine "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., 1996; 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 discussion of non-deterministic models, note that fuzzy sets were used by some authors to model site selection problems (Sule, 2001; Kahraman et al., 2003) and SCN design problems (Chen and Lee, 2006). A few papers based on the possibility 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.

5. Fostering robustness in SCN design

5.1. Robustness

The concept of *robustness* has raised a lot of discussion in the literature on decision-making under uncertainty. Roy (2002) suggested that 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; 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 with 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., 1996; 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 all plausible future scenarios (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. One necessarily selects a robust design, under randomness and hazards, by maximizing the expected value of these discounted cash flows. 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. Hites et al. (2006) introduced a multi-criteria evaluation of robustness. 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.

5.2. Responsiveness

Usually, responsiveness policies aim at providing 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, these policies shape the means that can be used to satisfy demands from internal resources and with preselected external 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; Tang and Tomlin, 2008). SCN design models usually assume that responsiveness policies are elaborated beforehand. When using stochastic programming, these policies 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.

5.3. Resilience

Resilience 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[7] 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.

Resilience strategies aim at obtaining 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 these concepts (Snyder et al., 2006; Murray and Grubesic, 2007), much remains to be done to address the problem adequately.

6. Conclusions

The body of literature on SCN design problems is extensive. However, in our opinion, several aspects of the problem are

[7] www.resilience.osu.edu

overlooked. Most design models make significant assumptions and simplifications falling short of current business needs. Several shortcomings and opportunities for research were identified in the previous pages, and we argued that a comprehensive methodology dealing with all relevant problem facets is in need. The main research directions proposed to develop a comprehensive methodology for SCN design under uncertainty are the following:

- **SCN risk analysis**. Numerous environmental uncertainties and SC vulnerabilities, ranging from business-as-usual randomness to major asset/partner failures, were discussed in the literature. However, in a specific context, the consequences of these event types can vary from catastrophic to low. For SCN design purposes, the random variables and vulnerability sources explicitly considered must be reduced to a manageable number. This requires the development of a multi-criteria filtering process, based on a subjective evaluation of the likelihood and severity of possible event types, to select the sources of uncertainty to incorporate in the SCN design model.
- **SCN hazards modeling**. A large literature exists on the modeling of various types of catastrophes however it is not adequate for SCN design. Considering each type of hazard separately is too cumbersome and one must rather work with multi-hazards having generic impacts on SCN resources/markets. The definition of multi-hazard arrival processes over multi-hazard zones is in itself a challenging problem. Adequate disruption severity metrics and recovery functions, related to key design variables/parameters such as facility/supplier capacity and customer demand, must also be elaborated. Very little work has been done in this area.
- **Scenario development and sampling**. Multi-period plausible future scenarios must be developed to support the optimization and the evaluation of SCN designs. In most practical situations, an infinite number of scenarios are possible but, given the complexity of the problem, only a few of them can be considered in the optimization process. Monte-Carlo methods can be used to generate some scenarios from the random variable distributions and the multi-hazard models, but this is not sufficient. An "importance" based sampling approach must be developed to ensure that all important plausible future facets (random, hazard and worst case events, evolutionary paths...) are covered in the small sample of scenarios selected.
- **Value-based SCN design models**. A large proportion of the SCN design models proposed in the literature minimize costs. This is not sufficient to help a business create and sustain a competitive advantage. To this end, the objective should be sustainable value creation. This has several implications: (i) the relationship between order winners and SC capabilities has to be understood and used to formulate demand and revenue functions, (ii) revenues and expenditures should be anticipated over a multi-period planning horizon, (iii) capital expenditures should be modelled closely and the firm financing constraints need to be taken into account. The ecological footprint of the SC is also increasingly linked to value creation. Design models considering these issues need to be developed. Current SCN design models anticipate revenues and expenditures through crude production, inventory and flow aggregations. The adequacy of this approach is to be challenged and alternative anticipation schemes should be considered.
- **Modeling for robustness**. SCN design models should be based on representative samples of plausible future scenarios, using stochastic programming and/or robust optimization approaches. Moreover, the objective should not be purely the maximization of expected value, but rather a strategic valuation measure incorporating aversion to RCF variability and to high-impact catastrophic events. This measure should weight scenarios based on random, hazard and worst case events adequately, and in an integrated way. To our knowledge, no SCN design model of this type is currently available.
- **Modeling resilience and responsiveness**. Deterministic SCN design models do not take responsiveness and resilience into consideration, and most stochastic models take them into account only partially. The explicit incorporation of risk mitigation constructs, such as back-up suppliers or insurance capacity, in our optimization models would lead to more robust SCN designs. Although some of these concepts were investigated with simple location models, much remains to be done to address this opportunity adequately.
- **Solution methods**. Although static deterministic SCN design models can often be solved with modern commercial solvers, this is far from being true for realistic multi-period stochastic models. Very few efficient heuristic methods have been developed to solve these models and this is another promising research direction.

All these elements make the elaboration of SCN design models capturing the essence of real problems quite complex. We recognise though that the models formulated should strike a balance between realism and tractability, or solvability, using data available in typical practical contexts. Achieving this objective remains a considerable challenge. In our opinion, however, the research directions proposed in this paper provide a path towards a SCN design methodology fostering sustainable value creation.

Acknowledgement

This research was supported in part by NSERC Grant no. DNDPJ 335078-05.

Appendix A. Supplementary references

Supplementary references associated with this article can be found, in the online version, at doi:10.1016/j.ejor.2009.06.011.

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