Chapter 10: How Much Flexibility Does It Take to Mitigate Supply Chain Risks?

Christopher Tang* and Brian Tomlin

*Corresponding author: UCLA Anderson School, UCLA, Los Angeles, CA 90095, USA

10.1 Introduction

In light of the number of severe, and well publicized, supply disruptions over the past decade, it is not surprising that firms are instituting risk assessment programs to gauge their vulnerability. Using both formal quantitative methods and informal qualitative ones, risk assessment programs attempt to systematically uncover and estimate supply chain risks. What is surprising, perhaps, is that there has not been a concomitant investment in risk reduction programs. While the exact reasons for this are not known, a number of researchers, e.g., Rice and Caniato (2004), Zsidisin et al. (2001) and Zsidisin et al. (2004), have offered the following as potential explanations for why risk reduction efforts are less widespread: (1) Some firms are not familiar with the different approaches for managing supply chain risks; (2) Lacking credible estimates for the probability of a major disruption, many firms cannot perform the formal cost/benefit or return on investment (ROI) analyses to justify risk reduction investments.

Given the inherent challenge of performing a rigorous ROI analysis, Tang (2006) argued that risk reduction programs must provide strategic value to the firms regardless of the occurrence of major disruptions. Indeed, disruption risk is only one of a number of risk categories firms need to account for in their risk programs. Routine risks, e.g., those frequently-occurring problems that cause mismatches in supply and demand or higher-than-expected procurement costs, also need to be considered. In their empirical study across a wide range of industries, Hendricks and Singhal (2005) found that supply chain glitches (resulting in a supply-demand imbalance) had a considerable, and long-lasting, negative impact on a firm's operating performance. Risk reduction efforts directed toward these routine risks may also have the side benefit of making a firm less vulnerable to rare-but-severe supply disruptions.

Risks are often measured on two dimensions – the likelihood of occurrence and the impact if the event occurs. Risk reduction strategies can, therefore, be categorized according to whether they tackle the likelihood or the impact. In the first category (likelihood), some strategies, such as the Poka-Yoke system, aim to prevent a risk from occurring, while others, attempt to reduce the likelihood. For instance, Lee and Wolfe (2003) illustrate how certain technologies, say, biometric systems for positive identification of personnel and smart container systems for monitoring internal temperature and pressure of each container, can be used to prevent containers being tampered with during the shipping process. Applying TQM and Six Sigma principles, it is possible for firms to reduce the likelihood of certain supply-chain risks. For example, the Container Security Initiative (CSI) is based on the inspection-at-source principle of TQM. Under this initiative, all containers are to be pre-screened at the port of departure before they arrive at U.S. ports so as to reduce the likelihood of a terrorist attack in the U.S. The second risk-reduction category (impact) refers to those strategies that focus on reducing the negative impact of a risk, and that is the focus of this chapter. In particular, we focus on the power of flexibility to moderate the impact of many different risk types.

Li and Fung (www.lifung.com), the largest trading company in Hong Kong for durable goods such as textiles and toys, has a supply network of over 4,000 suppliers throughout Asia and this network provides it with a degree of flexibility to absorb risks by quickly adapting to market conditions. In 1997, the Indonesian Rupiah devalued by more than 50% and many Indonesian suppliers were unable to deliver their orders to their U.S. customers as they were unable to pay for imported materials. Li and Fung reacted to the situation quickly by (1) shifting some production to other suppliers in Asia, and (2) providing financial assistance to those affected Indonesian suppliers to ensure business continuity. (The reader is referred to St. George (1998) for further details.) The flexibility to shift production amongst its suppliers enabled Li and Fung to mitigate the impact of the currency crisis. Flexibility, in its many forms, is a critical strategy for reducing the negative impact of supply chain risks. Viewing flexibility through the prism of the "Triple-A" principles (Alignment, Adaptability and Agility) espoused by Lee (2004), flexibility enhances a firm's adaptability and agility.

Tang (2006) highlighted the strategic value of 9 different risk reduction programs that each call for an increase in a different type of supply chain flexibility. While it is clear that flexibility provides strategic value to a firm and it enhances the supply chain resiliency, it is unclear how much flexibility is needed to mitigate supply chain risk. Without a clear understanding of the benefit associated with different levels of flexibility, firms are reluctant to invest in risk-reducing flexibility strategies, especially if a lack of precise risk data prevents a detailed ROI analysis. In this chapter, we present a framework for examining the benefits of flexibility. Based on our analysis, it appears that firms can obtain significant strategic value by implementing a risk reduction program that calls for a relatively low level of flexibility. Our findings highlight the power of flexibility, and provide convincing arguments for deploying flexibility to mitigate supply chain risks.

The rest of the chapter is organized as follows. In the next section, we discuss some key supply chain risks and the role that flexibility can play in mitigating the risks. In Sect. 10.3, we introduce a flexibility measure and review some stylized models intended to illustrate the power of flexibility. Based on our models, we show that only a small amount of flexibility is required to mitigate risk. Section 10.4 concludes this chapter. We note that this chapter is based on research presented in Tang and Tomlin (2007).

10.2 Supply Chain Risks and the Role of Flexibility

In this section, we categorize and discuss a variety of supply chain risks and how flexibility can be deployed to mitigate the negative impact of these risks.

10.2.1 Supply Risks

In addition to the risk of severe-but-rare disruptions (discussed as a separate category later), firms face a number of more routine, but still-important, supply risks.

- *Supply Cost Risk*. The effective per-unit price that a firm pays can fluctuate over time due to variability in raw material prices and exchange rates, among other things. For example, Intercon Japan's connector manufacturer sourced a special type of bronze from a single metal supplier (Asahi Metal). This resulted in Intercon Japan having very little control over the raw material cost, and it, therefore, bore a significant risk of uncertain connector costs. (The reader is referred to Tang (1999) and references therein for details.)
- *Supply Commitment Risk*. Under a partnership agreement between Canon and Hewlett-Packard (HP), Canon has been the exclusive supplier of engines for the HP LaserJet printers. To keep supply costs down, the agreement dictated that HP place its order 6 months in advance and, furthermore, HP was not allowed to change the order quantity once the order was placed. This arrangement gave rise to a commitment risk for HP as it could not react to changes in demand by revising previously-placed orders. (The reader is referred to Lee (2004) for details.)
- *Supply Continuity Risk*. There are a number of risks (quality, labor unrest, etc.) that can interrupt supply for a short period of time. In April 2007, Ford temporarily closed 5 assembly plants in response to faulty transmission parts provided by a supplier but, according to a Ford spokesperson, they "certainly [did] not expect it to be a long period of time." (See Reuters 2006 for further details.) Rare-but-severe risks that cause lengthy interruptions are discussed separately in Sect. 10.2.4.

Firms can deploy a number of flexibility strategies to mitigate the negative impact of these supply risks. In particular, they can deploy one of the following:

- *Flexible Supply Strategy via Multiple Suppliers*. As discussed above, Intercon Japan faced a supply cost risk as a result of the single-sourcing strategy of its connector supplier. Firms that maintain an active set of pre-qualified suppliers for a given component can shift order quantities across these suppliers in response to variations in supplier costs. As discussed in the introduction, Li and Fung availed of its multiple-supplier strategy to mitigate supply cost risks by ordering from suppliers with the lowest costs. Clearly a firm has more supply flexibility as the number of suppliers increases but does it need a lot of suppliers, or just a few, to effectively mitigate supply cost risk? This is one of the questions addressed in this chapter. We note that a multiple-supplier strategy can mitigate routine supply continuity risk by enabling the firm to increase orders placed at other suppliers if one supplier suffers a short-term interruption.
- *Flexible Supply Strategy via Flexible Supply Contracts*. As discussed above, HP faced a supply commitment risk because they were not allowed to revise their order quantity once submitted to Canon. To reduce HPs supply commitment risk, Canon agreed to offer HP some adjustment flexibility, that is, they allowed HP to adjust their order quantity upward or downward, but limited the adjustment to be no more than a few percent. This type of supply contract, one that specifies an upward/downward adjustment limit, is called a Quantity Flexible (QF) contract. QF contracts enable firms to mitigate their supply-commitment risk by shifting their order quantities across time. Clearly a firm has more flexibility as the adjustment limit in a QF contract increases but does it need a large limit or will a small one suffice to effectively mitigate the firm's commitment risk? This is one of the questions addressed in this chapter.

10.2.2 Process Risks

To improve internal quality and capabilities, firms have invested heavily over the past decade in programs such as Total Quality Management (TQM), Lean Manufacturing and Six Sigma. However, internal operations (including inbound and outbound logistics) are still susceptible to issues that can cause fluctuations in effective capacity and quality. For example, in 2004 IBM announced that yield problems at its plant in East Fishkill, New York contributed to the $150 million first-quarter loss by its microelectronics division (Krazit 2004). The lower-than-expected yields reduced the plant's effective capacity and limited IBM's ability to meet customer demand.

Consider a simple case in which a firm produces two products, each in a plant dedicated to that product. If one plant happens to be suffering from a lower-than-expected capacity, then the firm may be unable to meet demand for the associated product. Firms can mitigate process risk, e.g., fluctuating-capacity, by pursuing the following strategy.

- *Flexible Process Strategy via Flexible Manufacturing Processes*. In this strategy a firm configures plants to be able to produce a range of products. Again, consider the simple two-product, two-plant example but now imagine that the firm has configured both plants to be capable of producing both products. In this case, the firm can shift some production of the affected product to the unaffected plant, thereby reducing the risk of not being able to meet demand. (We note that, analogous to the flexible process strategy, a firm could institute a flexible supplier strategy to mitigate some of the supply risks discussed earlier.)

For firms that produce many different products, it may be prohibitively expensive to configure plants to be able to produce every product. While this "total flexibility" would offer the greatest protection against process risk, is this level of flexibility necessary for effective mitigation. This is one of the questions addressed in this chapter.

10.2.3 Demand Risks

Customer demand for a product fluctuates over time, and, therefore, uncertainty about the level of demand for a product is a routine risk faced by all companies. However, volume uncertainty is not the only demand risk firms need to manage. To increase revenue, many firms sell their product in more than one country and may need to localize their product for each country. For example, to satisfy certain country-specific requirements such as power supply and language driver, HP has to develop multiple versions for each model of their DeskJet printers. Each version serves a particular geographical region (Asia-Pacific, Europe, or Americas). Due to uncertain demand in each region, HP faces the problem of overstocking certain printers in one region and under stocking certain printers in other regions. (The reader is referred to Kopczak and Lee (1993) for details.) This example reflects a risk facing companies that sell multiple products: not only is the demand volume unpredictable but so is the demand mix, e.g., the demand for each of the product variants. Demand risks therefore encompass uncertainties in both volume and mix.

Firms can deploy a number of flexibility strategies to mitigate the negative impact of these demand risks. In particular, they can deploy one of the following:

- *Flexible Product Strategy via Postponement.* To reduce the overstocking and under stocking costs associated with its demand-mix risk, HP redesigned its DeskJet printers by delaying the point of product differentiation. Specifically, HP first manufactures and ships generic printers to the distribution centers in different regions. These generic printers are then customized for different country-specific markets at each distribution center. The generic printers are produced according to a make-to-stock system, while the country-specific printers are customized in a make-to-order manner. This postponement strategy has enabled HP to respond to demand changes quickly and effectively. (The reader is referred to Lee and Tang (1997) for a detailed description of various mechanisms for delayed product differentiation such as modular design, standardization, commonality, etc., (see Feitzinger and Lee 1997) for a detailed description of successful implementations of various postponement strategies at HP.) As the generic printers are completely flexible, delaying the point of product differentiation until the last stage of the process would offer HP the highest level of product flexibility for mitigating demand risks. However, the cost of postponing the point of differentiation until the last stage of the process can be excessive and may not be necessary to effectively mitigate demand risk. Later in this chapter, we address the question of whether limited flexibility, e.g., placing the point of differentiation early in the production process, can effectively mitigate demand risk.

- *Flexible pricing strategy via Responsive Pricing*. While flexibility is often associated with operations, certain companies have developed important flexibilities in sales and marketing. Dell is well known for their ability to shape consumer demand in response to supply availability. If there is a mismatch in demand and supply, Dell can rapidly adjust the price of computer configurations to better match demand to the available supply. The combination of their online ordering system and their supply-chain visibility gives them the flexibility to shift demand across products in response to supply-demand mismatches. We note that Dell is also able to influence demand not only through prices, but also through the use of the radio buttons on the site that recommend certain configurations. As with operational flexibility, there is the question of how much marketing flexibility is necessary to effectively mitigate demand risk. Focusing on pricing flexibility, we investigate this question later in the chapter.

10.2.4 Rare-but-Severe Disruption Risks

According to a study conducted by Computer Sciences Corporation in 2004, 60% of the firms reported that their supply chains are vulnerable to disruptions. While severe disruptions might be rare for any particular company, there have been a number of significant disruptions in a variety of industries over the past decade. When Chiron, the flu-vaccine maker for the US market, halted production due to a bacterial contamination problem at Chiron's plant in Liverpool in 2004, Chiron announced that they would not be able to deliver 48 million doses of vaccine for the U.S. market. This shortfall amounted to 50% of the total estimated demand and, so, the shortage threatened the health, and, indeed, life of many senior citizens. (The reader is referred to Brown 2004 for details.) Other notable disruptions include the following: in 2006, due to a fire hazard, Dell recalled 4 million laptop computer batteries made by Sony; Ericsson lost 400 million Euros after their supplier's semiconductor plant caught on fire in 2000; Land Rover laid off 1400 workers after their supplier became insolvent in 2001; Dole suffered a large revenue decline after their banana plantations were destroyed after Hurricane

Mitch hit South America in 1998; and Ford closed 5 plants for several days after all air traffic was suspended after September 11 in 2001. (The reader is referred to Christopher 2004; Martha and Subbakrishna 2002; Monahan et al. 2003; and Chopra and Sodhi 2004 for more details on some of these disruptions.)

Many of the flexibility strategies discussed above, e.g., multiple suppliers, quantity-flexible contracts, flexible processes, and responsive pricing, can also be used to mitigate the negative impact of a severe disruption, e.g., Sheffi (2001) and Sheffi (2005). For example, as the supply of certain components from Taiwan was affected by an earthquake, Dell's response was to lower the price of certain products so as to entice their online customers to "shift" their demands to other Dell computers that utilized components from other countries. The capability to influence customer choice enabled Dell to improve its earnings in 1999 by 41% even during a supply crunch (Martha and Subbakrishna 2002). To avoid the influenza-vaccine crisis from occurring in the future, the U.S. government could consider offering certain economic incentives to entice more suppliers, instead of the current two, to re-enter the flu vaccine market. With more potential suppliers, the U.S. government would have the flexibility to shift their orders to different suppliers when faced with a severe disruption to one supplier.

As noted in the introduction, firms may be reluctant to invest in flexibility to reduce the impact of rare-but-severe disruptions because a lack of precise likelihood estimates prevents them from conducting accurate cost-benefit analyses. However, the fact that the types of flexibility that mitigate the more routine supply, process and demand risks also mitigate rare-but-severe disruption risks should encourage managers to invest in flexibility.

10.2.5 Other Risks

While we focus in this chapter on the role that flexibility can play in mitigating supply, process and demand risks, it is important to recognize that these are not the only supply chain risks. Firms should also include the following in their risk management programs:

- *Intellectual property risks*. While outsourcing or off-shoring can result in lower manufacturing costs, it makes it difficult to protect intellectual property (IP). For example, even though the reform of the Intellectual Property protection law has made some good progress after China's WTO entry in 2001 (http://www.chinaiprlaw.com/english/news/news5.htm), some unfortunate incidents can still occur in China. For instance, multinational firms are not necessarily protected legally when their Chinese suppliers start producing unauthorized products using virtually identical design and materials. To elaborate, when the relationship between New Balance shoes and one of their Chinese suppliers went sour, this Chinese supplier started producing different types of shoes using a logo that resembles the New Balance's block "N" saddle design. New Balance filed a lawsuit in China without success and the saga continues. The reader is referred to Chandler and Fung (2006) for more details. As such, it is still difficult to protect IP and to eliminate the risk of counterfeits when a multinational firm outsources their manufacturing operations to their Chinese suppliers under certain licensing or contractual agreements.

- *Behavioral risks*. As the number of partners increases in a global supply chain, the level of visibility and control can be reduced significantly. For instance, according to a study conducted by AMR Research in 2006, if supply chain visibility is relatively low: few companies have demand/inventory information from downstream partners and over 56% of the companies take more than 2 weeks to sense changes in actual demand. The low visibility level and the low control level reduce the "confidence" of each supply chain partner regarding the following information: the replenishment lead time/order status quoted by upstream partners, demand forecasts provided by downstream partners, etc. Christopher and Lee (2004) argue that a low confidence level may induce damaging behavior such that the entire supply chain enters a "risk spiral" that can be described as follows. Each supply chain partner either "inflates" their order or "disguises" their on-hand inventory because of the lack of confidence in the replenishment lead time, demand forecasts, etc. The confidence level deteriorates further as every partner starts gaming the system, and hence, the "risk spiral" continues. To break this vicious cycle, supply chain visibility, timely communication, and coordinated corrective actions are needed to restore the confidence level of each supply chain partner.
- *Political risks*. A global supply chain can fall victim to political upheaval or political interference. Airbus offers an example of the latter risk. Airbus, a four-nation consortium, is facing an opportunity loss of 4.8 billion Euros due to a 2-year delay in launching the super-jumbo A380. In addition to technical problems associated with the wiring system, political battles may be a key reason for the delay because of the political pressure to "balance" the interests of 4 different European countries. As reported in Gumbel (2006), Airbus' parent, EADS is struggling to develop a restructuring plan to replace political bargaining with industrial logic.
- *Social risks*. Firms are not immune from changing views as to what constitutes socially-acceptable labor practices. Because Nike sourced their athletic shoes in various developing countries such as China, Pakistan, Thailand, Vietnam, etc., many citizens raised their concerns over the issue of Child Labor/working children. According to the International Labor Organization, over 250 million children between the ages of 5–14 are working and 61% of the working children are found in Asia. As some concerned citizens became watchdogs and launched websites, such as www.saigon.com/~nike, boycotting Nike products, Nike came under pressure to develop various social responsibility programs to respond to public opinion (www.nike.com/nikebiz).

10.2.6 The Role of Flexibility in Mitigating Risks

In this chapter we focus on the 5 types of flexibility described above and summarized in Table 10.1. Since our focus is on the benefit of flexibility, we do not consider the cost for implementing flexibility in our models. One can combine the cost and the benefit associated with different levels of flexibility to determine the optimal level of flexibility. However, the determination of the optimal level of flexibility is beyond the scope of this chapter.

Table 10.1 Flexibility strategies for reducing supply chain risks

Supply chain risk	Flexible strategy reducing the negative impact of the risk	Underlying mechanism
Supply	Flexible supply via multiple suppliers. Flexible supply via flexible supply contracts.	Shift orders quantities across suppliers. Shift order quantities across time.
Process	Flexible process via flexible manufacturing processes.	Shift production quantities across internal resources (plants or machines).
Demand	Flexible product via postponement flexible pricing via responsive pricing.	Shift production quantities across different products. Shift demands across different products.

Although these five types of flexible strategies have been described separately, firms can, of course, implement some of these strategies jointly. Here are some examples.

A firm can combine the multiple-supplier strategy and the flexible-supply-contract strategy by implementing different flexible supply contracts with multiple suppliers. Hence, a firm can establish a “portfolio” of suppliers, say, a long-term inflexible supply contract with one supplier at a lower supply cost, and a more flexible supply contract with another supplier at a higher supply cost. This portfolio approach has enabled many firms to mitigate their supply chain risks. Specifically, Zara, the most profitable fashion company in Europe, sources their stable items from China at low cost with very little flexibility in changing order quantity and makes their fashion items at their own plant in Coruna. The reader is referred to Ferdows et al. (2004) for details. In addition, Billington (2002) highlighted how this portfolio approach mimics the financial portfolio theory and how it enabled HP to reduce the average and the standard deviation of the procurement cost.

By combining the multiple-suppliers and the flexible-manufacturing-process strategies, a firm can have multiple plants with flexible manufacturing processes in multiple countries so that the firm can shift the production volume of a portfolio of products from one plant to a different plant quickly. This combined strategy offers the “operational flexibility” that would allow a firm such as Li and Fung to reduce supply risks including currency exchange risks. The use of operational flexibility to exploit uncertain exchange rates is called “operational hedging” and it has been examined by various researchers including Huchzermeier and Cohen (1996) and Kouvelis et al. (2006). The reader is referred to Boyabatli and Tokay (2004) for a review of recent research in the area of operational hedging.

For the sake of completeness, we note that, in addition to these five types of flexible strategies, there are other strategies that can enhance the overall flexibility of the entire supply chain. For example, to reduce the exposure to various types of supply chain risks, one can shorten the overall lead time by redesigning the supply chain network. For instance, Liz Claiborne launched a campus in China by bringing all stages of the textile supply chain to the campus. This campus concept enabled Liz Claiborne to reduce the lead time from concept to retail store from the existing 10–50 weeks to fewer than 60 days (Tang 2006a). Sun Microsystems implemented the “one touch” supply chain strategy by shifting most of the manufacturing operations to its contract manufacturers. With fewer steps in the supply chain process, this “one touch” strategy has enabled Sun Microsystems to reduce lead time, reduce cost, and increase supply chain visibility (Gary 2005). In this chapter, however, we restrict our attention to the 5 types of flexibility described above.

10.3 The Power of Flexibility: How Much Flexibility Do You Need?

In the last section, we described and highlighted the benefits of 5 types of flexibility strategies. We now examine a fundamental question: How much flexibility does it take to mitigate supply chain risks? To help answer this question, we first introduce a general flexibility measure that can be used for each of the flexibility types described in the last section. Let f denote the level of flexibility for a particular strategy such that a higher f refers to a more flexible supply chain. For example, in the multiple-supplier strategy, f would refer to the number of suppliers, whereas, in the process-flexibility strategy it would refer to the number of plants each product could be produced in. Each of the five flexibility strategies has a minimum and maximum level of possible flexibility. The minimum level, denoted by $f_{\min}$, corresponds to a supply chain with no flexibility, e.g., $f = 1$ in the multiple-supplier strategy. The maximum level, denoted by $f_{\max}$, corresponds to a supply chain with the highest level of flexibility theoretically possible, e.g., $f = \infty$ in the multiple-supplier strategy.

Let $P(f)$ be a performance metric for a supply chain with flexibility level f. Depending on the context, the performance metric $P(f)$ might be measured in terms of cost or profit. For example, in the case of the multiple-suppler strategy that aims to mitigate the impact of uncertain supplier costs, $P(f)$ might be the expected per-unit cost. We can measure the “relative” benefit of flexibility by using the following:

$$V(f) = \frac{\dfrac{P(f) - P(f_{\min})}{P(f_{\min})}}{\dfrac{P(f_{\max}) - P(f_{\min})}{P(f_{\min})}} = \frac{P(f) - P(f_{\min})}{P(f_{\max}) - P(f_{\min})} \tag{10.1}$$

Notice that $V(f)$ measures the percentage of benefit obtained by a supply chain with flexibility level f as compared to one with the maximum possible level of flexibility. Specifically, $V(f_{\min}) = 0\%$ and $V(f_{\max}) = 100\%$. Given the performance metric $V(f)$ associated with a flexibility level f, we can evaluate the impact of flexibility associated with each of the 5 flexibility strategies.

Clearly, a more flexible supply chain performs better than a less flexible supply chain and, therefore, the measure $V(f)$ is increasing in f. However, what is less clear is whether $V(f)$ is concave or convex in f. (See Fig. 10.1) If $V(f)$ is concave, then significant benefits associated with a flexibility strategy can be obtained with a low level of flexibility; e.g., when f is small. On the other hand, if $V(f)$ is convex, then a firm needs to invest in a high level of flexibility in order to obtain significant benefit. In the remainder of this section, we analytically examine the flexibility measure $V(f)$ for each of the 5 flexibility strategies. This examination is based on the analysis of different stylized models as reported in Tang and Tomlin (2007)

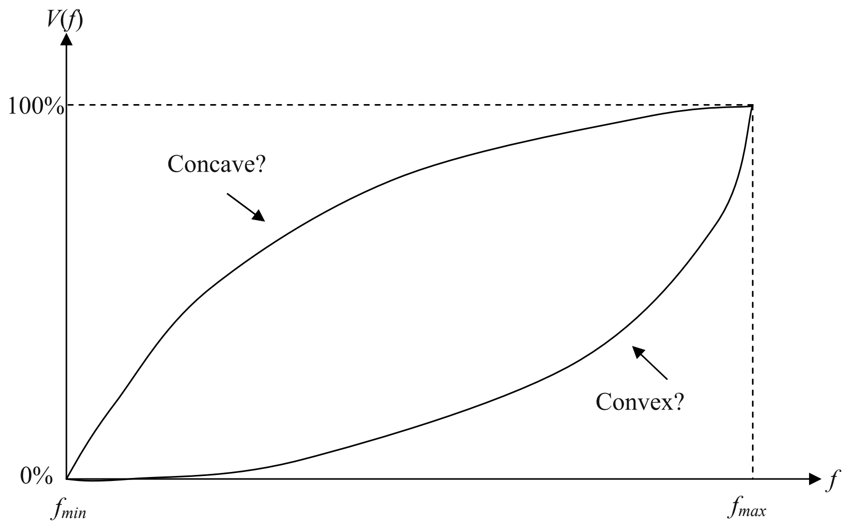

Fig. 10.1 The relative benefit of flexibility

As we will see in the following pages, $V(f)$ is in many instances concave. In other words, firms can significantly reduce their supply chain risk using only limited flexibility. This is of great practical importance. The higher the degree of flexibility required the more costly the investment and, therefore, the more likely it is that a precise ROI analysis will be required to justify the investment. The fact that a relatively low degree of flexibility is often sufficient may enable managers to justify flexibility investments more readily, even if precise estimates of costs, impacts, and likelihoods are not available.

10.3.1 Supply-Cost Risk: The Benefit of Flexibility via Multiple Suppliers

Firms faced with uncertain supplier costs may choose to maintain an active set of suppliers so that, at any given time, it can place orders with those suppliers who currently offer the lowest cost. Consider the following stylized example in which a manufacturer has an unlimited number of pre-qualified suppliers with uncertain supply costs. Let the unit cost of supplier $j = 1,2,.., \infty$, denoted by C_j, be \$5, \$10, or \$15 with equal probability 1/3. To satisfy the demand in each period, we assume that the manufacturer always orders from the supplier who offers the lowest unit cost. In this case, the flexibility level f can be defined in terms of the number of active suppliers and the performance metric $P(f)$ can be defined as the expected unit cost associated with sourcing from f suppliers.

Suppose that the manufacturer is committed to sourcing from one exclusive supplier, e.g., it chooses an inflexible sourcing strategy. Then the expected unit cost, denoted by $P(f_{min}) = P(1)$, is given as: $P(1) = 1/3\ (5 + 10 + 15) = \$10$. Next, consider the case in which the manufacturer can source from 2 suppliers, and so it has some flexibility. Because the manufacturer selects the supplier with a lower unit cost, the corresponding expected unit cost associated with sourcing from 2 potential suppliers, denoted by $P(2)$, can be expressed as $P(2) = E(\mathrm{Min}\{C_1, C_2\})$, e.g., the expected value of the minimum of the two supplier costs. By enumerating all possible scenarios, it can be shown that $P(2) = \$7.8$. Similarly, one can show that $P(3) = \$6.6$, $P(4) = \$5.9$, $P(5) = \$5.6$, and so on. Finally, if the manufacturer sources from $f_{max} = \infty$ suppliers, then $P(f_{max}) = \$5$. In this case, it is easy to check that $V(2) = 44\%$, $V(3) = 68\%$, $V(4) = 82\%$, and $V(5) = 88\%$. Therefore, 44% of the benefit associated with an infinite number of suppliers can be achieved when a firm orders from just 2 suppliers. As shown in Tang and Tomlin (2007), the underlying finding illustrated by this example, that $V(f)$ is concave, holds true regardless of the specific costs and probabilities used. Therefore, limited flexibility is very effective at managing supply-cost risk.

10.3.2 Supply-Commitment Risk: The Benefit of Flexibility via a Flexible Supply Contract

In many supply chains, contracts with suppliers limit the ability of a manufacturer to alter a previously placed order. A contract might specify an upper bound on the percentage by which the manufacturer can revise, upwards or downwards, a previous order. In this case, the flexibility level f can be defined in terms of the percentage bound placed on quantity revisions. Consider the following stylized supply chain comprising a supplier, a manufacturer and a retailer.[1] The supply cost is \$$c$ per unit, the wholesale price is \$$p$ per unit, and all unsold units have \$0 salvage value. We consider a 2-period model in which the retailer places his order only at the end of period 1. However, due to the supply lead time, the manufacturer needs to place an order with the supplier at the beginning of period 1, which occurs prior to the actual order to be placed by the retailer. The ordering process, as described here, is similar to the process as depicted in the Sport Obermeyer case prepared by Hammond and Raman (1995).

At the beginning of period 1, the manufacturer estimates that the retailer will order a quantity $D = a + \varepsilon$ at the end of period 1, where ε corresponds to the uncertain market condition to be realized in period 1. Based on the information about c, p, and D, the manufacturer orders x units at the beginning of period 1. Under a flexible supply contract, the manufacturer is allowed to modify this order from x units to y units after receiving the actual order from the retailer at the end of period 1. Consider the case when the retailer orders $d = a + e$ at the end of period 1, where e is the realized value of ε. Under the f-flexible contract, the modified order y must satisfy: $x(1–f) < y \le x(1 + f)$, where $f \ge 0$ represents the allowable percentage adjustment as specified in the contract. Let $P(f)$ be the manufacturer's expected profit under the f-flexible contract based on the optimal initial order x^* and the optimal adjusted order y^*. When ε is uniformly distributed, Tang and Tomlin (2007) showed that the benefit associated with the f-flexible supply contract is increasing and concave in f. Therefore, significant benefits associated with the f-flexible contract can be obtained when f is relatively small, say 5%. Again, we find that limited flexibility is very effective at managing supply-cost risk.

10.3.3 Process Risk: The Benefit of Flexibility via Flexible Manufacturing Processes

Process risks, resulting from yield or quality issues for example, cause fluctuations in the effective capacity of plants. Firms that produce multiple products can mitigate this capacity variability by building plants that have the ability to produce more than one product. Consider the following stylized example in which a firm sells 4 different products (1, 2, 3, and 4), each with a demand of $D_1 = D_2 = D_3 = D_4 = 100$ units. The firm owns 4 different plants; the capacity of each plant j = 1, 2, 3, 4, denoted by C_j, is equal to 50, 100, or 150 units with equal probability 1/3. In this setting, there is no redundant capacity in the sense that the average total aggregate capacity of all 4 plants is 400 units, which is equal to the total aggregate demand of all 4 products. To illustrate the benefit of process

[1] We note that Tsay and Lovejoy (1999) analyzed QF contracts previously. However, due to the multi-period nature of their model, an analytical characterization of the value of flexibility is not feasible.

flexibility, we focus on the following system configurations: a system is considered to possess "f-flexibility" when each plant has the capability of producing exactly f products and when the system is configured as illustrated in Fig. 10.2 which depicts the f-flexibility[2] system for $f = 1, 2, 3, 4$. When $f = 1$, each plant j is capable of producing product j only, where j = 1, 2, 3, 4. Hence, 1-flexibility system corresponds to the system with no flexibility, and so $f_{\min} = 1$. The 4-flexibility system corresponds to a system with total flexibility, and so $f_{\max} = 4$.

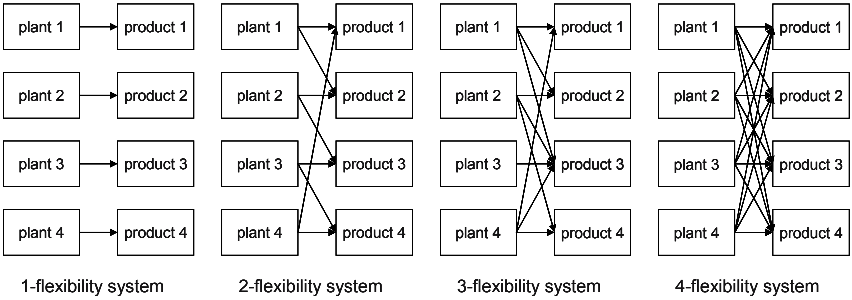

Fig. 10.2 f-flexibility manufacturing systems

Since each plant has 3 capacity scenarios, there are 81 possible plant-capacity scenarios for each of the f-flexibility manufacturing systems. By considering the probability of each of the 81 possible plant-capacity scenarios, Tang and Tomlin (2007) showed that the expected sales associated with the f-flexibility system, denoted by $P(f)$, is given as follows: $P(1) = 333.33$, $P(2) = 367.9$, $P(3) = 367.9$, $P(4) = 367.9$. By noting that $V(2) = 100\%$, we can conclude that significant benefits associated with process flexibility can be obtained with limited flexibility, e.g., the 2-flexibility system. (We refer the reader to Tang and Tomlin (2007) for a more general treatment of managing process risks with limited process flexibility.) Therefore, to reduce process risks, it is sufficient to deploy a manufacturing system with limited flexibility.

10.3.4 Demand Risk: The Power of Flexibility via Postponement

Postponement, or delayed differentiation, is an increasingly popular strategy for managing demand risk. By postponing the point of differentiation, a firm has

[2] To simplify our exposition, we restrict attention to this particular type of system configurations, which Jordan and Graves have referred to as chain configurations. We note that our usage of f for the level of flexibility corresponds to the parameter h in Jordan and Graves (1995). The reader is referred to Jordan and Graves (1995) for an in-depth analysis of a model in which different plants are capable of producing different numbers of products.

increased flexibility in matching its production mix to the demand mix. It can, therefore, reduce the amount of inventory required to provide a high customer service. The following description is a simplified version of the postponement model presented in Lee and Whang (1998). A firm produces 2 end-products by using a 2-stage production process. The firm adopts an "*f*-postponement" strategy when it takes *f* time periods to produce a generic semi-finished product at the first stage and (T- *f*) time periods to customize these generic products into two different end-products. Figure 10.3 depicts a process under the *f*-postponement strategy. Since the generic product is flexible, the production process is more flexible as *f* increases. We note that $f_{\min} = 0$ and $f_{\max} = T$. For any *f*-postponement strategy, define the performance metric *P*(*f*) to be the optimal average inventory level of the two end-products.

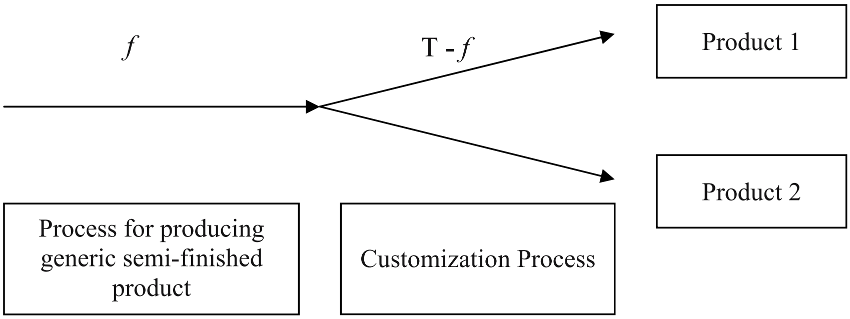

Fig. 10.3 An illustration of the f-postponement strategy

Let $D_i(t)$ denote the demand for product *i* to be realized t periods in the future, where i = 1, 2. Let the demand follow a Random Walk (RW) model; e.g., $D_i(t) = \mu_i + \varepsilon_{i1} + \varepsilon_{i2} + \ldots + \varepsilon_{i,t-1} + \varepsilon_{it}$, where i = 1, 2, $t = 1, \ldots, T$, and the ε_{it} are independently and identically distributed normal random variables with mean 0 and standard deviation σ. Lee and Whang (1998) proved the following result: *V*(*f*) is increasing and concave in *f*. Therefore, significant benefits associated with postponement can be obtained even if the point of differentiation is placed at an early stage of the production process, e.g., when *f* is small. Again, we find that limited flexibility delivers much of the benefits.

10.3.5 Demand Risk: The Power of Flexibility via Responsive Pricing

To this point, we have focused on operational flexibilities such as maintaining multiple suppliers or configuring plants to be capable of processing multiple products. We now turn to a marketing flexibility, namely the flexibility of delaying the time at which prices must be set. While van Mieghem and Dada (1999) study the benefit of complete price postponement, we want to investigate the value of limited flexibility, or in other words, partial price postponement.

Consider a stylized model in which a manufacturer sells 2 substitutable products (1 and 2) through a retailer over a selling season that starts after period T. At the beginning of period 1, the manufacturer estimates that the total demand for product i over the selling season is given by $D_i(1)$, where $D_i(1) = a_i + S_{i1} + S_{i2} + \ldots + S_{i,T-1} + S_{iT} - b\ p_i + \delta(p_j - p_i)$, i, j = 1, 2, j ≠ i. In this case, a_i represents the primary demand of product i, S_{it} represents the "shock" to the primary demand of product i occurring in period t, b measures price sensitivity, and δ measures product substitutability. In our model, we assume that the shocks S_{it} follows an auto-regressive process of order one, e.g., AR(1), so that $S_{it} = \rho_i S_{i,t-1} + \varepsilon_{it}$ for i = 1,2, and t = 1, 2, …, T, where $0 \leq \rho_i < 1$, and ε_{i1}, ε_{i2}, …, $\varepsilon_{i,T-1}$, $\varepsilon_{i,T}$ are independently and identically distributed normal random variables with mean 0 and standard deviation σ_i. Without loss of generality, we set $S_{i0} = 0$ for i = 1,2.

Consider the case in which the manufacturer and the retailer are both owned and controlled by a single firm. We also assume that the manufacturer has the capacity to meet the actual demand of each product over the selling season that starts after period T. In this integrated supply chain, the unit cost of each product i is given as c and we only need to decide on p_i; e.g., the retail price of each product i. (The wholesale price is determined internally between the manufacturer and the retailer.) Suppose that the firm has the flexibility to set and announce the retail price of each product i at the end of period f, where $f = 1, \ldots, T$. Once the retail price is announced, we assume that the firm is committed to sell each product at p_i during the selling season that starts after period T. This implies that the firm must announce the actual retail price no later than the end of period T.

Clearly, the firm would benefit from the flexibility of postponing its pricing decision because it would allow the firm to gain more accurate information about the market demand before setting the actual retail price. To formalize this thinking, we say that the firm employs an "f-timing" strategy when the actual retail price is determined at the end of period f. Thus, timing flexibility increases as f increases, and $f_{min} = 1$ and $f_{max} = T$. Define the performance index $P(f)$ as the optimal expected profit associated with an f-timing strategy. Tang and Tomlin (2007) proved that $P(f)$ is concave increasing for $0 < \rho_i < 1$ and linear increasing for $\rho_i = 0$. Since $P(f_{min}) = P(1)$ and $P(f_{max}) = P(T)$ are independent of f, one can conclude that $V(f)$ is also increasing and concave in f for $0 < \rho_i < 1$. As with the operational-flexibility cases, we find that many of the benefits associated with price postponement can be obtained for low values of flexibility, e.g., when f is small.

10.4 Concluding Remarks

Throughout this chapter, we have focused our attention on "defensive" flexibility strategies, that is, strategies that mitigate the negative impact of undesirable events. This focus should not be allowed to obscure the fact that flexibility can also be used as a "proactive" mechanism that enables firms to compete more effectively in the marketplace. Let us consider three successful examples of firms taking advantage of flexibility to compete.

- Seven-Eleven Japan, in order to reduce the process risks arising from variable traffic conditions in Japan, has implemented a flexible delivery strategy that utilizes trucks, motorcycles, boats, and even helicopters to ship their products from various distribution centers to their stores throughout Japan. This flexible delivery strategy has allowed Seven-Eleven Japan to ensure a Just-In-Time delivery of fresh products to its stores. This capability has helped Seven-Eleven Japan to become the most profitable convenience store in Japan. In addition, this multi-mode delivery system earned the respect of many Japanese earthquake victims in Kobe when Seven-Eleven Japan was the first company to deliver 64,000 rice balls in Kobe within 6 h by using 7 helicopters and 125 motorcycles. The reader is referred to Lee (2004) for details.
- Honda, in response to Yamaha's development, in the late 1980s, of low cost and high quality motorcycles, improved its process flexibility so that it could introduce new models of motorcycles more frequently. This flexibility strategy allowed Honda to gain significant market share from Yamaha. (The reader is referred to Stalk and Hout [1990] for details.) More recently, Zara, the Spanish fashion company, has earned its reputation as the "Fast Fashion" company. Specifically, Zara used a flexible strategy to speed up both the design and the production process so that it can change its complete fashion collection within 2–3 weeks. Consequently, Zara has become Europe's most profitable fashion company with double digit growth rate annually for the last 10 years. The reader is referred to Ferdows et al. (2004) for details.
- The airline industry was revolutionized in the 1990s by the implementation of flexible pricing strategies via dynamic pricing. When selling limited seats on an airplane with uncertain demand, airlines can adjust their ticket price dynamically so as to meet uncertain demand with limited supply. Cook (1998) reported that dynamic pricing has generated "almost $1 billion of incremental annual revenue" at American Airlines. In the context of e-tailing, dynamic pricing can increase online traffic. For instance, Lands' End's Overstock site (http://www.landsend.com) generated additional traffic after they introduced the "on the counter" event, whereby, every Saturday, Lands' End puts a new group of products for sale at a reduced price. The price of each item is then reduced by 25% if it is not sold by Monday, 50% by Wednesday, and 75% by Friday. Pre-announcing the markdown price schedule encourages many online shoppers to monitor the sales of these items so as to time their purchase accordingly. As online traffic increases, the total sales can increase as well.

In this chapter, we have examined the benefits of different flexibility strategies in the context of supply chain risk management. By considering 5 different flexibility strategies, and reviewing the stylized models presented in Tang and Tomlin (2007), we have shown that a firm does not need to invest in a high degree of flexibility to mitigate supply, process and demand risks; most of the benefits are obtained at low levels of flexibility.

In addition to these 5 different flexibility strategies, there are other flexibility strategies worth considering. One other common flexibility strategy is “inventory pooling.” When Toyota introduced its first hybrid car, the Prius, in the U.S. market in 2000, demand was highly uncertain because it was very unclear if U.S. consumers would embrace the hybrid concept. To encourage Toyota dealers to sell Prius without incurring the risk of overstocking, Toyota decided to own and stock all Prius at a central location and to take dealers’ orders via the internet (Lee et al. 2005). The success of the Prius inventory pooling concept was key to convincing the dealers to share Scion’s inventories among dealers when Scion was launched in the U.S. in 2003. Along with inventory pooling, creating a flexible workforce via cross-trained teams is another promising flexibility strategy. So et al. (2003) reported the benefits (in terms of productivity) associated with flexible cross-trained teams at the Federal Reserve Bank in Los Angeles.

We hope that the findings presented in this chapter and the arguments presented in Tang (2006a) provide a convincing argument for implementing flexibility strategies. In many real-life settings, exact cost-benefit analyses of flexibility investments are not feasible due to limitations of data availability. However, the robustness of the insight that only limited flexibility is needed to mitigate risk should encourage firms to build flexibility into their supply chains. Of course, when implementing a particular strategy in a particular context, a firm needs to establish a structured evaluation process that includes risk identification, risk assessment, decision analysis, mitigation and contingency planning. The reader is referred to Zsidisin et al. (2001) and Zsidisin et al. (2004) for a discussion of structured approaches.

References

AMR (2006) AMR Research Report on Managing Supply Chain Risk. AMR Research, Inc.

Billington C (2002) HP Cuts Risk with Portfolio Approach. Purchasing Magazine Online, February 21.

Brown D (2004) How U.S. Got Down to Two Makers of Flu Vaccine. Washington Post, October 16.

Boyabatli O, Tokay B (2004) Operational Hedging: A Review with Discussion. INSEAD working paper.

Chandler C, Fung A (2006) Not Exactly Counterfeit. Fortune, May 1, pp. 108–116.

Chopra S, Sodhi M (2004) Avoiding Supply Chain Breakdown. Sloan Management Review, vol. 46, pp. 53–62.

Christopher M, Lee H (2004) Mitigating Supply Chain Risk Through Improved Confidence. Cranfield School of Management working paper.

Feitzinger E, Lee H (1997) Mass Customization at Hewlett Packard: The Power of Postponement. Harvard Business Review, vol. 75, pp. 116–121.

Ferdows, K, Lewis M, Machuca J (2004) Rapid Fire Fulfillment. Harvard Business Review, vol. 82, pp. 104–117.

Gumbel P (2006) Trying to Untangle Wires. Time Europe Magazine, October, (http://www.time.com/time/europe/magazine/printout/0,13155,1543879,00.html).
Hammond J, Raman A (1995) Sport Obermeyer, Ltd. Harvard Business School Case # 5-696-012.
Hendricks K, Singhal V (2005) Association Between Supply Chain Glitches and Operating Performance. Management Science, vol. 51, pp. 695–711.
Huchzermeier A, Cohen M (1996) Valuing Operational Flexibility Under Exchange Rate Risk. Operations Research, vol. 44, pp. 100–113.
Jordan W, Graves SC (1995) Principles on the Benefits of Manufacturing Process Flexibility. Management Science, vol. 41, pp. 577–594.
Kopczak L, Lee H (1993) Hewlett-Packard: DeskJet Printer Supply Chain. Stanford Graduate School of Business Case.
Kouvelis P, Dong L, Su P (2006) Operational Hedging Strategies and Competitive Exposure to Exchange Rates. Olin School of Business, (Washington University) working paper.
Krazit T (2004) Trouble in East Fishkill? IBM chip group struggles. InfoWorld.com, April 21.
Lee H (2004) The Triple-A Supply Chain. Harvard Business Review, vol. 19, pp. 102–112.
Lee H, Tang CS (1997) Modeling the Costs and Benefits of Delayed Product Differentiation. Management Science, vol. 43, pp. 40–53.
Lee H, Whang S (1998) Value of Postponement. In Produce Variety Management: Research Advances, eds. T.H. Ho and C.S. Tang, Kluwer Publishers.
Lee H, Wolfe M (2003) Supply Chain Security Without Tears. Supply Chain Management Review, January/February issue, pp.12–20.
Lee H, Peleg B, Whang S (2005) Toyota: Demand Chain Management. Stanford Business School Case #GS42.
Martha J, Subbakrishna S (2002) Targeting a Just-in-Case Supply Chain for the Inevitable Next Disaster. Supply Chain Management Review, September issue.
Reuters (2006) Ford Shuts Down Truck Plants for Part Problem. April 27. Reuters.com.
Rice B, Caniato F (2004) Supply Chain Response to Terrorism: Creating Resilient and Secure Supply Chains. Supply Chain Response to Terrorism Project Interim Report, MIT Center for Transportation and Logistics, MIT, Massachusetts.
Sheffi Y (2001) Supply Chain Management under the Threat of International Terrorism. International Journal of Logistics Management, vol. 12, pp. 1–11.
Sheffi Y (2005) Building a Resilient Supply Chain. Harvard Business Review, vol. 10, pp. 3–5.
So K, Tang CS, Zavala R (2003) Model for Improving Team Productivity at the Federal Reserve Bank. Interfaces, vol. 33, pp. 25–36.
St. George A (1998) Li and Fung: Beyond ‘Filling in the Mosaic’. Harvard Business School Case # 9-398-092.
Stalk G, Hout T (1990) Competing Against Time. The Free Press, New York.
Tang CS (1999) Supplier Relationship Map. International Journal of Logistics: Research and Applications, vol. 2, pp. 39–56.
Tang CS (2006a) Robust Strategies for Mitigating Supply Chain Disruptions. International Journal of Logistics: Research and Applications, vol. 9, pp. 33–45, 2006a.
Tang CS (2006b) Perspectives in Supply Chain Risk Management. International Journal of Production Economics, vol. 103, pp. 451–488.
Tang CS, Tomlin B (2007) The Power of Flexibility for Mitigating Supply Chain Risks. Anderson School (UCLA) working paper.
Tsay AA, Lovejoy WS (1999) Quantity Flexible Contracts and Supply Chain Performance. Manufacturing & Service Operations Management, vol. 1, pp.89–111.

van Mieghem J, Dada M (1999) Price Versus Production Postponement: Capacity and Competition. Management Science, vol. 45, pp. 1631–1649.
Zsidisin G, Panelli A, Upton R (2001) Purchasing Organization Involvement in Risk Assessments, Contingency Plans, and Risk Management: An Exploratory Study. Supply Chain Management: An International Journal, pp. 187–197.
Zsidisin G, Ellram L, Carter J, Cavinato J (2004) An Analysis of Supply Risk Assessment Techniques. International Journal of Physical Distribution and Logistics Management, vol. 34, pp. 397–413.