

Supply portfolio risk

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In a single period framework, we develop a supply portfolio risk assessment tool for raw material procurement in the presence of supply risk (owing to contract breaches), demand risk and the spot price risk. Contract breaches are operational risk events that are classified under the “Clients, Products and Business Practices” category of the Basel II framework. We allow for the negative financial impact of intentional long-term fixed price contract breaches to be mitigated by using the spot market. The manufacturer uses the spot market to procure their need in the presence of a contract breach as well as to handle the shortfall/excess in customer demand. We use the CreditRisk⁺ framework, well known in finance literature, to extend the single supplier model to a portfolio of suppliers. This extension enables us to obtain, in the context of supply risk, the entire loss distribution at the portfolio level. In particular, akin to the value-at-risk statistic in finance, one can easily obtain a simple yet effective quantile measure of supply risk, coined as supply-at-risk, for a portfolio of long-term fixed price supply contracts.

1 INTRODUCTION

Supply chains today are becoming longer and more complex. They function in an increasingly ambiguous, uncertain and competitive environment. Firms are often procuring over longer distances and from possibly many more sellers and markets while switching more frequently to minimize the procurement costs. Academics as well as industry professionals are realizing that the types of risks being created in supply chains are very different and harder to identify and manage than those in the past.

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As explained by Kleindorfer and Saad (2005), understanding these risks and the interactions among them, has become critical to the operation of robust supply chains. Ritchie and Brindley (2007) also demonstrate the need for an integrated risk management perspective for supply chains. In the business consulting world, there is a growing interest in the identification and management of supply chain risks. Sheffi (2007) states that firms need to become more resilient and robust to prevent breakdowns and losses along the supply chain. A recent Deloitte Research report by Kambil and Mahidhar (2005) points to the need for timely information and control processes for effective risk management. More recently, in a global survey conducted by McKinsey & Co, Muthukrishnan and Shulman (2006) present various supply chain risks and firms' mitigation strategies. A third of the respondents in this survey stated that the supplier reliability risk has concerned them in their strategic/operational planning cycles.¹ Patents filed recently by IBM, GM and Cisco explicitly deal with managing various supply chain risks.² As observed in many different industries, major risks in supply chains are operational risks. One important source of operational risk in supply chains is that of contract breach. In the first half of 2005, Peabody Energy Corporation being one of world's largest private-sector coal company reported huge losses due to contract breach by one of its suppliers:

“. . .The Company recorded contract losses of approximately \$34 million in the quarter ended March 31, 2005, primarily related to the breach of a coal supply contract by a producer. The estimated loss related to the supply contract breach reflected amounts accrued for estimated costs to obtain replacement coal in the current market . . .” (Peabody (2005))

This risk of contract breach is the main focus of our work. Contract breach is a type of operational risk event classified under the “Clients, Products and Business Practices” category of the Basel II framework. It becomes especially important in the manufacturing context where there is often a strong need for a steady stream of supply to production facilities. In such cases, since demand (for raw materials at the production facility) is reasonably assured, buyers are using long-term contracts to mitigate the price risk. However, this exposes them to a significant source of risk that the long-term contracts may be breached by the sellers. In the event of breach, the manufacturer will have to start engaging other suppliers to attempt an alternate solution to the lost supply. We assume that finding another long-term supplier quickly and cost-effectively prior to the expected delivery date is not possible. Consequently the buyer goes to the spot market to procure their need. Incorporating the existence of a spot market is one of the key aspects of our model. The applicability of our framework is limited by the fact that not all raw materials have active liquid spot markets. Industrial goods such as copper, aluminum, tin and

¹Furthermore, 29% of the respondents counted the commodity shortages and price fluctuations as an important supply chain risk.

²These patents are associated with Publication numbers US2002/0188496A1, US2004/0260703A1 and US2006/0085323, respectively.

zinc may have liquid spot and futures markets. However, for commodities such as steel, pulp and some types of chemicals, market liquidity is a major issue.

In any case, spot markets are in general becoming increasingly liquid and transparent around the world with the extensive use of converging information technologies. As market frictions go down, the sellers may bypass the buyers and directly trade in the spot markets. In contrast, we also observe a reverse trend such that Chinese firms increasingly bypass the open markets to prevent paying high prices and directly go to the commodity sources, eg, African countries, to procure critical commodities such as zinc, uranium, timber, etc (Behar (2008)). An editorial comment that appeared in the *Financial Times* (Bove (2006)) demonstrates the financial impact of lower contract prices for Chinese steel buyers when the iron ore price soars in the spot market. Most recently, this trend is becoming more pronounced in steel markets. According to Matthews (2008b), ArcelorMittal, the largest global steel maker, sell only 20% of their steel via contracts, the rest of the capacity is sold directly to the spot market where higher profit opportunities lie. In such a volatile global commodity markets, the risk of deliberate contract breaches is high and therefore unexpected consequences have to be planned for. Recently, as the spot market prices began to plummet, contract breaches by the buyers of the commodities became commonplace. As noted by Matthews (2008a), iron ore buyers are turning to the spot market instead of paying much higher negotiated contract prices to the sellers. One such example is the case of Australian iron-ore producer Mount Gibson Iron Ltd stating that in November 2008, three of its customers had defaulted on their contracts to purchase iron ore in the spot market.

Haksöz and Seshadri (2007) suggest that the breach event (that is *ex post* intentional by the seller, but *ex ante* unforeseen by the buyer) be incorporated into the contract at the beginning of the relationship as an explicit abandonment option. By providing this option as an incentive to the seller, the buyer is able to lock-in a fixed price until the end of the contract duration, which will give a steady stream of supply, strongly mitigating the price risk. Creating these incentives is becoming necessary as the spot markets become increasingly developed making it increasingly difficult for buyers to obtain favorable fixed prices from the sellers.

Our model builds upon this notion of an abandonment option for contract breach by explicitly allowing for a fine to be paid in the event of contract breach. The commodity seller has to pay the fine as a remedy for breach in order to reduce the loss to the buyer. However, such fines are considered as lump sum payments that do not necessarily compensate for the price and demand risks borne by the buyer. One recent example reported by Reuters-UK (2008) is the forward aluminum contract cancellation by Century Aluminum Co by paying a total of US\$1.7 billion to Swiss-based Glencore International AG. Century Aluminum Co states that they would like to sell their production capacity to the ever-increasing spot market.

We treat the procurement problem in a single period setting and are rewarded by semi-explicit solutions. An important enhancement of our model over the above prior studies in this direction is that we extend the basic model to a portfolio of supply contracts. We do this using the CreditRisk⁺ framework, which is well known in the finance and insurance literature. The *Deloitte Research* report by

Kambil and Mahidhar (2005) mentioned earlier emphasizes the importance of the high-impact–low-probability losses and increasing interdependencies in supply chain disruptions. CreditRisk⁺ can be effectively used to model dependencies in loss types and analytically characterize the tail of the loss distribution. Given our emphasis on supply chain disruptions, our work relates strongly to issues in operational risk management. Please refer to the book by Panjer (2006) for a theoretical perspective, Cruz (2002) for a practice oriented view and McNeil *et al* (2005) for mathematical tools on operational risk management.

It is noteworthy that our use of CreditRisk⁺ differs significantly from prior financial and actuarial studies. These have used CreditRisk⁺ to understand the impact of unfortunate unforeseen losses from individual exposures aggregating into a loss distribution at the portfolio level. Such unfortunate losses are typically associated with poorly performing firms or industries. In contrast we exploit the CreditRisk⁺ setup to focus on intentional contract breaches which may happen in the exact opposite circumstances, namely the spot markets performing much better than expected *a priori*. The main contributions of this paper are twofold. First, by combining supply loss and spot price risk together with demand risk it comprehensively quantifies the overall financial impact of a supply contract breach. This is a contribution towards risk assessment at the individual supplier level. Second, by computing the loss probability distribution from potentially several such supply contract breaches it provides an effective tool to assess and measure the risk in supply contracts at a portfolio level. The loss distribution yields an estimate of supply-at-risk, which can be defined in a similar manner to value-at-risk (VaR) in the finance literature, and which can summarize the risk profile of a buyer and make the impact of supply disruptions on shareholder wealth more transparent. Dollar exposure to breach at contract level and dollar loss probability distribution at portfolio level are both useful inputs for contract design. In particular they can be analyzed to optimally determine the actual contract duration, contract price and the fine payable in the event of contract breach. In a single contract model, Haksöz and Kadam (2008) show that while minimizing the supply loss risk, the breach fine becomes one of the critical parameters that cannot be naively designed.

It may be possible to use the portfolio component of our setup in the context of more general definitions of contract breaches: not just those motivated by favorable spot price realizations. It may also be possible to do this for supply disruption events apart from contract breaches, for example, production and transportation disruptions, accidents, fires, other operational risk events occurring at the suppliers' processes, etc. However, we do not explore these angles in this paper. Note that these operational risk events can be classified under the "Business Disruption and System Failures" and "Damage to Physical Assets" categories of the Basel II framework. Such a generalization for various interrelated operational risk events, if possible, will require a more careful definition of "exposure amounts" defined later in the paper. In the current setup these exposure amounts are guaranteed to be positive in the event of a supply contract breach. This may not be possible in the context of a wider notion of supply disruption.

Surely, intentional contract breaches may initiate long legal disputes. In this paper, we ignore these legal costs that may arise after the contract breach and focus on operational losses. Furthermore, it seems logical that the buyer may also intentionally breach the contract and end up paying legal damages. For instance, Snaveley (2006) describes the case of Visteon Corp that paid American Axle & Manufacturing Inc an arbitration award of nearly US\$14.9 million for violating an agreement to buy forgings in December 2001. In this paper, we ignore the possibility of buyer's contract breach.

The organization of the paper is as follows. Section 2 reviews the relevant previous work. In Section 3, we present our main model for a single seller–buyer setting in a single period. In Section 4, we generalize this model and obtain the supply risk measure for a portfolio of contracts. Then, we provide an illustrative case study to demonstrate the value of the risk measure in a real-life setting. Finally, we conclude with a general discussion and future research directions in Section 5.

2 RELATED LITERATURE

Our research relates to different streams of literature in operations management and finance. One relevant stream is the supply chain procurement in the presence of a spot market and the valuation of supply contracts. A recent review is made by Haksöz and Seshadri (2007) that covers many aspects of supply chain procurement in static/dynamic settings with different types of uncertainty (demand, price) in the presence of a spot market. The authors also develop an abandonment option written in the long-term contract at the beginning of the contract duration. This option gives the right but not the obligation to abandon the long-term contract any time before the end of the contract duration. They value this option as an American option with dividend paying stocks and approximated the value. Based on their findings, interesting managerial insights are derived that are useful in the negotiation and contract design phase of bilateral procurement relationships that gain importance in today's global, ever-changing markets. The framework we propose extends their work by incorporating demand uncertainty for the buyer and combining the effect of price and demand risks.

A seminal paper related to the problem we address is by Ritchken and Tapiero (1986). They address the optimal design of options contracts that will meet the risk–reward preferences of a buyer in the presence of demand and price uncertainties. Li and Kouvelis (1999) study risk sharing contracts with price uncertainty. Later, Martínez-deAlbéniz and Simchi-Levi (2005), Wu *et al* (2002) and Spinler *et al* (2003) have studied the supply chain contracting problem in different settings where options could be designed and exercised in addition to the spot and long-term procurement to mitigate demand and price risks. Most recently, Haksöz and Seshadri (2009) studied the production and trading strategy of a commodity manufacturer that can intelligently use the spot market to gain additional profits while supplying via long-term contracts.

Recently Gaur *et al* (2006) studied the value of postponement and early exercise to order and stock inventory. They do this in the presence of demand and price risk

that are correlated with the assets traded in the financial market. The model they use is essentially that introduced by McDonald and Siegel (1985), in which a risk-adjusted valuation is developed for incomplete markets by using the market price of risk derived by the aggregate risk averse investors of the firm. To model risk aversion, supply chain management literature has generally used the preference-based utility maximization perspective proposed by Sandmo (1971). In this line of work, Eeckhoudt *et al* (1995) first incorporated risk aversion in the standard newsvendor model and then various similar problems were studied by Agrawal and Seshadri (2000a,b), Chen and Federgruen (2000) and Chen *et al* (2006). On the other hand, demand risk has been studied together with price uncertainty in revenue management literature. Often the key assumption made is that the price has a Poisson distribution with given demand intensity. For example, one can see this setup in Gallego and van Ryzin (1994) or Caldentey and Bitran (2003). Unlike the revenue management and dynamic pricing literature, in our paper, the spot market price is an exogenous random variable, not a decision variable. Instead of deciding how to vary prices to induce demand, we would like to decipher how the changes in the spot market price affects the buyer's profits and the seller's likelihood of contract breach. Another relevant stream of literature is the VaR literature, which aims to provide a single risk metric for financial loss over a given time period. There has been a considerable amount of work in the financial literature that addresses various aspects of VaR. Excellent reviews exist on this topic. See, for example, Tapiero (2004) for a good conceptual overview of recent results. There has also been some research that combines the VaR concept with operational decisions. Tapiero (2003) addresses the inventory control problem *ex post* as a disappointment aversion problem, also known as regret models.³ He focuses on the inventory management problem with the financial loss due to variations under/above the targeted inventory cost. His model considers the asymmetric valuations of the decision maker for deviations from the optimal inventory as well as the uncertainty in cost parameters.

Our research also draws some inspiration from law literature that studies the breaches in the contract and remedies in such cases. One representative paper by Mahoney (2000) states that there are a number of barriers to design efficient contracts, therefore, inefficient contracts have to be supported by damage measures. Given the increasing complexity and uncertainty in the world of supply chain contracts, it makes sense to acknowledge the possibility of breach and impose a fine for contract breach. Thus, Mahoney (2000) effectively lends support to our model where breach fines are incorporated in contract terms.⁴

Since the main tool we use in measuring portfolio risk is CreditRisk⁺, literature on CreditRisk⁺ also becomes relevant. The primary source of documentation on this model is the CreditRisk⁺ technical document from Credit Suisse

³See, for example, Bell (1985) and Gul (1991) and references therein for regret/disappointment models in decision making.

⁴In a subsequent paper, Mahoney (2005) suggests that the options valuation methodology is a good candidate to explain the law's choice of various damage measures used in contracts.

by Wilde (1997). Informal summary descriptions may also be found in books such as Bluhm *et al* (2002). A comparison with other industry standards is given in Crouhy *et al* (2000). The original framework has come a long way in terms of modifications and enhancements, such as those in Gordy (2002). A comprehensive collection of such improvements can be found in Gundlach and Lehrbass (2004). Most prior work on CreditRisk⁺ has been in the context of banking and insurance and, to the best of our knowledge, this framework has not been applied previously to measuring supply chain risk.

3 MODEL FOR INDIVIDUAL SUPPLY CONTRACTS

Consider a manufacturer procuring raw materials via a portfolio of fixed-price long-term contracts. All contracts are initiated at time 0 and have a delivery date of τ . For any given contract i , $i = 1, \dots, n$, let Q_i be the contracted quantity and C_i be the contracted price (or cost in book value terms). For each contract, the buyer is exposed to several risks. On the demand side the actual realized demand may be much higher or lower than the contracted quantity. This is demand risk. In the traditional newsvendor setup, it affects the buyer through the opportunity cost of lost demand or financial loss from a low salvage price. Nowadays it is often possible to cover up the shortfall or sell off the excess by trading in a spot market. Then the demand risk affects the buyer via the volatility in spot prices. We can think of this as the price risk. To capture demand and price risks, we introduce two random variables \mathcal{D}_i and \mathcal{P}_i signifying the end of period demand and spot price, respectively, for the contract i . On the supply side the buyer is exposed to the risk of contract breach by the supplier, for several systematic or idiosyncratic reasons. In the presence of a spot market, the risk from an intentional contract breach by the supplier becomes especially significant. The supplier may be able to get a much higher price by trading in the spot market than delivering at the contracted low price and decide to breach.⁵

In this paper, we assume that the contract breaches are only due to favorable spot prices. On the other hand, Haksöz and Kadam (2008) discuss contract breaches in a more general setting, and offer some interesting insights from the buyer's perspective.

Suppose the fine payable by the seller in the event of breach is \mathcal{F}_i per item ordered ie, $Q_i \mathcal{F}_i$ in total. After procuring the products from the seller, the buyer adds some value into the product and sells it in their own market. We do not model the actual value adding process in this paper. Without loss of generality we assume that there is one-to-one correspondence between the quantity of the component/part

⁵In theory, contract breaches would become rare events if suppliers were allowed contract breaches only in the event of bankruptcy for the entire supplier firm. However, this is not the reality and selective contract breaches by suppliers are commonplace. See, for instance, the study by Henke *et al* (2008) conducted in the automotive industry.

procured and used in the final product.⁶ We do not consider varying levels of usage in the end product. Instead we assume simply that the value added by (or US dollar worth to) the buyer from contract i is \mathcal{V}_i . (However, we do acknowledge that in certain cases for example, chemicals, the value added could be proportional to the spot price.) The firm does not actually sell the component per se, it sells the end product that uses the component. Thus, the US dollar worth of the value added per item can be thought as putting a markup on the fixed contract price after adding value in the manufacturing process. At time τ , if the demand is higher than the procurement volume, ie, $\mathcal{D}_i > \mathcal{Q}_i$, then the extra demand is not lost. Instead, the supplier goes to the spot market for raw materials, pays the price \mathcal{P}_i and fills the gap. If the procured volume is higher, $\mathcal{Q}_i > \mathcal{D}_i$, then the remaining inventory will be sold in the spot market at price \mathcal{P}_i . Since our model does not operate in multiple periods, there is no inventory being carried to the next period.⁷

We assume that there is a per unit transaction cost of \mathcal{T}_i for trading in the spot market. The buyer's profit, in the absence of breach, at time τ is given by:

$$\pi_i(\text{no breach}) = \begin{cases} (\mathcal{V}_i - \mathcal{C}_i)(\mathcal{Q}_i) + (\mathcal{V}_i - \mathcal{P}_i - \mathcal{T}_i)(\mathcal{D}_i - \mathcal{Q}_i) & \text{if } \mathcal{D}_i > \mathcal{Q}_i \\ (\mathcal{V}_i - \mathcal{C}_i)(\mathcal{D}_i) + (\mathcal{P}_i - \mathcal{C}_i - \mathcal{T}_i)(\mathcal{Q}_i - \mathcal{D}_i) & \text{if } \mathcal{D}_i \leq \mathcal{Q}_i \end{cases}$$

In each case the second term computes the net cash inflow from trading in the spot market. Upon simplifying this expression we obtain:

$$\pi_i(\text{no breach}) = \mathcal{V}_i \mathcal{D}_i - \mathcal{C}_i \mathcal{Q}_i + [\mathcal{P}_i - \mathcal{T}_i \{I_{\mathcal{D}_i < \mathcal{Q}_i} - I_{\mathcal{D}_i > \mathcal{Q}_i}\}](\mathcal{Q}_i - \mathcal{D}_i) \quad (1)$$

In this expression, the last term captures the profit from trading in the spot market. Here $I_{\mathcal{D}_i > \mathcal{Q}_i}$ is an indicator function that assumes the value 1 when $\mathcal{D}_i > \mathcal{Q}_i$. In the event of breach, the entire demand is satisfied by the spot market and there is an additional cash inflow from breach fines:

$$\pi_i(\text{breach}) = (\mathcal{V}_i - \mathcal{P}_i - \mathcal{T}_i)\mathcal{D}_i + \mathcal{F}_i \mathcal{Q}_i \quad (2)$$

Thus, the buyer's exposure to contract breach from contract i can be easily computed as the difference (1)–(2). This is the dollar amount at stake, that may be lost, purely due to contract breach. Let us denote this exposure by ϵ_i for contract i . This can be expressed as:

$$\epsilon_i = (\mathcal{P}_i + \mathcal{T}_i - \mathcal{C}_i - \mathcal{F}_i)(\mathcal{Q}_i) - 2\mathcal{T}_i \{I_{\mathcal{D}_i < \mathcal{Q}_i}\}(\mathcal{Q}_i - \mathcal{D}_i) \quad (3)$$

⁶An example for this model is the procurement of parts/components such as microchips, DRAMs for PCs. The procurement volume for the chips will be determined by the end product (computer, server) demand. Therefore, the buyer has to compute the optimal procurement volume for a certain component in presence of demand risk for the end product, where the demand for the end product will be exactly the same for the component since we assume one-to-one correspondence. The purchasing price is fixed with a long-term contract arrangement. We assume that the profits are realized at time τ , that is, at the end of the contract duration.

⁷Seifert *et al* (2004) study a similar single period model in order to compute the optimal mix of long-term contracts and spot market purchasing in a mean–variance framework.

In a fair contract the contracted price would be based on the location parameter (eg, mean or median) of the spot price distribution and the per unit breach fine \mathcal{F}_i would reflect the per unit transaction cost \mathcal{T}_i of trading in the spot market. In a fair contract the supplier would not be expected to breach. However, there is positive probability that the realized spot price exceeds a threshold where it is rational for the supplier to breach. We now explore this possibility in more detail.

First, we presume that the contract breach occurs due to a favorable spot price for the seller. Given this assumption, it is impossible to design a contract that is guaranteed to be fulfilled. This is because future spot market prices are unknown. All that the buyer can do is to minimize their loss when the contract is breached. Towards this end higher breach fines may be imposed. In our setup this also translates into a lower chance of the contract breach as we proceed to show now.

In order for the contract breach to be a rational decision, the supplier will need to recover the cost of trading in the spot market, and the fine payable to the buyer. The spot price net of these costs will have to exceed the contracted price for this to be a profitable breach. All of this effectively implies that the spot price should exceed some predetermined threshold in order for the supplier to decide to breach the contract. However, this may just result in a lower bound for the threshold as reputational and other costs may make a breach undesirable for the supplier. Nevertheless, we use it as the actual threshold value and derive the probability of breach as the probability that the spot price exceeds that threshold:

$$P(\mathcal{P}_i \geq \mathcal{F}_i + \mathcal{T}_i + \mathcal{C}_i) = 1 - \Phi(\mathcal{F}_i + \mathcal{T}_i + \mathcal{C}_i) \quad (4)$$

where $\Phi(\cdot)$ is the cumulative distribution function (cdf) of the spot price.

It is important to note that the buyer could offer incentives such as a renegotiation option for the contract price at predetermined times during the contract duration to mitigate the contract breach risk. We do not include renegotiation options in this model for reasons of analytical tractability.

It is easy to verify that having defined the breach in this way, the exposure conditional on breach is always positive. The buyer can take this into consideration when determining the representative exposure at breach, which acts as an important input into the portfolio model. For instance, this could be done by computing the median or expectation of the exposure over the domain where it is positive. The probability of losing that exposure, which acts as the other key input to the portfolio model, is readily obtained from the assumed probability distribution of spot prices. We illustrate this in more detail in Section 4.1. All of the above results are fairly general in assumptions involving probability distributions for end of period spot price and demand. Consequently, it is possible to embed stochastic models for price and demand processes, potentially correlated with each other and with market movements, within this framework.⁸ However, we retain the flexibility of specifying general distributions at the individual supplier level and build in a more concrete structure in the portfolio approach described next.

⁸In particular, if the price process follows geometric Brownian motion, the end of period price will be lognormally distributed. In this case, both the expected profits and the probability of contract breach can be computed explicitly.

4 MODEL FOR A PORTFOLIO OF SUPPLY CONTRACTS

Given a clear understanding of the profit and risk profile for each supply contract, we are now in a position to build the probability distribution of loss from a portfolio of supply contracts. A buyer may have a number of supply contracts for specific commodities and they may purchase different quantities at different prices from multiple suppliers. Supply contract breaches may be driven by systematic forces such as industry-wide business cycles or regional macro-economic shocks. In order to model the dependency structure in the contract breach outcomes, we group the contracts. Grouping can be based on the commodity transacted. For example, the buyer may procure aromatics from a set of suppliers that might be distinct from the set of petrochemicals suppliers. Grouping could also be done at the level of sellers, or more broadly, at the level of markets in which they operate. Each group of supply contracts is assumed to have a systematic tendency for contract breach that is common to the entire group. From a contract breach perspective, the groups themselves are assumed to be independent. Thus, the buyer has initiated at time 0 the contracts $i = 1, \dots, n_s$ from $s = 1, \dots, S$ supply groups. Each contract comes from exactly one supply group.⁹ Typically, one would expect the number of groups to be much fewer than the number of contracts. Any (including none) of the contracts may be breached. For every contract i breached and the contracted quantity purchased from the spot market, the buyer has a net loss that is the US dollar equivalent of the exposure amount ϵ_i given in (3).

Given the above setup, the probability distribution of losses can be obtained by using the CreditRisk⁺ framework. Mathematical details for this can be obtained in the CreditRisk⁺ Technical document. A brief summary is given in Appendix A. The most important aspect to note is that this framework allows for a flexible dependency structure between different exposures, yet gives a quick computation of the loss probability distribution without recourse to computationally expensive Monte Carlo simulations.

In practice, the construction of the curve that shows the loss probability distribution can be done by using any software that implements the CreditRisk⁺ framework. Until recently, an Excel spreadsheet implementing this framework was publicly available at www.csfp.com. Even though the spreadsheet is now hard to find in the public domain, the documentation on the framework itself is publicly available. It is possible for a third party to implement the framework on its own; this has been widely implemented in the financial industry. For this paper we used our own version of the framework implemented in R statistical programming language.

The actual inputs to the framework are quite simply the exposure amounts and contract breach rates, ie, contract breach probabilities for the time horizon in mind. Contract breach rates can be inferred from supplier ratings for instance. Exposure amounts for a supplier can be computed from the average of the differences between supplier-specific profits with and without breach.

⁹This restriction can be relaxed further to allow for belongingness to multiple groups; what is presented here is a simpler version of the CreditRisk⁺ framework.

Once a loss probability distribution is known, supply-at-risk (θ) is simply that loss level at which the cumulative probability is θ . Thus, a 95% supply-at-risk is that loss level for which the cumulative probability is 95%.

In practice, this type of risk measure for procurement and supply chain executives would be very useful. Using such a measure, one can not only observe frequent supply losses, but also see what might happen in extreme cases. In particular, these extreme cases (tail events) are becoming critical in any type of operational risk framework, since their severities are large once they occur. Yet they generally occur very rarely. Moreover, from the loss distribution, one can obtain the expected shortfall, in other words, conditional supply-at-risk, which is the average loss conditional on the event that the loss exceeds supply-at-risk.

Supply-at-risk (or the other portfolio risk metrics defined above such as conditional supply-at-risk) can help in choosing suppliers as well. In a brute force approach, one could simply consider each of the alternative portfolios, and compute and compare their supply-at-risk quantities.¹⁰ For instance, suppose that the existing supply-at-risk is 100 and the buyer wishes to add a new supplier to this portfolio. Suppose that adding supplier A increases supply-at-risk to 110 and adding supplier B increases supply-at-risk to 150. Then purely on the supply-at-risk criterion, supplier A is preferable. It is important to note that the portfolio benefits of including supplier A may far outweigh the price considerations at the individual supplier level, for example, supplier B may offer a better price, but the portfolio effects are damaging.

4.1 Numerical illustration

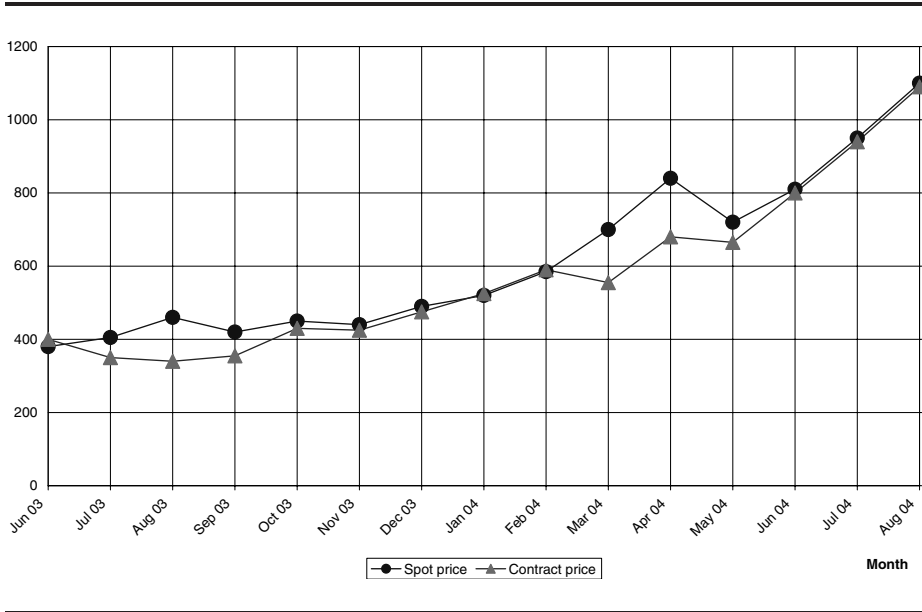
The following is an illustration of the methodology we propose. The illustration is motivated by an actual global procurement case study written for BASF Corporation.¹¹ Even though BASF uses various types of commodities in their manufacturing processes, for our illustration, we focus on one type of petrochemical commodity, ie, aromatics, widely used in critical processes. Aromatics consist of petrochemical derivatives, mainly benzene, toluene and xylene that are used to produce a variety of end products such as polyurethane, nylon, resins, acrylonitrile butadiene styrene and polystyrene, which are eventually sold to furniture, automotive, textile, plastics and consumer electronics firms.

BASF procures the aromatics needs from three different regions, namely the United States, Europe and Asia. BASF has separate business units that solely focus on the best procurement policies on each of these regions. Each region has both spot and contract markets. Trader characteristics exhibit regional differences. For instance, the Asian market is more open and comfortable with spot trading

¹⁰A more sophisticated approach would be to use the notion of risk contributions. These would identify an individual supplier's contribution to some measure of unexpected loss at the portfolio level. Details on how to define and use these risk contributions are explained in the CreditRisk⁺ Technical Document, Section A13.

¹¹Interested readers are referred to the case by Kabakis *et al* (2005).

FIGURE 1 Contract and spot price evolution in the European aromatics market.



than the European market. Risks involved in the operation can also be considered different for each region. For our numerical study, we only use the European aromatics market.¹² For this market, we assume that BASF procures from 20 separate suppliers via long-term contracts. Based on the supplier evaluation and selection process of BASF, we divide the group of 20 suppliers into three clusters based on their reliability, quality and safety features as described in the case study. BASF uses a simple ratings-based system, that is, attaching A, B, C type of suppliers in descending order of their procurement reliability. We assume that BASF works largely with A and B category suppliers and has very few contracts with C category suppliers. That is, the supplier portfolio is composed of 50% A, 40% B and 10% C type suppliers. For the sake of this illustration we assume that all potential contract breaches are intentional. Figure 1 displays the spot market and contract price evolution of the European aromatics market during the period June 2003–August 2004. The spot and the contract price do have a tendency to track each other. Overall, the volatility increases over time.

Suppose that at the end of August 2004, a one-month contract is initiated with each of the above suppliers. Contracted quantities are assumed to be equal for this numerical illustration. BASF procures six million metric tonnes of aromatics annually from Europe. Specific monthly contracted quantities for each supplier

¹²It is straightforward to extend this methodology for global conglomerates which operate many related business units, facing multiple breaches of contracts, which possibly have more than a hundred suppliers, procuring more than three to four markets.

TABLE 1 Contracted quantities for the supplier portfolio.

Contracted quantity (metric tonnes per month)	Supplier type
25,500	A
26,650	A
27,760	A
28,870	A
29,980	A
35,100	A
36,200	A
37,300	A
38,400	A
29,500	A
30,590	B
31,400	B
32,300	B
33,200	B
30,600	B
31,700	B
32,800	B
33,900	B
34,100	C
34,100	C

are given in Table 1. Total quantity procured from (A; B; C) type suppliers are (315,260; 256,490; 68,200) metric tonnes per month.

In August 2004, the spot price is US\$1,100 per metric tonne. If we assume that the spot price returns on a monthly basis are normally distributed then the prior spot price history shows that return R follows a normal distribution with parameters $N(\text{mean} = 0.0838, \text{sd} = 0.1035)$. Then, the future spot price $1,100(1 + R)$ is normally distributed as $N(1,214, 114)$. In the absence of information on contract prices, we suppose that the future contract price is set equal to median spot price. In the absence of information on breach fines, we assume that the breach fine covers exactly the additional transaction cost to the buyer procuring from the spot market. We also assume in this illustration that the future demand will not deviate from contracted quantity. Given these simplifying assumptions the exposure expression in (3) reduces to:

$$\epsilon_i = (P_i - \overline{P}_i) Q_i \quad (5)$$

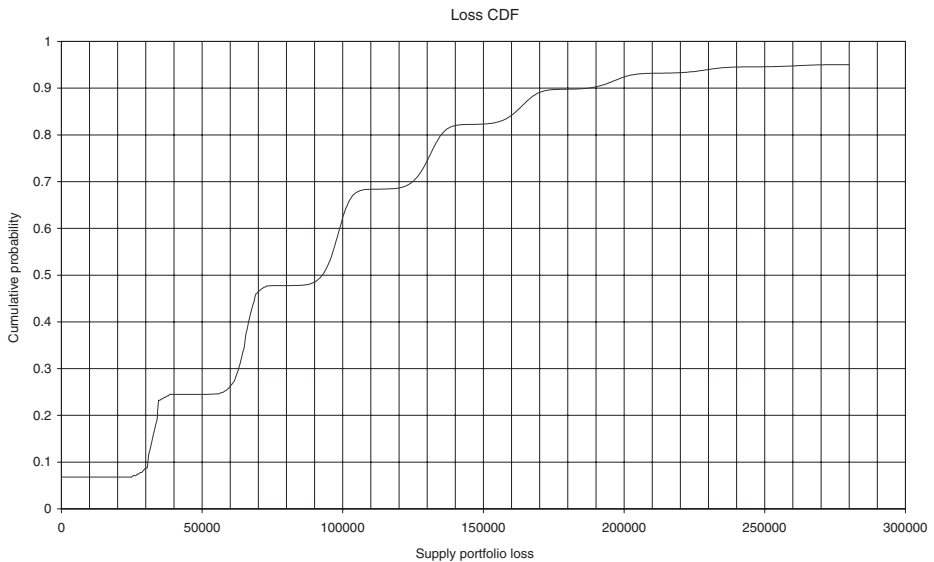
where the new quantity \overline{P}_i is the median spot price in the future. CreditRisk^+ requires one representative input for exposure whereas this expression yields a random variable for exposure. Hence, we choose to compute the median exposure, the median being computed over the domain of positive exposures, as the summary statistic to input into CreditRisk^+ . We choose the restricted domain of positive exposures because unless the exposure is positive there will be no breach and

the CreditRisk⁺ computations are only for events in the presence of breach. By virtue of the simplified exposure expression in (5) above, the median exposure is the 75% quantile on the spot price distribution times the quantity contracted. This is because when the spot price is less than or equal to its median (50% quantile) the exposure is not positive. Thus the domain of positive exposures corresponds to the domain of spot prices on the right half of the median spot price. The median of spot prices computed over this restricted domain is easily seen to be $(50 + 100)/2 = 75\%$ quantile. Thus, the exposure input is given by $1,291 \times 25,000 = \text{US}\32.275 million. Again in this case we do not have much information on the actual probability of breach. As we do not have information on transaction costs or breach fines, we cannot derive them strictly from the spot price distribution.

In reality the breach probabilities are more likely to be obtained from a combination of historical data, expert opinion and potentially third-party supplier ratings. For simplicity of illustration we assume that the probability of losing the exposure is approximately 0.25. We adjust this further upwards and downwards depending on supplier rating. Such an adjustment for the sake of this illustration is pretty *ad hoc*, but in the presence of more concrete information a more systematic approach may be adopted. Finally, we assume that the exposures to the 20 suppliers are dispersed around the median exposure with a very small variance. With these inputs to the CreditRisk⁺ framework we obtain the cumulative portfolio loss probability distribution as shown in Figure 2. In this figure, every additional supplier contract breach contributes to an incremental portfolio loss shown. Since there are few suppliers and their exposures are large relative to the total exposure, it is natural to see jumps in the cdf plot (this is equivalent to having modes or spikes in the probability density function (pdf) plot). The jumps decrease in height as the loss level increases because the chance of several suppliers breaching their contracts is lower than the chance of just one or two of them doing so. Thus, the first supplier to breach their contract will create a small loss but with a high likelihood. The tail of the related density function will be long as the convergence of the cdf to one is very slow. This implies that there is a positive, although small, likelihood of obtaining very large losses.¹³

There are also some interesting numerical results from a managerial perspective. First, although the total annual dollar exposure was roughly US\$640 million, the median loss is only US\$93 million, ie, roughly 15%. However, the supply-at-risk, when computed at the 90% level is US\$187.5 million, ie, roughly twice the median loss. The supply-at-risk number can be verified by examining the cdf curve in Figure 2. It crosses the 90% level at US\$187.5 million. (cdf at US\$187 million is just under 90% whereas cdf at US\$187.5 million is just over 90%.) In other words, BASF has a 5% chance of losing at least US\$187.5 million from its supplier portfolio that is exposed to multiple contract breaches. Such insights are not easy to obtain without considering a portfolio setting.

¹³For instance, the cdf at loss level US\$270 million is 0.9499 which means that the chance of obtaining supply portfolio losses over US\$270 million is at least 5%.

FIGURE 2 Supply loss distribution.

Using this approach, industry buyers of various commodities or quasi-commodities (for which there is an open market exchange even though it may not be highly liquid) can have a better sense of the supply risk they are exposed to while purchasing via long-term contracts.

5 CONCLUSIONS

In this paper, we have taken the first novel step in understanding the financial impact of supply contract breaches, which are classified under “Clients, Products and Business Practices” in the Basel II framework, for global manufacturers. Our conceptual approach augmented with analytical methods from both operations management and finance, specifically operational risk management, provides an effective tool for supply chain managers who are constantly bombarded with demands for better risk management.

Our model provides a tool for supply risk assessment due to contract breaches in the presence of demand and spot price risks. It is also a good starting point to decide on the optimal risk mitigation strategies such as purchasing insurance for supply interruption as well as creating effective operational and financial hedging strategies. The buyer can easily have backup suppliers as an operational hedge as well as use futures contracts and options in the commodity market as financial hedges.

The methodology we describe provides a handle on the operational hedging aspect.¹⁴ The optimal hedging strategy for the global procurement is an important question to be answered for large buyers of commodities such as the automotive, chemical, consumer goods, aerospace and metal industries. Many global firms are in the process of forming their procurement risk management teams and investing in their enterprise risk management capabilities more seriously.¹⁵

There are a number of extensions to this work. First, the supply-at-risk measure can be computed in a multi-period and dynamic setting, where the risk exposures vary over time. In that case, inventory storage becomes an issue. Hence, time-based risk measures need to be developed. Second, an empirical testing of our methodology is required since our numerical example has limitations. Moreover, in this paper, we only attempt to assess the total supply risk buyers are exposed to due to supply contract breaches. Another fruitful future research question is to select the optimal portfolio of suppliers that will minimize the supply-at-risk measure. Then, we can update the composition of suppliers that is in the portfolio dynamically while minimizing the supply risk. One should clearly understand the spot market evolution as well as the likelihood of the supplier breaching the contract to evaluate the success of the supplier portfolio.

In the end, we believe that the major business impact of such a model could be further strengthened with a large amount of real-life data, which is unfortunately the missing link in supply chain research. We hope this work creates motivation along those directions.

APPENDIX A BRIEF SUMMARY OF CreditRisk⁺

CreditRisk⁺ is a Poisson mixture model of dependency, the mixing being achieved by group-specific Gamma distributed random variables. In the manner in which we apply CreditRisk⁺ to supply portfolio risk situation, the common tendency to breach contracts within each supply group is modeled via a Gamma distribution. The breach probability of each contract is Poisson distributed, with the intensity parameter for the Poisson distribution itself being Gamma distributed.

The key assumption in such mixture models is that of conditional independence. Conditional on a supplier belonging to a particular supplier group, the breach tendencies of suppliers within the group are independent. In other words the only way in which two suppliers tend to breach together is driven by their belongingness to the same group. In particular, in CreditRisk⁺ any two suppliers within the same group can be treated as independent, conditional on our knowledge of the Poisson intensity that drives breaches in that group. Suppliers in different supplier groups are unconditionally independent.

The aim of the CreditRisk⁺ framework is to compute the loss distribution for the entire portfolio. There are at least two ways of going about this. Recent

¹⁴For tools and techniques to hedge operational risks in the finance industry, see Cruz (2002).

¹⁵For example, Hewlett-Packard reported cost savings of around US\$425 million by using a procurement risk management approach (Nagali *et al* (2008)).

developments have made it possible to do this in a much quicker and cleaner manner using the fast Fourier transform to invert the characteristic function. However, the original CreditRisk⁺ approach was using Panjer recursion to invert the probability generating function; and this original implementation is known to encounter difficulties with numerical stability in the tail of the distribution.

In the original approach, the idea was to first discretize the (continuous) exposures ϵ_i into exposure bands. The choice of band size was *ad hoc* but controlled by the user. This discretization permitted the use of probability generating functions. The important thing to note here is that the probability generating function for the entire portfolio can be conveniently obtained given the analytically tractable distributions chosen (Poisson, Gamma) and the assumption of conditional independence. Since Gamma mixed Poisson random variables have negative binomial distributions and thus fall in the Panjer class, Panjer recursion can be used to invert the probability generating function for the portfolio loss. Details of this recursion algorithm are given in Wilde (1997).

The end result of the above Panjer recursion is a probability distribution of portfolio losses that accounts for the dependency structure of contract breaches. As mentioned before an alternative to using discretization, probability generating functions and Panjer recursion is to directly work with the characteristic function and use the fast Fourier transform to invert the loss distribution. Details of this technique are given in Gundlach and Lehrbass (2004).

REFERENCES

- Agrawal, V., and Seshadri, S. (2000a). Effect of risk aversion on pricing and order quantity decisions. *Manufacturing and Service Operations Management* **2**(4), 410–423.
- Agrawal, V., and Seshadri, S. (2000b). Risk intermediation in supply chains. *IIE Transactions* **32**(9), 819–831.
- Behar, R. (2008). China in Africa. *Fast Company*, June, 100–123.
- Bell, D. E. (1985). Disappointment in decision making under uncertainty. *Operations Research* **33**, 1–27.
- Bluhm, C., Overbeck, L., and Wagner, C. (2002). *An Introduction to Credit Risk Modeling*. Chapman & Hall/CRC, London.
- Bove, R. (2006). Muscling in on iron. *The Financial Times*, 23 March.
- Caldentey, R., and Bitran, G. (2003). An overview of pricing models for revenue management. *Manufacturing and Service Operations Management* **5**, 203–229.
- Chen, F., and Federgruen, A. (2000). Mean–variance analysis of basic inventory models. Working Paper, Graduate School of Business, Columbia University, New York.
- Chen, X., Sim, M., Simchi-Levi, D., and Sun, P. (2006). Risk aversion in inventory management. Working Paper, University of Illinois at Urbana-Champaign.
- Crouhy, M., Galai, D., and Mark, R. (2000). A comparative analysis of current credit risk models. *Journal of Banking and Finance* **24**, 59–117.
- Cruz, M. G. (2002). *Modeling, Measuring and Hedging Operational Risk*. John Wiley & Sons, Hoboken, NJ.

- Eeckhoudt, L., Gollier, C., and Schlesinger, H. (1995). The risk-averse (and prudent) newsboy. *Management Science* **41**(5), 786–794.
- Gallego, G., and van Ryzin, G. (1994). Optimal dynamic pricing of inventories with stochastic demand over finite horizons. *Management Science* **40**(8), 999–1020.
- Gaur, V., Seshadri, S., and Subrahmanyam, M. G. (2006). Optimal timing of inventory decisions with options. Working Paper, Stern School of Business, New York University.
- Gordy, M. B. (2002). Saddlepoint approximation of CreditRisk⁺. *Journal of Banking and Finance* **26**, 1335–1353.
- Gul, F. (1991). A theory of disappointment aversion. *Econometrica* **59**, 667–686.
- Gundlach, M., and Lehrbass, F. (eds) (2004). *CreditRisk⁺ in the Banking Industry*. Springer, Germany.
- Haksöz, Ç., and Kadam, A. (2008). Supply risk in fragile contracts. *MIT Sloan Management Review* **49**(2), 7–8.
- Haksöz, Ç., and Seshadri, S. (2007). Supply chain operations in the presence of a spot market: a review with discussion. *Journal of the Operational Research Society* **58**(11), 1412–1429.
- Haksöz, Ç., and Seshadri, S. (2009). Value of spot market trading in the presence of supply chain contracts. Working Paper, Sabancı University, Turkey.
- Henke, M., Weimar, M., and Besl, R. (2008). Supplier risk management in the automotive industry. Conference Presentation, POM 2008, La Jolla, CA.
- Kabakis, C., Lei, S., Sieberger, M., and Stuckle, W. (2005). *BASF Global Procurement Petrochemical Products: Challenges in Changing Global Commodity Markets*. WHU Otto Beisheim Graduate School of Management, Vallendar, Germany.
- Kambil, A., and Mahidhar, V. (2005). *Disarming the Value Killers: A Risk Management Study*. Deloitte Research.
- Kleindorfer, P. R., and Saad, G. (2005). Managing disruption risks in supply chains. *Production and Operations Management* **14**(1), 53–68.
- Li, C.-L., and Kouvelis, P. (1999). Flexible and risk-sharing supply contracts under price uncertainty. *Management Science* **45**, 1378–1398.
- Mahoney, P. G. (2000). Contract remedies: general. *The Encyclopedia of Law and Economics* **IV**, paper 4600.
- Mahoney, P. G. (2005). Contract remedies and options pricing. *The Journal of Legal Studies* **24**(1), 139–163.
- Martínez-deAlbéniz, V., and Simchi-Levi, D. (2005). A portfolio approach to procurement contracts. *Production and Operations Management* **14**(1), 90–114.
- Matthews, R. G. (2008a). Corporate news: steelmakers squeeze suppliers – as weak demand weighs on raw-material prices, Mills look to Jettison contracts. *The Wall Street Journal (Eastern Edition)*, 18 November.
- Matthews, R. G. (2008b). Steel surcharges draw ire. *The Wall Street Journal Europe*, 7 July.
- McDonald, R. L., and Siegel, D. R. (1985). Investment and the valuation of firms when there is an option to shut down. *International Economic Review* **26**(2), 331–349.

- McNeil, A., Frey, R., and Embrechts, P. (2005). *Quantitative Risk Management: Concepts, Techniques, Tools*. Princeton University Press, Princeton, NJ.
- Muthukrishnan, R., and Shulman, J. A. (2006). Understanding supply chain risk: a McKinsey global survey. *The McKinsey Quarterly*.
http://www.mckinseyquarterly.com/Operations/Supply_Chain_Logistics/Understanding_supply_chain_risk_A_McKinsey_Global_Survey_1847?gp=1
- Nagali, V., Hwang, J., Sanghera, D., Gaskins, M., Pridgen, M., Thurston, T., Mackenroth, P., Branvold, D., Scholler, P., and Shoemaker, G. (2008). Procurement risk management (PRM) at Hewlett-Packard Company. *Interfaces* **38**(1), 51–60.
- Panjer, H. H. (2006). *Operational Risk Modeling Analytics*. John Wiley & Sons, Hoboken, NJ.
- Peabody (2005). Peabody Energy Corporation BTU Quarterly Report 10-Q, 8 August.
- Reuters-UK (2008). Century to pay glencore to cancel aluminum deal.
<http://uk.reuters.com/article/idUKN0819324920080708>, 8 July.
- Ritchie, B., and Brindley, C. (2007). An emergent framework for supply chain risk management and performance management. *Journal of the Operational Research Society* **58**, 1398–1411.
- Ritchken, P. H., and Tapiero, C. S. (1986). Contingent claims contracting for purchasing decisions in inventory management. *Operations Research* **34**, 864–870.
- Sandmo, A. (1971). On the theory of the competitive firm under price uncertainty. *American Economic Review* **61**, 65–73.
- Seifert, R. W., Thonemann, U. W., and Hausman, W. H. (2004). Optimal procurement strategies for online spot markets. *European Journal of Operational Research* **152**, 781–799.
- Sheffi, Y. (2007). *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*. MIT Press, Boston, MA.
- Snavely, B. (2006). Visteon pays \$14.9 million award in contract dispute. *Automotive News*, 23 October.
- Spinler, S., Huchzermeier, A., and Kleindorfer, P. (2003). Risk hedging via options contracts for physical delivery. *OR Spectrum* **25**(3), 379–395.
- Tapiero, C. S. (2003). Value at risk and inventory control. Working Paper, ESSEC, France.
- Tapiero, C. S. (2004). *Risk and Financial Management: Mathematical and Computational Concepts*. John Wiley & Sons, Chichester.
- Wilde, T. (1997). *CreditRisk⁺ A Credit Risk Management Framework*. CSFB.
- Wu, D. J., Kleindorfer, P., and Zhang, J. E. (2002). Optimal bidding and contracting strategies for capital-intensive goods. *European Journal of Operational Research* **137**, 657–676.