# Integrating Physical and Financial Risk Management in Supply Management

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# Integrating Physical and Financial Risk Management in Supply Management[1]

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## 1. Introduction

This paper provides a brief overview of recent contributions and open research challenges to the use of options and other derivative contract forms in support of commodity hedging and supply management in B2B markets. Such derivatives play an important role in integrating long-term and short-term contracting between multiple buyers and sellers in commodity markets. A primary question of interest in this context is hedging risk exposure associated with commodity procurement decisions. In the usual context, Sellers compete to supply Buyers in a market for which, in the short run, capacities and technologies are fixed. Buyers can reserve capacity through contracts for physical delivery obtained from any Seller, and Buyers can also hedge these contracts through financial contracts on the same underlying indices from financial intermediaries. Output on the day can be either obtained through executing such contracts or in the associated spot market. Such contract-spot markets have become prominent under e-commerce (e.g., Geman, 2005), and include commodity chemicals, electric power, natural gas, metals, plastics, agricultural products and basic foodstuffs, and are increasingly important for cap and trade mechanisms for carbon emissions and other market-based approaches to environmental regulation.

Prior to the emergence of B2B exchanges and the contracting innovations of interest here, the focus in procurement and supply management was on bilateral negotiation, which gave rise to an extensive literature on supply chain contracting (see Cachon (2003) for a review). The point of departure in this paper is that contracting, screening and supplier management will remain essential elements of supply chain management, and especially for non-codifiable goods and transactions.[3] However, the existence of exchanges has introduced a fine-tuning mechanism that improves operational performance and simultaneously helps to value longer term contractual, capacity and technology decisions. The centerpiece of this new perspective is the integration of traditional forms of contracting with shorter term market-driven transactions and associated derivative instruments.

To set the stage, it is important to understand the typical organizational context surrounding contracting and spot market purchases. A common feature of markets supporting commodity procurement for major buyers is the following. Any particular buyer has a limited set of sellers

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[1] This paper has been written for the edited book by H. Geman, *Risk Management for Commodity Markets*, forthcoming Wiley Finance, 2008.

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[3] See Kogut and Zander (1992) for a discussion of codifiability of transactions. The essential ingredient for tradable contracts is that these be standardized, both in terms of terminology and financial terms as well as for the underlying product or service that is the focus of these contracts. Off-grade or customized products may still be codifiable, but they may cease to be suitable for broad market-based transactions if they are only used by a few companies. In this case, as we discuss in more detail below, these customized products may have prices sufficiently correlated with basic tradable products of the same family to allow financial hedging.

who compete for the buyer's business in the contract market, while still having access to a larger set (often a much larger set) of sellers who compete in the shorter term market (the spot market) and whose actions determine a competitive spot market price. Contract sellers for a particular buyer are restricted to a pre-qualified set that are able to satisfy credit and settlement requirements, assurance of supply, access to supporting logistics, and other traditional supplier management issues. These features give rise to a setting in which buyers have restricted seller bases (of perhaps 1-5 pre-qualified contract sellers) in their contract markets, while using spot markets as a second source of supply as well as a means of hedging their physical procurement and evaluating the price levels they receive in their contract purchases. The interaction between contracting, spot market purchases and hedging is, thus, both of interest in the optimal portfolio of contracts and sellers for a buyer, as well as providing an interdependent valuation and hedging process.

Consider the beverage industry. Aluminum is an important element of the cost structure. For major buyers like Anheuser Busch or Heineken, a restricted set of sellers is used, even though the aluminum spot market price is a key benchmark for sourcing and hedging and is determined by the actions of scores of global players. Here, sourcing arrangements with main sellers are typically set according to the spot price plus processing costs, and contracts are marked to market on a daily basis. Second, there may be value-added services undertaken by these contractors to take aluminum ingots and prepare them in a more suitable fashion for can production, and again here this would be done only with specifications for these services worked out with a few sellers. Thus, the typical setup in metals is for a restricted set of contract sellers, with spot purchases and hedging used to “top up” contract purchases or hedge overall cash flows associated with aluminum procurement.

As a second important example, consider the restructured electricity market, where producing Sellers (Generators) and Buyers (Load Serving Entities and Distribution Companies) can sign bilateral contracts to cover the demands of their retail and wholesale customers. These bilateral contracts may cover purchases for up to a year in advance. Alternatively, Sellers and Buyers can interact “on the day” in a spot market. How much of their respective capacity and demand Sellers and Buyers should or will contract for in the bilateral contracting market, and how much they will leave open for spot transactions, is a fundamental question examined in a growing literature on energy trading (e.g. Schofield, 2007).

The same general market structure obtains in many other markets, from cocoa and sugar, to natural gas, to logistics, to plastics and to the commodity end of semiconductor devices. Against this background, this paper provides some perspectives on the theory and practice that is now maturing in companies with major commodity exposures to integrate physical and financial risk management in improving both their buying performance (through better price discovery) and the quality of their earnings (through better risk management). The paper proceeds as follows. The next section briefly reviews background literature on optimal contracting and options theory. Section 3 presents a modeling framework and an example of short-term and long-term contracting to introduce the subject. The framework is used to provide an overview of recent contributions in the literature, focusing primarily on the management science and operations research literature (which has been the primary outlet for work on supply management). Section 4 discusses the application of these results for hedging electricity sourcing decisions. Section 5 discusses open research questions for supply management backed by B2B exchanges.

## 2. A Primer on Previous Supply Management Contracting Literature

The literature on contracting in economics has been driven by the transactions cost framework developed by Coase (1937) and Williamson (1985), and subsequently formalized in the Principal-Agent literature (Laffont and Tirole 1998). The basic hypothesis of this approach is that transactions with one or more Buyers will be structured so as to minimize the total production and transactions cost of these transactions, including contracting, incentive and monitoring costs. One of the key elements of B2B markets is arguably the reduction in transactions cost associated with automating transactions and providing appropriate IT platforms to support these. These problems are usually modeled in a context in which relationship-specific investments are required for efficient contracting, and such investments become the subject of hold-up behavior (what Williamson terms "ex post opportunism") after they are made. Clearly, a well-specified ex ante contract with verifiable information, as suggested by Williamson (1985), can be an important element in reducing these incentives.

A key question addressed in the economics literature has been the efficiency of various contracting structures. A well-known result in the economics contracting literature is Allaz and Vila (1993), which examines the efficiency of pure forward contracts in an oligopoly setting but with a deterministic spot market (which is fixed and common knowledge). Assuming homogeneous Sellers and instantaneous scalability (with no capacity limitations), they provide an important benchmark on the factors than can influence the efficiency of forward markets. Allaz and Villa show that forward markets can yield inefficient outcomes because of strategic use of these markets by Sellers with market power. The basic results from financial economics provide the underlying analytical framework for derivative instruments in the contracting markets of interest (see Geman 2005 for a survey of recent advances). The essential characteristics of the financial engineering modeling in the literature on derivative instruments include: continuous time stochastic dynamics for the underlying spot price; and on-going trading opportunities among market participants for the derivatives based on standard contracts. Option instruments and valuation models allow for different degrees of flexibility w.r.t. execution, including fixed expiration dates (European options), flexible expiration dates (American options) and various exotic options, such as Asian options that have payoffs that are based on average spot performance over a given period (Merton, 1990). Each of these options forms, either in markets or in contracts, has found important applications in supply risk management.

In the context of supply chain contracting, an additional distinction is required in the types of options involved, between purely financial options and those connected to physical delivery of a particular good at a particular time and place. The early discussion and literature was focused on physical delivery options to fulfill a Buyer's sourcing needs. These options would entail delivery at a particular time and place (e.g., FOB Pittsburgh). In these markets, options backed by physical delivery are central to the Buyer's problem of arranging for sufficient supply to meet the Buyer's demand. However, once a functioning spot market exists, this market can be used to define financial options on the basis of the spot price. Major Buyers would then find it in their interest not only to arrange optimal sourcing from the contract and spot markets, for physical delivery of goods, but also to use the financial options defined in the market as risk hedge instruments. Thus, in livestock or grain markets, options serve both the purpose of fulfilling sourcing requirements for

Buyers, but the same markets allow price discovery through active parallel trading of options for purely financial hedging purposes. It is this mix of physical and financial instruments that characterizes well functioning and liquid spot markets. Normally, the mix of options in such markets going to physical delivery is low, perhaps on the order of 1% of total transactions, the remaining trading being purely financial to hedge residual risk.

A key factor influencing the incentives of Sellers and the Buyer to sign contacts is the existence of imperfect market access on the day, capturing possible access inefficiencies of the spot market, including cost and quality differences between contract markets and the spot market. In addition, in supply management for commodities, different grades and specifications for commodities often require prior contracting and procurement relations. These alternative situations give rise to various forms of commodity risk management, as shown in Table 1 below.

**Table 1: Alternative Contexts for Commodity Risk Management of Supply**

| **Description of Context** | **Instruments used in Optimal Portfolio** | **Examples** |
|---|---|---|
| Cost and access differences small and only standard commodities are sourced | Bilateral contracting and financial hedge instruments are defined on a common spot market and optimized jointly | Energy<br>Commodity metals |
| Cost and access differences are large and only standard commodities are sourced | Bilateral contracting used for most physical procurement, with spot market used for topping up supply, and for financial hedge instruments | Logistics services (standard air and maritime cargo)<br>Fed-cattle (beef), Hogs and Lamb markets |
| Non-standard commodities are sourced, but their prices are highly correlated with those of standard commodities | Bilateral contracting used for all physical procurement, with financial hedge instruments, defined on correlated standard products, used as an overlay | Plastic Resins and commodity chemicals |

The standard problem of commodity sourcing and hedging for a Buyer can be stated as follows:

$$Maximize\ E\{\Pi(Q,\tilde{D},\tilde{P}_S)\} \qquad \text{(CSH)}$$

subject to:

$G(Q,F_D,F_{P_s}) \geq 0$ Physical Delivery Constraints

$H(Q,F_D,F_{P_s}) \geq 0$ Value-at-Risk (VaR) Constraint(s)

$Q \in X$ Other Constraints on Available Instruments where the maximization in (CSH) is over the vector of available financial and physical instruments $Q$ at the time of contracting, where "demand" uncertainties are represented by $\widetilde{D}$ and where spot price uncertainty is represented by the random variable $\widetilde{P}_S$, with respective cdf's of $F_D$ and $F_{Ps}$. On the day, once $D$ and $P_s$ are observed, instruments are executed to fulfill the physical delivery constraints and to optimize profits by executing all options that are "in the money" or needed for physical fulfillment. This problem "on the day" can sometimes be interesting, but it is usually straightforward. The problem of setting up and solving the overall portfolio problem integrating financial and physical instruments is less straightforward and typically sufficiently complicated that simulation vehicles must be used for valuation and optimization. Various forms of the (CSH) problem have been developed for different types of markets, and the details for these differ considerably across these markets.

The VaR constraint in (CSH) is usually represented as:

$$Pr\left\{\Pi(Q,\widetilde{D},\widetilde{P}_S) - F \geq -VaR\right\} \geq \gamma$$

where $\Pi(Q,\widetilde{D},\widetilde{P}_S)$ are the cash flows resulting from the vector of contracts Q, where F represents fixed capital payment obligations, and VaR is the maximal Value-at-Risk allowed for the period in question, with confidence level γ (see Crouhy et al. (2000) for a discussion of VaR). In the case where the normality assumption is reasonable for $\Pi(Q,\widetilde{D},\widetilde{P}_S)$, this standard VaR constraint translates into a simple function of the mean and standard deviation of $\Pi(Q,\widetilde{D},\widetilde{P}_S)$. Finding the efficient frontier (in E{Π}, VaR space) is then easily solved in the standard fashion via mathematical programming or simulation optimization techniques. Multi-period VaR constraints are also discussed in Kleindorfer and Li (2005) and Geman and Ohana (2008). For more complex problems, including sophisticated models of the evolution of the spot price and various exotic options, simulation can be used to tackle a wide variety of problems that arise in practice.

## 3. A Modeling Framework and a Simple Illustrative Case[4]

To gain some intuition, let us first consider the simplest case in which a Buyer can satisfy demand D in a particular period by purchasing input using either forward contracts (from pre-qualified Sellers) at a cost of r/unit or on a spot market at a cost of P/unit. It is easiest to think of the input in the simplest Non-storable Uniform Product Model (e.g., hotel rooms of a particular type for a particular day of the year). We imagine the Buyer's decision problem at the time the choice is made on the appropriate mix of these alternative procurement arrangements (which is to say at the time the Buyer is deciding on how much input to purchase under forward contracts). At this point in time, we assume that the Buyer's demand D and spot price P are both random variables with known distributions, whose actual realizations will be known at the time when spot purchases are made. We assume that product sold under forward contract is slightly better in the sense that to achieve the same yield from a spot purchase requires an additional cost of $a$/unit, $a >$

[4] This section is based on Wu and Kleindorfer (2005).

*0*, of input processed. Let us also suppose that the Buyer can sell back to the spot market at the spot price *P* any of the input it purchases under a forward contract that is not needed. Finally, suppose the Buyer expects production costs per unit of input processed to be b/unit and the Buyer expects to sell output produced at a wholesale price w, where we assume that $w > r \geq \mu = E\{P\}$, so that profits can be made at the expected spot price $E\{P\}$, and the expected value of this price is no less than the current going rate for forwards. The Buyer purchases $Q \geq 0$ units under the forward contract and produces *D* units on the day, purchasing $X^+ = Max\ [Q - D, 0]$ units on the spot market and selling $X^- = Max\ [D - X, 0]$ units purchased under the forward contract to the spot market. The Buyer's profits under this arrangement would be calculated as follows:

$$\Pi_B(Q) = (w-b)D - rQ - (P+a)(D-Q)^+ + P(Q-D)^+ \qquad (1)$$

where $z^+ = Max\ [z, 0]$. The first term is just the gross margin per units sold in the wholesale market; the second term is the cost of the forward purchases; the third term is the cost of spot purchases (computed at the full price of $P + a$); and the final term is the revenue from excess forwards sold in the spot market. This simplifies to:

$$\Pi_B(Q) = (w-b)D - rQ - P(D-Q) - a(D-Q)^+ \qquad (2)$$

Denoting the cdf of demand D (as estimated at the time of contracting) as $F_D(x)$ and denoting mean spot price as $\mu = E\{P\}$, a little calculus shows that this standard Newsvendor problem (see Cachon (2003)) reduces to the following rule for the optimal portfolio of marketing arrangements (i.e., the optimal mix of forward and spot purchases):

$$I: \quad Q = 0,\ X^+ = D,\ X^- = 0 \qquad if\ r \geq \mu + a$$

$$II: \quad Q^* > 0,\ X^+ = (D - Q^*)^+,\ X^- = (Q^* - D)^+ \qquad if\ r < \mu + a \qquad (3)$$
$$where\ Q^*\ is\ given\ as\ F_D(Q^*) = \Pr\{D \leq Q^*\} = \frac{a - (r - \mu)}{a}$$

Thus, regime I entails purchases only in the spot market, while regime II entails non-zero purchases in both the spot and forward markets. Focusing on regime II, where the expected full price of spot purchases exceeds the unit cost of the forward ($\mu + a > r$), it is easily seen that the intensity of use of spots versus forwards depends on the all the cost and demand parameters, as well as on the volatility of demand (the latter through the Newsvendor rule determining $Q^*$ as a function of the cost parameters and the cdf of the demand distribution). In this simple case of a risk-neutral Buyer, only the mean of the spot price distribution enters into the decision rule. We will see that the volatility of the spot price is also an important element of the optimal portfolio choice problem when a few additional complexities are introduced.

The above simple problem can be extended in various ways, e.g., by adding risk aversion or risk constraints (e.g., of the Value-at-Risk or VaR type, as explained in Crouhy et al. (2000)), by allowing production decisions to be different than demand decisions, by modeling price sensitivity of the Buyer's demand, by incorporating economies of scale in the Buyer's production function, by introducing capacity constraints and economies of scale for potential Sellers of forward contracts, by introducing competition into both the contracting and spot markets and by considering more complex marketing arrangements. These complexities give rise to changes in the rules for determining the optimal mix of contracting arrangements, but the basic intuition remains similar to that of the above simple problem, namely purchasing forwards allows the Buyer and Seller to avoid the risks of price and demand volatility, but it entails risks of its own in terms of opportunity costs of more favorable prices in the spot market and the ability to fine tune purchases or sales at the last minute. To introduce some of these complexities, let us now consider a slightly more general version of the above problem, which will allow us then to motivate and summarize the literature on optimal contracting for commodities. We first describe a three-period timeline for trading in the B2B exchange, either using contracts or using the spot market (see the figure below). The reader can think of this as setting up the physical and financial contracting to solve the problem (CSH) for next months or next quarter's procurement of a particular Buyer's production needs for some specific commodity input (e.g. aluminum or electric power).

Period 0: Before the fact, at Period 0, capacity and technology choices are made by Buyers and Sellers. As we will see, these choices will be different when rational managers know that they can fine tune demand and supply through the spot market than when such a possibility does not exist.

Period 1: At Period 1, with updated information on the distribution of spot prices, Sellers and Buyers contract with one another, using options and forwards, for delivery of some good (either storable or non-storable) at Period 2.

Period 2: Finally, at Period 2, after possibly additional information updating, options are called, forwards are executed, deliveries are made and additional sales and purchases are made in the short-term spot (or cash) market.

Between Period 1 and Period 2, there may be additional trading of options and additional, possibly continuous, updating of information on spot prices. To keep matters simple, we will assume a discrete-time framework with no secondary trading. Thus, we will only be concerned with the indicated decision instants Period 0, 1 and 2.

| | | | | |
|---|---|---|---|---|
| | Information Revelation | | Information Revelation | |
| $t_0$ | | $t_1$ | | $t_2$ |
| Capacity<br>Technology<br>Choices | | Contracting<br>Trading | | Short-term/Spot<br>Procurement and<br>Production |

We characterize the technology of each Seller by the triple $(b, \beta, K)$, where $b$ is the Seller's short-run marginal cost of providing a unit of output, $\beta$ is the per unit/per period capacity cost (assumed pre-committed prior to contracting at $t_1$) and $K$ is the Seller's total available capacity, assumed fixed in the short-run (i.e., at the time contracting decisions are made).[5]

[5] See Martinez-de-Albeniz and Simchi-Levi (2005) for an analysis of the case in which capacity decisions are made at the same time as contracting decisions, as might be the case for some leasing decisions. The results for this case are quite similar to those derived by Crew and Kleindorfer (1976) for the diverse technology pricing and capacity problem

There may also be differences in the cost of finishing and transporting a unit of product to market depending on whether a forward contract is used, providing ample time for the Seller to plan for the fulfillment requirements, or whether the spot is used. In addition to these "production cost" differences, there may also be additional costs for the Buyer (these are referred to as "adaptation costs", denoted by "a" in the simple model above) if purchasing product in the spot market rather than under planned contracts. The reader might think of these as off-spec quality or yield costs that are typically higher under spot purchases than under pre-planned contract and alliance purchases.

Contracts between Sellers and Buyers can take many forms in this model, depending on the amount of quantity flexibility involved and who has decision rights over it. It is useful to begin the analysis by assuming only a single aggregate Buyer.[6] We will also consider only forwards and call options, with the call option execution being in the hands of Buyers, in order to keep matters simple. The decision variables for Sellers are the optimal contracts of the form [r, e, L] to offer to the Buyer, where L is the number of units offered, r is the reservation or contract cost per unit of capacity, and e is the execution cost per unit of output. Thus, if e = 0, then the contract is a pure forward as units ordered will have been paid for in advance with a fixed price r; if e > 0, the contract is an options contract. One can also think of r as the pre-paid part of a fixed forward and e as the additional part of the unit forward price paid on the day of delivery (e.g., for transportation and processing costs). We will take both r and e to be fixed, though they could themselves be state-dependent or random (for example, the execution price might be defined as the additional cost of delivery on the day, and these might not be known except stochastically until the day of delivery).

The decision variables for the Buyer are how much to contract $Q$ at Period 1 with each Seller, and at Period 2, how much to execute from the contract (denoted $q$) and how much to procure from the spot market (with spot market purchases denoted by x). The (distribution of) Buyer's total demand $D$ on the day (at Period 2) is assumed to be common knowledge. Whatever its demand $D$ is (which may depend on price in its own final markets and on other variables), the Buyer will attempt to fill this demand from its contract(s) and from the spot market at minimum cost. For example, if the Buyer only has one contract *[r, e, Q]*, and is choosing how much of this to execute versus filling demand from the spot market, it is easy to see that the cost minimizing fulfillment strategy is to order the following quantity from his contract:

$$q(P_S, D, Q, e) = MIN[D, Q]\psi(P_S - e) \leq Q \qquad (4)$$

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in public enterprise pricing. Intuitively, the optimal capacity/contracting choices embody tradeoffs between the volatility of future demand and the capacity and variable costs that must be committed at the time of contracting to meet this demand. The results imply that high capacity costs and low variable cost capacity should be used to meet the first slice of contract demand, that the next highest capacity costs and next lower variable cost capacity should be used to meet the next slice of contract demand, and so forth. This is similar to the outcome in terms of the optimal amounts of generating plants of different types to be installed in electric power planning to meet an uncertain demand over the long run.

[6] The assumption of a single Buyer is without loss of generality in understanding equilibrium prices and contracts, provided there is no market power by Buyers. This is so since Buyers can simply be ranked according to their Willingness-to-Pay and awarded capacity accordingly, as would happen for example under an auction mechanism or other efficient market design.

where $P_s$ is the spot price on the day and where $\psi(z)$ is the indicator function which takes the value of *1* if its argument *z* is positive and *0* otherwise. This means that if $e = 0$, then $q = Min\ [D, Q]$ will be taken under (what is then effectively) a forward contract.

The spot market price $P_s$ is uncertain before it is revealed in Period 2. The spot market price is assumed here to be exogenous (open, competitive) and not subject to the influence of any of the contract market participants. The distribution function of the spot price is denoted *f(p)* with mean $\mu = E\{P_s\}$; *f(p)* is also assumed to be common knowledge.

The objective of the Buyer is to maximize expected profit by choosing among the available forward and spot contracts. The objective of the Seller is to maximize expected profit, jointly obtained from sales in both the contract market and the spot market and subject to the Seller's capacity constraint. Either Buyer or Sellers may have additional risk-based constraints on their transactions, such as those derived from a Value-at-Risk framework. We will consider these risk-related issues further below.

A key factor influencing the incentives of Sellers and the Buyer to sign contacts is the existence of imperfect market access on the day, capturing possible access inefficiencies of the spot market via a function $m(P_s)$, which is defined as the probability that the Seller can find a last-minute Buyer on the spot market when the realized spot price is $P_s$. This market access probability can also be thought of as the proportion of the Seller's capacity that can be typically sold at the last minute. This function will be determined by different factors in different market settings but generally may be thought of as a measure of the liquidity of the market. When quality issues are present (which we will not formally analyze here) then $m(P_s)$ might also reflect the quality risk associated with spot purchases. We will use another approach, discussed below, to represent such quality risks.

As an instance of the above framework, consider the simplest case of a single risk-neutral Seller and a single risk-neutral Buyer[7], and we assume no adaptation cost and no contract/spot production cost differences.

The Buyer's problem at Period 1, is to determine the optimal number of options, *Q* to contract for with the Seller, taking into consideration the Buyer's demand at Period 2. To fine *Q*, the Buyer solves the problem using backward induction. At Period 2, the Buyer derives its optimal demand. If only the spot or cash market were available, then the Buyer's demand function at Period 2 would be given by the normal downward sloping demand curve[8],

$$D_S(P_S) = arg\,max\left[U(D_S) - P_S D_S\right] = (U')^{-1}(P_S) \qquad (5)$$

[7] The consequences of risk aversion are intuitive. While the equilibrium results for integrated contracting and options markets remain an open research question at the point of this writing, as the reader can anticipate, risk aversion would tend to increase reliance by the respective party on the contract market rather than being exposed to the price volatility and access risk of the spot market.

[8] We are assuming here that the Buyer's demand curve is only a function of the prevailing price. More generally, the Buyer's WTP/Profit function *U* would depend on the state of the world, namely on external factors such as economic conditions, the weather, etc. For details on this more general case, see Spinler et al. (2003).

where $U(D_s)$ represents the profit to the Buyer from producing and selling $D_s$ units, with first derivative $U'$ and with inverse function $(U')^{-1}$, with $U$ assumed to be strictly concave and increasing (this basically says that the normal demand curve $D_s(p)$ at Period 2 is downward sloping). In the presence of contract procurement $Q$, the Buyer's actual optimal demand curve on the day is seen to be kinked, accounting for the presence of the contract fulfillment, with the solution:

$$D = MAX\left[D_s(P_s), Q\right] = MAX\left[(U')^{-1}(P_s), Q\right] \tag{6}$$

At Period 1, the Buyer's problem is to contract a reservation level $Q$ so as to maximize its expected profits from contracts and spot procurement, given spot purchase opportunities that will be available on the day. This gives rise to the following problem:

$$Maximize_{Q \geq 0}\ E\{U(D) - rQ - rq - P_s x\} \tag{7}$$

with $q$ as specified in (4) above, $x = D - q$ = spot purchases, and $D$ given by (6) above.

In (7), the first term is Willingness-To-Pay (WTP) (or profits) at $P_s$, evaluated at the realized demand $D$; the second and the third term together are the payment for the goods delivered under the long-term contract, and the fourth term is the payment for goods x purchased in the spot market. One sees in (7) the nature of the general problem facing a Buyer with choices in several markets (in this case in the contract market and in the spot or cash market). The Buyer is interested in maximizing profits from sales in its own market. The Buyer can utilize a long-term marketing arrangement (in this case represented by $Q$) as well as a shorter-term marketing arrangement (in this case represented by $x$). The Buyer executes his rights to buy $q$ units under the contract $Q$ at some "call date" and buys on the spot or cash market remaining units needed to cover profit-maximizing demand. The Buyer must anticipate the required demand and the dynamics of this process at the time he signs contracts. In the process, the Buyer will be comparing the cost of signing a contract with the (as yet unknown) price of spot purchases. The distribution of $P_s$ and all of the underlying cost and technology conditions determining profits $U(D)$ are assumed known to the Buyer as a part of solving the above problem (7).

It can be shown (e.g., Wu and Kleindorfer (2005)) that the Buyer's optimal procurement strategy is to reserve the following number of units $Q$ under contract:

$$Q(r,e) = D_S(G^{-1}(r + G(e)) = (U')^{-1}(r + G(e)) \tag{8}$$

at Period 1, where $G(p)$, called the ``effective price function", is defined as

$$G(p) = E\{MIN[P_S, p]\} \tag{9}$$

and where $G^{-1}(g)$ is the inverse function of $G(p)$. It is easily shown, and intuitive, that $Q(r, e)$ is decreasing in both of its arguments. We note in passing that the effective price function $G(e)$ captures the notion of the price that the Buyer will have to pay for an additional unit of supply if they have the option of purchasing under contract the additional unit at an execution price of $e$. If $e = 0$, as in the case of a pure forward contract, then $G(0) = E\{P_s\}$, the mean spot price.

At Period 2, the optimal strategy for the Buyer is rather simple: If $P_s \geq e$, the Buyer will exercise all its options/contracts and procure any additional needs from the spot market; Otherwise if $P_s < e$, the Buyer will forgo its contracts but procure its entire needs from the spot market. If $e = 0$, the case of a pure forward, the Buyer will always "accept" the full forward contract. [Note: Many other cases are possible, with salvage values, penalties for not accepting deliveries of forwards, buy-back arrangements, minimum take quantities, etc. Most of these turn out to be special cases of the above general framework.]

One can invert (9) to obtain the price the Buyer is willing to pay per unit for a contract with reservation price $r$ and execution price $e$, namely:

$$r = G(U'(Q)) - G(e) \qquad (10)$$

Note that the conventional wisdom of $r = E\{P_S\} - e = \mu - e$ does not hold here, as the Seller can only sell a percentage of his capacity if he only wants to sell at the last minute (Period 2). If he wants to sell in the contract market in advance at Period 1, he has to sell at a price less than $\mu - e$ in order for the Buyer to be interested.

Taking the Buyer's optimal response into consideration, the Seller's problem is to maximize his expected profit (neglecting fixed capacity investment, which is assumed fixed in this model) at Period 1 by bidding a contract in the form of [$r, e$], i.e.,

$$Maximize_{(r,e)\geq 0} E\left\{rQ(r,e) + (e-b)q + \left(P \ -b\right)^{+} m(P_S)\left(K-q\right)\right\} \qquad (11)$$

Subject to: $q(P_S, D, Q, e)$ as in (4); $Q(r,e)$ as in (8).

where it is assumed that non-performance penalties are sufficiently high that the Seller does not sell under contract any more output than he has (i.e., $(r, e)$ are set so that $Q(r, e) \leq K$ is assumed)[9]. In the Seller's profit function, the first two terms represent the Seller's revenue from the contract, the third term is the Seller's cost of supplying $q$ units to the Buyer, and the fourth term is the Seller's profit from the spot market.

Under weak regularity assumptions, it is straightforward to show that the Seller's optimal strategy is to bid its unit production cost ($e = b$), and then setting $r$ by maximizing its expected profit (11) given $e = b$. The actual solution for the optimal reservation price $r$ depends on whether the Buyer exhausts the Seller's capacity or not. The explicit solution is as follows (assuming that there is no competition in the Seller market, i.e., only one Seller); if $Q(r, e) < K$, then $r^*$ is proportional to the Seller's opportunity cost $E\{m(P_s)(P_s - b)^+\}$ of selling a unit in the spot market and inversely proportional to the Buyer's demand elasticity at the optimal reservation demand formula $Q(r, e)$ given by (5), i.e. if $Q(r,e) = Q(r,b) < K$, then

[9] Models assuming that the Seller may "overbook" are also common in the literature, e.g. where a penalty is paid by the Seller for each unfulfilled but contracted unit demanded on the day.

$$r = \frac{E\left\{m(P_s)(P_s - b)^+\right\}}{1 - 1/\eta_r(Q(r,b))}; \quad Q < K \tag{12}$$

where $\eta_r(Q)$ is the elasticity of $Q(r, e)$ with respect to r (i.e., $\eta_r(Q) = [\partial Q(r,e)/\partial r][r/Q(r,e)]$. If the solution to (12) yields a value of $r$ such that at $e = b$, $Q(r, e) > K$, then $r$ should be set to take additional rents from the Buyer by charging a reservation price $r$ just high enough to equate $Q$ and $K$. From (9), this occurs at:

$$r = G(U'(K)) - G(b); \quad Q = K \tag{13}$$

Why do the Seller and Buyer have the incentive to use the contract market even when they are both risk neutral? Consider first the Buyer. At Period 1, the Buyer is paying an overall price less than the average spot market price, since (it can be shown) $r + G(b) = G(U'(Q)) \leq G(U'(0)) \leq \mu$. The Seller is also willing to sell this option, since he is making more profit in the contract market than in the spot market per unit of capacity as long as $r > E\{m(P_s)(P_s - b)^+\}$, which also can be shown to be his minimum requirement to participate in the options market. The Buyer is willing to buy this option as long as the combined price $r + G(b)$ is less than mean spot price $\mu$. Thus, for risk neutral traders, the active contract market trading spread lies between $E\{m(P_s)(P_s - b)^+\} \leq r \leq G(U'(0)) - G(b) \leq \mu - G(b)$. An increase in $m(P_s)$, which may be thought of as increased spot market liquidity, effectively shrinks the trade spread, even to the extent of suppressing the contract market entirely. Indeed, in this simple model, with no adaptation or production cost differences between spot and contract market production, when $m(P_s)=1$, the contract market disappears..

We may extend the base model to allow contract production to be cheaper than spot production, reflecting the benefits of advanced planning. Thus, assume that contract production has variable cost $b_c$ and spot production has variable cost $b_s$ with $b_c < b < b_s$. Then the above options trade spread stretches in both ways,

$$E\left\{m(P_s)(P_s - b_s)^+\right\} < E\left\{m(P_s)(P_s - b)^+\right\} \leq G(U'(0)) - G(b) \leq \mu - G(b) < \mu - G(b_c) \tag{14}$$

indicating a stronger incentive for both parties to contract. In particular, even when the Seller has a perfect market access with $m = 1$, he still engages in long-term contracting, as well as spot purchases, trading as long as $b_s > b_c$.

We have focused in the above discussion only on production cost differences, but similar results would obtain if the Buyer had to pay additional adaptation costs (i.e., with an eye on (1)-(2), when $a > 0$) when procuring at the last minute from the spot market relative to contract purchases. These effects might derive from better quality control, better yield management, better planning of capacity, any other advantages deriving from the longer-term planning and partnering inherent in contract versus spot procurement. On the other side of the coin, there may be additional costs to set up and negotiate contract procurement and these would obviously work to the advantage of spot procurement.

Generalizing the framework of this example has been a central research challenge in the Management Science and Financial Engineering literature. A few important milestones can be noted here.

Spinler, Huchzermeier and Kleindorfer (2003) generalizes the single-Seller results of Wu, Kleindorfer and Zhang (2002) to the state-dependent case, whereby the WTP functions characterizing demand for Buyers could themselves depend on the state of the world (e.g., both demand and spot price might depend on temperature, as is the case for electricity and beverage markets). Mendelsohn and Tunca (2007) provide an important generalization of Wu, Kleindorfer and Zhang (2002) to the case of a closed spot market, where spot market price is determined endogenously (in a single Seller context). That is, the more capacity is withheld from the contracting market for sale in the spot market, the lower the resulting spot price distribution. Within this closed spot market framework, they focus on the impact of establishing the spot market (B2B exchange), where the Seller plays the role of Stackelberg leader. They derive necessary and sufficient conditions for the existence of the exchange. They analyze the impact of the exchange on the participants as a function of information quality. A surprising result is that the introduction of the exchange ($m > 0$) does not necessarily benefit the participants. This is because the exchange contributes to price volatility and quantity uncertainty. As a result, the Seller and the Buyers can all be worse off with the exchange than without, driving participants away from the exchange (spot market) to contracting. On the other hand, when the exchange is highly liquid, volatility will not be amplified by the exchange and Buyers and the Seller will rely completely on the exchange, even to the extent of forgoing contracting altogether. The corresponding conditions in the framework of Section 2 are when the Seller has perfect spot market access and/or when the cost of assuring codifiability is low (i.e., $m$ is close to $1$).

Wu and Kleindorfer (2005) capture the interaction of competing technologies with alternative market structures, which accommodate both the extent of competition (in terms of the number of Sellers) as well as the relative cost and access advantages of alternative Sellers. The essential results in Wu and Kleindorfer are the following. First, it is shown that greedy contracting is optimal for the Buyer, i.e., it follows a merit order based on the index $r_i + G(b_i)$, where $(r_i, b_i)$ is the bid of Seller i, with $r_i$ being Seller i's reservation price and $b_i$ is the execution price of i's contract, where $b_i$ is (optimally set at) Seller i's marginal cost of supply (per the results of Section 3 above). Second, the necessary and sufficient conditions for market equilibrium are characterized. A key result is the "law of one price", i.e., each Seller who participates in the options market, must sell the option at the same "effective price" (i.e., the same $r_i + G(b_i)$). Third, in the absence of cost advantages of contract production over spot production, the two-part tariff structure of equilibrium contracts is efficient. This last result is important to underline: options-supported B2B markets, if competitive, assure efficiency. Complex flexibility provisions and penalty costs are not required; the standard options structure with competition achieves efficiency. This contrasts starkly with the inefficiency of pure forward markets in the well-known result of Allaz and Vila (1993). The difference here is in contract design; remove the restriction that contracts must all be pure forwards ($e = 0$), and the Allaz-Vila forward-market inefficiency disappears under competition.

The Wu and Kleindorfer (2005) results have also been generalized to integrate long-term capacity decisions at Period 0 (see Wu, Kleindorfer, Sun and Zhang (2005)) with contracting and spot market decisions, where the long-term decisions are modeled in a game theoretic framework with payoff functions based on the anticipated short-run game among Sellers that will materialize via the exchange given their capacity decisions. This long-term game illustrates the nature of efficient technology mixes likely to survive in long-run equilibrium when firms with heterogeneous cost structures compete and follows the early work of Crew and Kleindorfer (1976) on the question of efficient diverse technology choices. The model results show that, in the long-run, Sellers are segmented into four disjoint groups: participation in the options market only; participation in both the options market and the spot market; participation in the spot market only; and participation in neither market (those forced out-of-business). Note that these results assume the standard proportional bid-tie capacity allocation rule in case of a Seller bid-tie, namely when several Sellers have the same winning bid price, their capacity is allocated to Buyers in proportion to the amount of capacity these Sellers have bid into the market. Different allocation rules can effect the existence and structure of equilibrium outcomes, as discussed in Wu and Kleindorfer (2005).

Motivated by Williamson's transactions cost framework, Levi, Kleindorfer and Wu (2003) provide an explicit modeling of codifiability and relationship-specific investment. Their model introduces fixed (relationship-specific) costs into contracting following Kleindorfer and Knieps (1982) and brings the following insights into the literature: (1) Underlying technology cost differences drive higher relationship-based investment; (2) Lower codifiability (in the form higher adaptation costs for non-contract procurement) results in overall demand decreases at market equilibrium, and there is a shift to more intensive use of contracts, but with fewer Suppliers in the contract market.

## 4. Hedging Electric Power Supply

We imagine an integrated utility, called the "Company", which may own or lease generation, and which has a trading division that can sign contracts for Power Purchase Agreements (PPAs), as well as puts, calls and forwards based on an underlying wholesale spot market. We abstract here from transmission constraints or markets.[10] For simplicity, we also imagine that the Company provides energy to retail customers at prices that are regulated. We will take the simplest possible approach to the regulated sector, assuming a fixed, exogenously determined regulated price per KWh, independent of time. More complicated regulatory scenarios are easily incorporated into the framework developed. This feature of customer demand at regulated prices, together with the weather-driven level of spot prices and the non-storability of electric power, makes electricity supply a risky business.

We are interested in formulating the Company's optimal portfolio problem for procuring and hedging its purchases of energy. The portfolio will be characterized by different levels of time-indexed instruments (puts, calls, forwards, etc.) that might be called upon either to fulfill retail demand or simply as part of profit-oriented trading/hedging activities by the Company's trading division. We refer to all potential assets for the portfolio, including owned/leased generation and PPAs, as "instruments".

[10] To the extent that these are based on principles of Locational Marginal Prices, transmission constraints and options could also be included as part of the portfolio optimization described below.

Following Kleindorfer and Li (2005), we think of each instrument as having a capacity (measured in MW), that can be called or sold in a specific period (consisting of specified hours during a given week or month, typically the 5x16 hours of "peak" or the 7x8 hours of "off-peak"). Each instrument entails a reservation price, possibly zero, per MW to reserve, and an execution price, per MWh, if used. In this framework, instruments such as "own generation" and certain PPAs that have been pre-committed have a fixed execution price (e.g., the marginal running cost of own generation), but may be thought of as available at a reservation price of zero. Purchased forwards, which are prepaid, fixed obligations to deliver power, may be viewed as call options having a zero execution price that therefore will be executed by the Company on the day. Forwards sold by the Company have the same characteristic, i.e., they may be viewed as options contracts with a zero execution price (that therefore will be executed on the day).

To set up the model, we will assume that the planning period for the instruments in question is a month, with hours in the month being denoted by the set T = {1, …, 720}. We will consider additional subsets of T below, such that certain instruments may be valid only for certain subsets of time (e.g., peak hours). We need the following additional notation:

$Q_i$ = the amount (in MW) of instrument i that is purchased/sold
$r_i$ = reservation price per MWh for call asset i[11]
$c_i$ = execution price per MWh for call asset i
$s_i$ = reservation price per MWh for put asset i
$p_i$ = execution price per MWh for put asset i
$T_j \subseteq T$ = index of those hours of type "j", where j = 1, …, J (types of time periods might be, for example, peak periods, off-peak periods, weekends, etc.)
$I_{cj}$ = the set of indices for all call instruments (used in the summation below) that can be executed during hours of type *j*
$I_{pj}$ = the set of indices for all put instruments (used in the summation below) that can be executed during hours of type j
n = the number of all instruments (so $n = \sum_{j=1}^{J} \left| I_{cj} \cup I_{pj} \right|$ )
$m_i$ = Lower bound or minimum amount allowed for instrument $Q_i$
$M_i$ = Upper bound or maximum amount allowed for instrument $Q_i$

The random variable of "monthly cash flows" depends on the level of each instrument $Q_i$ in the portfolio, where some instruments, within each month, may apply to different periods of time (e.g., just the peak periods or just the off-peak periods, or to some other selection of periods). We can write cash flows (for some period, say month *t*) in the following general form:

$$\Pi = \sum_{\tau \in T} (P_{c\tau} - P_{s\tau}) D_{c\tau} + \sum_{j=1}^{J} \sum_{\tau \in T_j} \left[ \sum_{i \in I_{cj}} \left[ (P_{s\tau} - c_{i\tau})^+ - r_i \right] Q_i + \sum_{i \in I_{pj}} \left[ (p_{i\tau} - P_{s\tau})^+ - s_i \right] Q_i \right] \qquad (15)$$

[11] Thus, to reserve $Q_i$ MWs of callable capacity during a specific period of length L, the price paid is $r_i Q_i L$, where the maximum reserved/callable capacity during any hour of the period is $Q_i$ MW. The reader can think of the reservation price in $/MWh as the allocated cost to each of the hours of the period in question, though instruments will be typically traded for a groups of hours in a month, e.g., 100 MW of capacity callable for any peak hour during a specific month.

where $\tau \in T$ are the sub-periods within the month in question, each assumed to be of length 1 hour, and where we have indexed spot price $P_s$ and the execution prices $c_i$ and $p_i$ for the options by time periods, in case these execution prices are time sensitive (e.g., different prices for peak or off-peak for the same instrument). Note that once an instrument is purchased, it is available for all hours covered by the instrument (e.g., a peak-period call option of $Q_i$ MW is available for any peak hour in the month, subject to requirements—usually 24 hours in advance—to execute the option).

Using (15), it is easily seen how this problem fits the standard form of (CSH). The profit function is clear (though additional payments to capital providers would be accounted for as in (16) below in the risk constraint). As to the physical fulfillment constraints, these are also straightforward as long as the spot market is completely reliable as a source of power on the day (and very high reliability is typical of such markets). The VaR constraint in (CSH) is represented as:

$$Pr\left\{\Pi(Q,\widetilde{D},\widetilde{P}_S) - F \geq -VaR\right\} \geq \gamma \qquad (16)$$

where $\Pi(Q,\widetilde{D},\widetilde{P}_S)$ are the cash flows (15) resulting from the vector of contracts Q, where F represents fixed capital payment obligations, and VaR is the maximal Value-at-Risk allowed for the period in question, with confidence level γ. In the case where there are sufficient sub-periods in T to make the normality assumption reasonable for $\Pi(Q,\widetilde{D},\widetilde{P}_S)$, this standard VaR constraint translates into a simple function of the mean and standard deviation of $\Pi(Q,\widetilde{D},\widetilde{P}_S)$. Since the profit function is linear in $Q_i$ for every realization of the random variables involved, finding the efficient frontier (in $E\{\Pi\}$-$VaR$ space) is then easily solved in the standard fashion via Quadratic programming. Multi-period VaR constraints are also discussed in Kleindorfer and Li (2005) and Geman and Ohana (2008). For more complex problems, including sophisticated models of the evolution of the spot price and various exotic options, simulation can be used to tackle a wide variety of problems that arise in practice.

## 5. Some Open Research Questions and Implications for Practice

The open questions associated with B2B exchanges and contracting can be described under two general headings. First are the needed model-based developments to capture the essence of the supply-demand coordination problem and the necessary options-based instruments to achieve efficiency in particular market contexts. Second is the continuing development of theory to understand the necessary guidelines for the structure and governance of sustainable business models for the exchanges supporting these instruments. Open research questions in these areas are noted in all of the references below and especially in Geman (2005).

Developing the requisite internal capabilities in a company for B2B operations has been the focus of thousands of papers in trade magazines and the popular press, and more recently have been the subject of deeper research. In addition to the general challenges of taking advantage of new B2B opportunities via the web, there are special challenges associated with integrating long-term and short-term contracting along the lines of this paper. First and foremost, it is foreign territory for most organizations to integrate finance and supply management/operations, and this is precisely what is required in order to have the full benefit of the options approach described here. Companies wishing to do so must radically expand the traditional focus of procurement on cost, quality and dependability to include tracking of spot market conditions, valuing options in operational and hedging terms, and linking these activities to an appropriate risk management structure. Companies that have done this well have recognized the need to develop capabilities in trading, data management, and financial reporting and management. These include new skills in pricing and valuation of contracts, new approaches to managing the portfolio of sourcing options for key manufacturing inputs, and a very different approach to customer and customer segment valuation and management.

A further important open research challenge is capturing more complex product structures. The above discussion, for example, has implicitly assumed a single homogeneous commodity, such as electric power or aluminum (of a standard grade). Many problems entail complexities of by-products, non-heterogeneous products or grades. To illustrate, consider the fed cattle (beef) industry. Traditional (B2B) contracting models consider a single homogenous product model where a single unit of input is processed to produce a single unit of output. In fed-cattle supply chains, where there are spot markets for beef and beef products, one unit of input (beef) is processed to produce proportional amounts of multiple-outputs (hamburger, steak etc.). The proportional product model can be applied in several other important markets as well (pork-hog, petroleum). In Boyabatli et al. (2008), results are provided for the proportional product model on the optimal mix of long-term and short-term (spot) contracting decisions in the context of fed-cattle supply chains. The paper analyzes the effects of product market volatility, correlation and the proportion of products on the optimal decisions and performance measures of packers in their choice of the optimal portfolio of contracts (or marketing arrangements). This research points to interesting additional sources of risk and additional roles for commodity derivatives in proportional output product structures.

There are many other open questions as well in the supply risk management area. These include, foremost, needed model-based developments to capture the essence of the supply-demand coordination problem in specific markets (such as the fed-cattle example noted above) and the necessary options-based instruments to achieve efficiency. They also include integration of inventory options and dynamics (e.g., Milner and Kouvelis, 2007). Notwithstanding these unresolved challenges, the last decade has seen huge progress in integrating physical and financial contracting through B2B markets and through the continuing integration of economics, finance and operations. In particular, the emerging framework presented in this paper on the use of B2B exchanges and supporting options instruments is proving to be a central feature underlying the integration of risk management and procurement in commodity-intensive companies. As always, empirical validation and testing in specific sectors will continue to be the foundation of harvesting the benefits of these innovations.

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