Manufacturing & Service Operations Management

OM Forum—Operations and Finance Interactions

John R. Birge

To cite this article:
John R. Birge (2015) OM Forum—Operations and Finance Interactions. Manufacturing & Service Operations Management 17(1):4-15. http://dx.doi.org/10.1287/msom.2014.0509

MANUFACTURING & SERVICE OPERATIONS MANAGEMENT
Vol. 17, No. 1, Winter 2015, pp. 4–15
ISSN 1523-4614 (print) | ISSN 1526-5498 (online)

http://dx.doi.org/10.1287/msom.2014.0509

OM Forum

Operations and Finance Interactions

John R. Birge
The University of Chicago Booth School of Business, Chicago, Illinois 60637,
john.birge@chicagobooth.edu

This paper, based on my remarks at the 2013 MSOM Distinguished Fellow Award ceremony, describes my views on the interface between operations and finance and the lessons that each field can gain from considering their interactions. The key points are that, whereas operational models often avoid financial considerations such as the role of investors and other market participants, both firm and market financial activity can have a significant effect on the impact of operational decisions. Some of these considerations, such as the implications of market arbitrage, can void the relevance of operational models that ignore financial issues. The paper discusses such operational areas where financial activity has significant potential for impact on operations, as well as points where operational considerations provide new perspectives on financial decisions. In particular, I review basic concepts, provide examples, and give some empirical observations in my work about the implications of the absence of arbitrage, the differences between systematic and idiosyncratic risk, the valuation of limited production resources, and the inclusion of imperfect market assumptions.

Keywords: arbitrage; systematic risk; production; inventory policy
History: Received: July 22, 2014; accepted: November 2, 2014. Published online in *Articles in Advance* December 17, 2014.

1. Introduction

Operations management models typically only consider the level and organization of a firm's transformational activities without considering the financial implications of those activities. On the other hand, financial management models generally focus on the management of a firm's financial resources and the relationships between the management of those resources and owners (or investors broadly) assuming that the operational activities (other than perhaps the manager's intensity of involvement) are separately determined. Whereas this principle has some justification in perfect markets from the Modigliani–Miller theory (Modigliani and Miller 1958) that the financial structure of the firm is irrelevant for valuation (and, hence, that operational decisions can be made separately), markets are, of course, imperfect and, even in perfect markets, the financial market plays an important role in the impact of operational decisions (and vice versa). A goal of this paper is to explain where financial considerations are particularly important for operational models (and, again, vice versa), to show how operational models can accommodate financial market characteristics, and to describe what these observations might imply for empirical observations of firm operations.

The basic principles from either the operational or financial management perspective appear in many textbooks, but descriptions of operations and finance interactions are not so extensive. From a modeling perspective, earlier exceptions include Dotan and Ravid (1985), which describes a model with production and debt decisions, Lederer and Singhal (1994), which investigates how financing options can affect technology choice, and Kogut and Kulatilaka (1994), which models the value of flexibility as in financial option valuation as a form of operational hedging as described in Van Mieghem (2003). A few empirical results, such as those in Kashyap et al. (1994), which examines the effect of interest rates on inventory levels, and Hennessy and Whited (2005), which calibrates a model that incorporates both operational and financial decisions with various market frictions, also considers the interactions of operations and finance, but these papers are exceptions to the general separation of analyses of operational and financial decisions. As explained in §§2 and 3, omitting such interactions can, however, distort both the operational- and financial-focused points of view, leading to conclusions that are contradicted in reality. As also argued here, a consistent and comprehensive view that considers these interactions can correct for some of these distortions and lead to results more in line with actual operations.

From the operations management perspective, the operationally relevant financial issues described here are the financial market's measure of the value of a firm, the role and distinction of systematic risk in that valuation, and the impact on operations of the market imperfections of financial distress cost and tax policy. From a financial viewpoint, the main operational issues described here that affect financial outcomes are the early commitment of resources (and often prices) before market observations, the roles of production flexibility and fixed capacity, and the reactions of suppliers and customers to contract and credit offers. These concepts will be illustrated through simple stylized models that try to capture essential factors in firm decisions.

Since the main goal here is to inform manufacturing and service operations management models, the structure of the paper follows the main financial topic points. Section 2 describes the influence of basic financial market considerations that have an influence even without the introduction of market frictions. Section 3 then discusses the particular influence of financial distress and tax frictions. Section 4 presents conclusions and discussion of extensions of these models to broader contexts.

2. The Implications of Arbitrage-Free Financial Markets and the Role of Systematic Risk

A basic implication of financial markets without frictions is that arbitrage (the ability to earn a profit from a costless investment with no risk of loss) cannot exist in equilibrium. Assuming that price information is costlessly available (which is at least a rough approximation of functioning markets), prices adjust whenever any agent would try to exploit the arbitrage. With no frictions (such as costly or slow information diffusion and transaction costs), the observed state would then allow no arbitrage opportunities. Of course, arbitrage opportunities might exist over small time intervals but, for virtually all operational activities (especially in developed markets), the timescale (e.g., for physical product transformations or completed and observed services) would tend to make arbitrage opportunities generally impossible.

Avoiding arbitrage requires consistency ensuring that prices in different markets or at different points in time cannot lead to financial trades that would result in unbounded riskless profits. As an example, consider a producer that uses a commodity input to manufacture a more specialized product. The commodity input is available at time t at a spot price, $s_t = \$1$, per unit. The commodity may also have a forward price $f_{t,t+1}$ representing the price to be paid at $t+1$ to purchase one unit of the input in an agreement made at time t. Now, suppose the model also includes a holding cost $h_t = \$0.05$ to carry one unit of the input in inventory for one period and a penalty cost $p_t = \$0.15$ for delaying shipment to customers of one unit of output for one period. Fixing these holding and penalty costs in the model while randomly generating spot and forward prices can lead to inconsistencies that represent arbitrage opportunities. For example, if $f_{t,t+1} = \$1.10 > \$1.05 = s_t + h_t$, there is an opportunity to enter into contracts to buy any amount in the spot market at \$1, hold the input for one period for \$0.05, and then sell in one period for \$1.10. If these prices were actually observed, most likely, as soon as the producer would start the trade, the price of the next forward contract would fall or the spot price of the input or the holding facility would rise, pushing prices back to parity.

Suppose on the other hand that the forward price is \$0.75, whereas the spot price minus the penalty cost is \$0.85 ($= s_t - p_t$). The producer then has an incentive to purchase a forward contract now and to produce only in the next period, delaying delivery to the customer. This is a somewhat subtler form of arbitrage because it relies on the customer's behavior, but, assuming the value to delay from t to $t+1$ is worth the penalty cost p_t to the customer, the customer would presumably be willing to shift demand to $t+1$ for a \$0.25 discount on the producer's current price, which would again lower s_t and raise $f_{t,t+1}$. The other (perhaps likely) alternative is that the estimate of the penalty p_t is too low.

In these and more complicated cases with multiple markets and a variety of intermediate holding, transportation, and transformation prices, keeping prices consistent takes care in modeling. Assuming independent processes (or constants) for prices that should depend on one another can lead to model results that are far from intended optimality when adjustments for no-arbitrage are included. Constraints such as limits on inventory or backordering can mask the presence of arbitrage and give models a deceptive appearance of reality that is more a model artifact than a description of behavior. These hidden artifacts can arise whenever a model excludes transactions that some market participant can perform, perhaps at some cost that limits but may not eliminate arbitrage opportunities.

The following subsections describe implications of consistency that result from the optimality conditions of basic market models. The main conclusions from these analyses are that consistent models of public firms (which should seek to maximize their market value) distinguish risk from the overall market (i.e., *systematic* risk) from risk that only involves the firm (i.e., *idiosyncratic* risk) and that transforming the distribution of future outcomes can yield such consistent models by re-weighting the probabilities of events to capture the premium that the market places on risk. These observations hold most particularly when market conditions allow trade without friction, but the general principles apply in practical situations with various types of friction as described in §3.

2.1. Capital Asset Pricing Model and Market Risk
Besides ensuring consistency within the model for prices, particularly with respect to financial transactions and commodity prices, no-arbitrage assumptions also imply how future uncertain payoffs from operational decisions should be valued. For public firms, they should represent market values, since the decisions maximize the value to the owners as investors. This value-maximization goal, which is assumed in the descriptions below, is generally the legal fiduciary duty of corporate directors and managers as their agents. From this perspective of representing the owners, since investors can diversify against idiosyncratic risks that belong to the firm alone, firm managers should only concern themselves with systematic risk that cannot be diversified. In the idealized market settings considered in Sharpe (1964) and Lintner (1965), this leads to the capital asset pricing model (CAPM) that implies that future cash flows should be discounted with a combination of the risk-free rate and a premium that depends on correlation to an overall market value and a common market risk premium.

The CAPM can be viewed as resulting from the solution of an optimization model solved in equilibrium by investors to determine a portfolio of assets to maximize expected return over a given period of time subject to a constraint that the portfolio's risk (measured by the variance on return) does not exceed a limit. The analysis of this optimization model (see Appendix A) implies that when the market includes a risk-free asset (approximated, for example, by a U.S. Treasury bill that is guaranteed by the United States government), the solution of the optimization model scales directly with the investor's risk constraint so that investors would optimally all hold the same proportion of their risky investments in each asset and vary their risk exposure using the proportion held in the risk-free asset. The Lagrange multiplier λ_m on the risk constraint measures the market's value for risk as the *market risk premium* and leads to the following simple formula for the present value s of any future cash flow $\tilde{f}$ (where $\tilde{}$ indicates a random variable) with mean $\bar{f}$ and covariance $\mathbb{C}\mathrm{ov}(\tilde{f}, \tilde{r}_m)$ with the market portfolio's return, $\tilde{r}_m$:

$$s = \frac{1}{1+r_f}(\bar{f} - \lambda_m \mathbb{C}\mathrm{ov}(\tilde{f}, \tilde{r}_m)). \tag{1}$$

Slightly fewer assumptions and multiple factors yield similar relationships in the arbitrage pricing theory (APT) of Ross (1976). Empirically, Fama and French (e.g., Fama and French 1992, 1993) and many others have observed other risk factors in addition to aggregate market indices (e.g., the S&P 500 index), but most studies still find little influence from idiosyncratic risk (and perhaps because of market imperfections, such as tax treatments (Birge and Yang 2007), idiosyncratic risk may even have a positive effect (see, e.g., Ang et al. 2006)). The overall implication, at least without large market imperfections, is that public firms should discount cash flows for contributions to systematic risk but not for idiosyncratic risks. The description here considers public firms that trade on markets; private companies may have other objectives and reasons that prevent owners from diversifying their portfolio. They may still, however, want to maximize the option to sell the firm and should then consider potential public value. Discussion of other market imperfections that might change valuations from the ideal appears in the next section.

As noted earlier, the observation that idiosyncratic risk should not factor into decisions in this framework implies that an expected utility objective that reflects the risk of a future payoff as a function of the individual firm's cash flow must somehow distinguish between the systematic and idiosyncratic components of the risk in that payoff. As an example of the difference, consider two identical cash flows (A and B) at the same future time $t = 1$ such that both are identically distributed with a mean \$100 and a standard deviation of \$20. Cash flow A is the result of a contract to sell all of the output of a random production process where the yield of the process only depends on the performance of an individual machine or worker (whose work performance is not affected by economic conditions). Cash flow B is the result of (certain) production at a fixed posted price in response to uncertain demand that is highly correlated with the market. Following CAPM, since the covariance of A's future value $\tilde{f}_A$ with the market return is $\mathbb{C}\mathrm{ov}(\tilde{f}_A, \tilde{r}_m) = 0$, the present value of cash flow A, s_A, should be the same as that of a certain cash flow of \$100. Assuming a risk-free rate of r_f that gives a one-period discount factor of $1/(1+r_f)$ yields

$$s_A = \frac{100}{1+r_f}. \tag{2}$$

For cash flow B, we need to find the covariance of B's future value $\tilde{f}_B$ with the market as $\mathbb{C}\mathrm{ov}(\tilde{f}_B, \tilde{r}_m)$. We could try to do this historically for similar cash flows, e.g., previous year's sales of the same product and to provide the sales estimates as rates of increase over the previous year's sales. Indeed, Gaur and Seshadri (2005) find that such estimates can be quite useful in predicting sales.

If we suppose that cash flow B results from sales of a particular truck, for example, we could use the historical data in Table 1 for the previous 10 years of

Table 1 **North American Truck Production, 2003–2012 (WardsAuto Group 2014), and S&P 500 Index Returns (Yahoo! Finance 2014)**

Year	Truck production	Change (%)	S&P 500 change (%)
2012	8,841,625	12.59	8.81
2011	7,853,153	11.05	11.20
2010	7,072,056	47.33	20.24
2009	4,800,234	−29.18	−22.29
2008	6,778,191	−24.75	−17.41
2007	9,007,847	−0.36	12.72
2006	9,040,264	−7.75	8.55
2005	9,800,086	−0.78	6.77
2004	9,876,983	2.38	17.14
2003	9,647,745	2.30	−2.89

North American truck production and the value of the S&P 500 index over the same time period to find correlation. In this case, if the future value of cash flow B is $\tilde{f}_B = (1+\tilde{r}_{\text{truck}} - \bar{r}_{\text{truck}})100$, where $\tilde{r}_{\text{truck}}$ is given by the distribution of the change in truck production, then $\mathbb{C}\text{ov}(\tilde{f}_B, \tilde{r}_m) = 100 * 0.0218 = 2.18$. If λ_m is also estimated from this data using an average of 1.67% for one-year U.S. Treasury yields as a one-year risk-free rate over the time period, then $\lambda_m = (\bar{r}_m - r_f)/\sigma_m^2 = (0.043 - 0.017)/0.020 = 1.30$ resulting in a risk adjustment of $\lambda_m \mathbb{C}\text{ov}(\tilde{f}_B, \tilde{r}_m) = 2.83$. If $r_f = 5\%$, cash flow A has value $s_A = \$95.24$, whereas the unconditionally identical cash flow B has value $s_B = \$92.54$.

In this simple example, the difference in the present value of these otherwise identical cash flows at a one-year horizon is about 3%. Larger variations would occur at longer horizons, for goods with higher market sensitivity (e.g., many luxury or discretionary items as noted in Gaur and Seshadri 2005), and during periods with a high market price of risk. Whereas long-run averages provide similar estimates of λ_m to this purely illustrative example, recent results (e.g., Martin 2013) suggest that the market risk premium can be quite volatile and may have risen to five times its long-run average during the 2008–2009 financial crisis, which would have implied substantial differences even at short time horizons between valuations of products with low and high market sensitivity.

2.2. Model Adjustments for Market Risk

Although the CAPM version here may be useful for evaluating general market trends and the value of unconstrained demand, it can become cumbersome for evaluating operational decisions such as capacity levels since the capacity decision affects the covariance of resulting cash flows with the market. At high utilization levels (i.e., low capacity), all production would be sold (at full price) most of the time. In that case, the cash flow has little correlation with the market and, hence, should be discounted as a fairly certain cash flow at close to the risk-free rate. If the capacity is high so that utilization is low, however, sales would closely follow the unconstrained demand with high market correlation and a large risk adjustment.

Since the discount factor depends on the capacity decision, a model with a fixed discount rate that includes a capacity decision is inconsistent with market valuation. Calculating the covariance of the future cash flow with the market as a function of the capacity can address this situation, but such a calculation is complicated directly. Fortunately, another consequence of the absence of arbitrage is that we can adjust the probability distribution of the cash flow to remove the market risk and then treat the cash flows as if they were risk free.

The foundation of this adjustment is again the result of analyzing the optimality conditions for an optimization problem (see Harrison and Kreps 1979) that defines the *fundamental theorem of asset pricing* that a market without arbitrage is equivalent to the existence of a probability distribution that yields all market prices with risk-neutral valuation. Appendix B presents this optimization model and its consequences for a simple case using basic linear programming duality. The absence of unbounded riskless profits then yields an *equivalent martingale measure* (EMM) under which future cash flows can be evaluated as if they were risk free. When this distribution is unique, forming a risk-neutral equivalent form of an operational model requires only finding the appropriate transformation to the EMM. This distribution is, however, not unique unless the market is *complete* (see Harrison and Kreps 1979) such that every cash flow that depends on future conditions (possible states of the world) can be reproduced using trades among securities available in the market. In incomplete markets in which some future cash flows are not available from the market, multiple alternative representations may exist. In that case, a decision maker's risk aversion can have an effect that can guide the choice of distributions or utility functions (see Smith and Nau 1995).

Even in the case of a unique equivalent martingale measure, the risk-neutral equivalent distribution may not always be obvious. For distributions that correspond to the forward distribution of a standard or geometric Brownian motion, such as the normal or lognormal distribution, respectively, that each depend on underlying nondiversifiable risk factors, such as the overall market return, the transformation involves only a shift in the mean of the factor distributions. With these transformations, objectives can be evaluated as if the agents were risk neutral. In the case of linear models, it is also equivalent to use the original natural probability distribution but to adjust the constraints (see Birge 2000).

As an example of the equivalent constraint adjustment, consider the decision to determine a common capacity x with cost c per unit of capacity to produce in a future period quantities $y_j(\omega)$ of products $j=1,\ldots,n$ with production margin u_j (equal to price minus marginal production cost) already committed (hence, not random) and the demand for each product $d_j(\omega)$ is log-normally distributed such that $\log d_j(\omega)=\mu_j+\beta_j f(\omega)+\epsilon_j(\omega)$ where μ_j and β_j are parameters, $\epsilon_j(\omega)$ is a normal random variable, and $f(\omega)$ corresponds to the market risk factor, which we assume is normalized to an increase of λ for one unit of variance over the period until revenues are realized. The transformation, which then provides an equivalent martingale measure, is to subtract $\alpha_j=\lambda\beta_j$ from $\log d_i(\omega)$, which corresponds to reducing the original future period values by a factor $e^{-\alpha_j}$, the risk premium for $d_j(\omega)$. With this transformation and a single period discount factor e^{-r_f}, the model for choosing optimal capacity is to solve the following two-stage stochastic program with recourse (see Birge and Louveaux 2011):

$$\min \quad c^T x + e^{-r_f}\,\mathbb{E}[-u^T y(\omega)] \tag{3}$$

$$\text{s.t.} \quad -x+\sum_{j=1}^{n} y_j(\omega)\le 0; \tag{4}$$

$$y_j(\omega)\le e^{-\alpha_j} d_j(\omega), \quad j=1,\ldots,n, \text{ a.s.}, \tag{5}$$

which then only requires the additional factor in (5) to adjust for risk. We can observe that when x is low so that (4) is binding but (5) is not, then $y_j(\omega)$ is effectively a constant for all j, i.e., the future cash flow has no risk. The model then applies the risk-free discount factor e^{-r_f} in this case, which is appropriate since $y_j(\omega)$ is indeed riskless. On the other hand, if x is large, then demand constraints (5) are binding so that $y_j(\omega)=e^{-\alpha_j}d_j(\omega)$. The second-stage objective is then

$$e^{-r_f}\,\mathbb{E}\Bigg[\sum_{j=1}^{n}(-u_j)e^{-\alpha_j}d_j(\omega)\Bigg] = e^{-r_f}\,\mathbb{E}_Q\Bigg[\sum_{j=1}^{n}(-u_j)d_j(\omega)\Bigg] = \mathbb{E}\Bigg[\sum_{j=1}^{n}e^{-r_j}(-u_j)d_j(\omega)\Bigg], \tag{6}$$

where the middle expression gives the risk-neutral equivalence and the right expression includes a separate discount factor $r_j=r_f+\alpha_j$ that would be applied for each unconstrained future cash flow proportional to $d_j(\omega)$.

This example demonstrates how a single discount factor cannot adjust for the low-x case when e^{-r_f} is appropriate and the high-x situation when separate factors e^{-r_j} should be used, but how the transformation to the equivalent martingale measure allows for interpolation between these extremes. Birge (2000) gives additional examples and extensions for using this approach in more general models by simply adjusting constraints as in (5).

With a single product ($n=1$), (3)–(5) becomes a standard news vendor problem, which then can be solved using the equivalent martingale measure (for a log-normal distribution as assumed here). The result (see Birge and Zhang 1999 for details) is that the news vendor solution x^* has the following form with these parameters:

$$F_Q(x^*)=\frac{e^{-r_f}u-c}{e^{-r_f}u}, \tag{7}$$

where F_Q is the distribution function corresponding to the equivalent martingale measure Q, or

$$x^*=e^{-\alpha}F^{-1}\left(\frac{e^{-r_f}u-c}{e^{-r_f}u}\right), \tag{8}$$

for α, the demand market risk premium, and F, the natural distribution of the demand. The result in (8) is that, in the case of fixed future prices and uncertain lognormal demand, the quantity adjustment for market risk is simply to discount the future revenue by the demand's market risk premium. As shown in Birge and Zhang (1999), this is equivalent to using the CAPM formula in (1) for risk adjustment as given in Singhal (1988). Whereas this risk adjustment can be significant for capacity decisions, it is generally small over short horizons for inventory decisions, but, in such a dynamic setting, the purchase price of inputs would generally also be correlated with the market, leading to holding costs for their market risk. These costs should then also be adjusted for market risk. As shown in Berling and Rosling (2005), this adjustment can lead to significant differences in stocking levels depending on the market risk of these costs.

This general approach to adjusting cash flows can also allow for efficient valuation of capacity decisions that involve discrete choices such as fixed payments for shifting production from one facility or region to another. By adjusting the relevant random processes for systematic risk, tools from financial option theory (see, e.g., Hull 2009 for the financial basis and Trigeorgis 1996 for more operational settings) can be applied to simplify the capacity valuation. Aytekin and Birge (2009), for example, consider the valuation of production in markets with different currencies and a fixed charge to switch production from one location to another. Assuming a standard model of the exchange rate, the paper provides a closed form solution for the value of the capacity across the two markets. The result also gives a bound on the value of adding capacity in a different currency region for any level of volatility in the exchange rate so that capacity investment decisions can be quickly filtered as potentially viable or not worthy of further consideration if the value bound does not exceed the capacity investment cost. Many other operations management studies (see, e.g., Devalkar et al. 2011; Goel and Gutierrez 2011; Lai et al. 2010, 2011; Secomandi 2010a, b; Secomandi and Wang 2012; Wu et al. 2012) also take advantage of this valuation methodology in characterizing operational policies in the presence of financial markets.

The overall lessons from the no-arbitrage market assumptions are that operational decisions, such as production capacity and stocking levels, can affect firms' exposures to market risks and, therefore, the present value of cash flows in operational models should incorporate the market value of that risk to ensure that these models do not effectively assume arbitrage opportunities that are not likely to exist in reality. The no-arbitrage implication of an equivalent risk-neutral distribution or martingale measure makes valuation possible in these contexts and can, in some cases, be accomplished with simple updates of the constraints or distribution parameters. The resulting models with these updates then allow for valuation in a variety of contexts. With minimal frictions (such as the costs to shift capacity), these valuations only include risk-neutral expectations. Other frictions, such as additional risk-aversion of the managers or costs of financial distress, can motivate additional considerations. Section 3 describes an approach when the frictions involve distress costs (which has an effect like risk aversion) and taxes.

3. Markets with Frictions

When markets allow free trading of assets and include all possible cash flows, apart from adjusting for the risk of the market as in §2, the Modigliani–Miller theory implies again that operational and financial activity can be separated. In such perfect markets, the capital structure or financing form of the firm does not matter. The amount of debt, which obliges a borrower to repay a borrowed amount with defined interest at specified times, versus equity, which gives an investor a share of an enterprise's value, should have no influence on the firm's value in this setting. This justifies fully separating a firm's financing decisions from its operational activity. Plant sizes and order quantities can be determined without regard to how the initial investments and payments are financed.

This theory changes, however, whenever the market has imperfections or frictions, which include transaction costs, regulations, taxes, and various effects from agency issues, such as a manager's acting in the manager's own interest instead of acting for the firm (see, e.g., Jensen and Meckling 1976), and information asymmetry, such as the firm's having more precise knowledge of its product market than its lenders and investors. This section describes the impact of two imperfections: taxes, which generally provide a benefit to debt, and bankruptcy or financial distress costs, which usually give a disadvantage to debt. A discussion of additional issues in capital structure choice in particular appears in Harris and Raviv (1991). The basis for this discussion appears in Xu and Birge (2004).

For this development, consider (3)–(5) where $n = 1$ for simplicity (so that again this is equivalently a news vendor model). Without financial constraints, an optimal capacity choice x^* can be built with $x^* = F^{-1}(1-c)$, where $r_f = \alpha = 0$ and $u_1 = 1$ for simplicity. This requires a payment of cx^*, an optimal investment level, which the firm could obtain from equity investors or borrow, e.g., from a bank. Without market imperfections, the decision on how to obtain this amount would be done separately, but, with the frictions of financial distress costs and tax benefits from debt, the capacity decision depends on the form of financing.

For taxes, assume a proportional tax rate τ that applies to any profits of the firm, where, in this two-period world, we treat the capacity investment as an expense that is deducted directly from any revenues. The main advantage we identify for taxes is that the firm can deduct the interest on its debt; therefore, the uncertain future taxable amount is $d(\omega) - cx - iD$, where iD is the amount of interest paid on a loan with principal D. If the firm has a loss (i.e., $d(\omega) \le cx + iD$), then we assume no taxes are paid but the firm does not receive any payment back from the government. (More general multiperiod models might consider separate tax treatment of capital expenditures and losses used to offset other income or carried forward or backward to apply against future or past profits, respectively.) Other advantages for debt might include its ability to control managers by restricting the amount of free cash available that they might redirect for personal purposes and potential signaling to the market about the firm's ability to meet the debt obligation.

For financial distress as a cost of debt, in this framework, if the firm is unable to meet the debt obligation (here, full payment of principal and interest), the firm enters bankruptcy and incurs a deadweight loss proportional to the remaining funds in the firm. This common assumption in the finance literature (e.g., Leland 1994) has some theoretical justification in the time required for accountants and lawyers to value the firm's assets and any losses in sales of assets that are discounted following bankruptcy because of information asymmetry or other coordination issues. Such costs also have empirical support (see, e.g., Andrade and Kaplan 1998 for corporate defaults and Campbell et al. 2011 for housing) and have become an industry standard (see, e.g., Vasiček 2002 and Basel Committee on Banking Supervision 2005). Besides this direct loss in the event of default, other disadvantages of debt might include inefficiencies in lending from information asymmetry and any negative market signals derived from the use of debt (in a dynamic setting where debt might indicate that the firm is generating less cash than necessary to sustain operations).

We include the tax advantage and financial distress cost of debt in the following model that maximizes firm value:

$$V^* = -\min_{(x,D,i)\geq 0} \; cx - \int_0^{D(1+i)} \gamma y g(y)\,dy - \int_{D(1+i)}^{cx+iD} y g(y)\,dy - \int_{cx+iD}^{x} (y - \tau(y - cx - iD)) g(y)\,dy - \int_x^{\infty} (x - \tau(x - cx - iD)) g(y)\,dy \tag{9}$$

$$\text{s.t.} \quad D - \int_0^{D(1+i)} \gamma y g(y)\,dy - (1+i)D \int_{D(1+i)}^{\infty} g(y)\,dy = 0, \tag{10}$$

where g denotes the density of demand and γ is the fraction recovered in the event of default on the debt. The objective represents the (negative of the) net value of the firm overall where cx is expended, and then returns fall into one of four groups according to the demand realization. The lowest level of demand from 0 to $D(1+i)$ corresponds to default on the loan, in which γ of the sales are recovered. The second interval (from $D(1+i)$ to $cx+iD$) corresponds to sales that are sufficient to avoid default but lead to overall losses (and no taxes). The third demand group (from $cx+iD$ to x) corresponds to taxed profits with production below capacity, while the fourth interval (above x) includes taxed profits with production at capacity. The complicating factor in this model is the constraint (10) that represents fair pricing of the loan. This constraint effectively assumes that the financial market is competitive and that no information asymmetries exist (or the bank can costlessly monitor production and infer the demand distribution) so that the interest rate i is set to make a loan of value D have a zero net present value.

We can write the optimization problem in (9) and (10) in terms of x and D with $i(D)$ determined by (10). The result is that an interior optimal solution occurs at the solution of the following two first-order conditions:

$$(1-\tau)\int_x^{\infty} g(s)\,ds + c\tau \int_{cx+i(D)D}^{\infty} g(s)\,ds - c = 0; \tag{11}$$

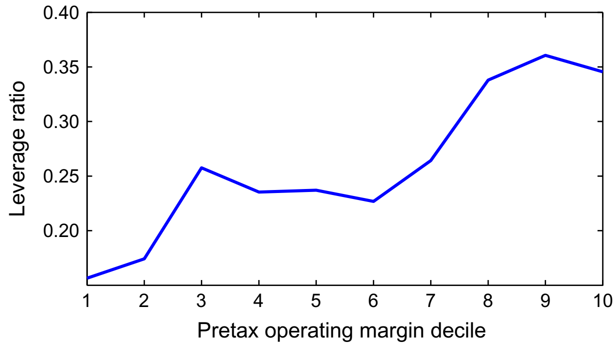
$$\tau\left(i + D\frac{\partial i}{\partial D}\right)\int_{cx+i(D)D}^{\infty} g(s)\,ds - (1-\gamma)\left(1 + i(D) + D\frac{\partial i}{\partial D}\right) \cdot D(1+i(D))\,g(D(1+i(D))) = 0. \tag{12}$$

The first condition (11) includes the standard news vendor optimality condition with the addition of $c\tau(1 - F(cx + i(D)D))$ as the marginal value of the tax deduction for the cost of the capacity x, which only has value when the firm is profitable. The absence of a deduction in the event of a loss creates a distortion to reduce investment below a no-tax solution even in the absence of debt. With debt, the break-even point rises, reducing the effective tax deduction of the capacity cost and further reducing investment; expected profit, however, increases as the firm gains the interest rate deduction. The second condition reflects the marginal benefit of this debt for tax purposes in the first term and the marginal cost from the deadweight loss in the event of default on the debt in the second term.

As shown in Xu and Birge (2004), these conditions lead to a capacity on debt such that firms cannot borrow beyond an upper bound $\bar{D}$, regardless of interest rate. The conditions also imply a first order impact of the capacity decision on the optimal debt level through the tax benefit term, whereas the debt level has effectively a second-order impact on the optimal capacity level, since it is only the change in the break-even level from the interest payment that enters the first equation in (12). As explored in Xu and Birge (2004), this difference in relative influence implies that while operational and financial decisions are dependent in this framework, correctly identifying the operational decision x^* is more critical than determining the optimal financial structure through optimal debt D^*.

The equations in (12) also lead to a potentially nonmonotonic relationship between the leverage ratio, D^*/V^*, and c (or the profit margin) in which high debt levels can occur at both low and high margins since, at low margins, x^* is also low, leading to little variation in revenues and low default risk to support higher leverage, and at high margins, low chances of losses overall reduce default risk and again can support high leverage. This is supported empirically for profitable firms in Xu and Birge (2006), which includes a dynamic model in which firms update future demand forecasts based on prior observations. Birge and Xu (2011) expands this model with the addition of fixed costs that are independent of production levels and amount to an operating leverage that take the place of debt. Firms with high operating leverage, therefore, also lower debt from this substitution, leading to a cubic curve form for the relationship of leverage to profitability with rising leverage for firms with losses (because of high operating leverage that substitutes for debt) followed by the decreasing and then increasing relationship for profitable firms. Figure 1 shows these aggregate results of the average quarterly leverage (total debt over total market value) for firms in Compustat from 2000 to 2013 grouped by

Figure 1 (Color online) Average Leverage Ratios for Deciles of Pretax Operating Margin for Firms in Compustat Averaged over Quarters Reported from 2000 to 2013



Source. Standard and Poor's Compustat, via Wharton Research Data Services, accessed July 2014.

deciles of average quarterly pretax operating margins over the period. The lowest two deciles correspond to negative operating margins where this basic model predicts increasing leverage; the upper deciles correspond to positive operating margins where the model predicts a U-shaped relationship.

The results in Birge and Xu (2011) provide further empirical support of these observations for the nonmonotonic cubic relationship between profitability and leverage, which does not appear in models of capital structure and investment in the finance or general economics literature (although a nonmonotonic relationship between production quantities and leverage appears in rare instances such as the duopoly model in Brander and Lewis 1988). In the case considered here, the operational news vendor framework of (9) and (10) with early commitment to price and capacity includes a different impact on the firm's risk through the capacity investment x than in most financial models, such that of Dotan and Ravid (1985), which assume production at capacity (or otherwise given at some production function of inputs) and clearance at a random future price. Although the fixed-production-variable-price situation appears in many ways equivalent to the news vendor setup, the models differ in the relationship between the future cash flow distribution and the capacity or production decision. In the news vendor framework, the cash flow distribution is highly concentrated (i.e., low relative variance) at low capacity values and more diffuse at high investment levels. Standard price processes associated with a fixed production quantity would not have those characteristics. For example, a process parameterized only by the mean price at a given quantity would not reflect the changing future value distribution in (9) and (10) where the relative volatility of the cash flow increases with x. This operational feature has support in other empirical uses of the news vendor framework, such as Bray and Mendelson (2012), representing a perspective where operational details can provide insights into firm behavior that other models do not capture.

A key implication of this modeling framework is that the capacity decision endogenously determines the firm's cash flow risk and, hence, the cost of debt. In models where firm value evolves exogenously or price risk is simply a multiplier on production capacity, this effect is lost. Operational decisions of the firm, such as capacity levels, are bound with the firm's risk and should not be separated from other decisions that affect firm risk. Recognizing this interdependence reveals relationships that do not appear in exogenous-value driven firm models.

To display the relationship between capacity and sales volatility in the news vendor framework with early price commitment, Figure 2 shows the coefficient of variation in production (not including salvage values) for increasing levels of capacity assuming demand with a normal distribution with mean of 100 and maximum coefficient of variation of 20% with no capacity limit (i.e., an unconstrained standard deviation of sales of 20). The figure shows a strong increase in this measure of production volatility as the capacity increases to high capacity levels when the volatility approaches its maximum. The standard financial model with unit sales at the capacity level and a constant coefficient of variation in price would instead yield a constant coefficient of variation as the capacity increases.

Figure 3 considers an empirical version of Figure 2 to observe whether the relationship assumed in the news vendor setting has empirical support. Since firm capacity relative to demand is difficult to observe directly, the dependent variable (x axis) here is the

Figure 2 (Color online) Coefficient of Variation (COV) in Production for Increasing Values of Capacity

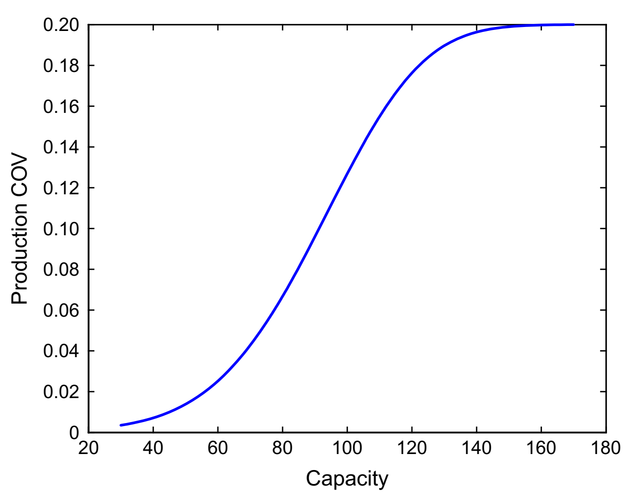
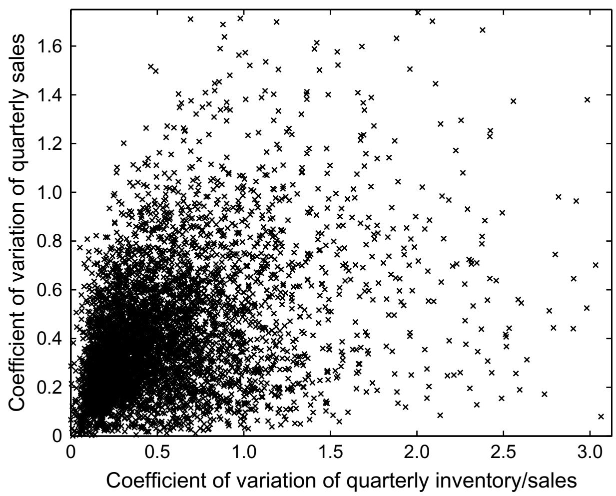


Figure 3 **Coefficient of Variation in Quarterly Sales for Increasing Coefficient of Variation of Quarterly Inventory over Sales for Firms Reporting Positive Inventory from 2000 to 2014**



Source. Standard and Poor's Compustat, via Wharton Research Data Services, accessed July /2014.

coefficient of variation in quarterly inventory as fraction of sales for all Compustat firms reporting positive inventories ($N = 5{,}328$) from January 2000 to June 2014. The independent variable is the coefficient of variation of quarterly sales (to correspond to Figure 2). Figure 3 gives a scatter plot of these observations, which, as can be seen, display a strong increasing relationship that also appears to flatten at higher levels of this capacity measure as in Figure 2. A linear model of this relationship has an intercept of 0.33 and a coefficient of 0.15 on the independent variable with a t-statistic of 22.0 or p-value of 10^{-102}, confirming that this measure of relative capacity is positively correlated with the relative volatility of sales as in the news vendor model. A nonlinear model including a quadratic term has an intercept of 0.28, a coefficient of 0.25 on the linear term of coefficient of variation of quarterly sales with a t-statistic of 27.1 (p-value of 10^{-151}) and a coefficient of -0.012 on the quadratic term with a t-statistic of -15.6 (p-value of 10^{-54}). A fit of a logistic model (as suggested by Figure 2) for the logarithm of the ratio of the coefficient variation of sales to the difference between the coefficient of variation of sales and a maximum in this data set of 13 yields an intercept of -3.82 with a coefficient on the independent variable of 0.31 with t-statistic of 19.98 or p-value of 10^{-85}.

This model of investment, production, and a competitive lending market also has implications for agency issues in managers' incentives as in Jensen and Meckling (1976) and for coordination with suppliers. Xu and Birge (2008) consider the implications of varying compensation schemes on managers' decisions, showing, for example, that profit-based bonuses can significantly distort decisions for low-margin producers while the effect of such bonus compensation for high-margin producers is not significant, agreeing with stylized facts and empirical studies (e.g., Mehran 1992) that higher-margin growth firms tend to use more bonus compensation.

To examine implications in this context for the impact of financing needs on supply chain coordination, Yang and Birge (2011) present a model that builds on the single firm with competitive lending model in (9) and (10) by adding a supply chain partner who can extend trade credit to relieve a buyer's financial constraints. In that model, trade credit serves a risk-sharing purpose that shifts a portion of the customer firm's demand risk to the supplier, coordinating the chain. Trade credit then enters the customer firm's financing structure before outside borrowing, which the paper also supports empirically with evidence from the seasonal financial structure of firms with high end-of-year (fourth quarter) sales.

4. Conclusions

This paper has described some of the ways in which operational and financial decisions interact. The basic assumption of no (lasting) arbitrage in financial markets yields that, to avoid arbitrage opportunities, models should distinguish systematic risks that depend on market risk factors from risks that are idiosyncratic and could be diversified by investors. Adjusting for the risk premium of the market risk components can provide this separate treatment with an appropriate change of the distribution of future cash flows with other adjustments possible to reflect individual risk preferences.

Beyond the linkage of financial markets to enforcing consistency in prices and to eliminate arbitrage, models of market frictions also connect operational and financial decisions such that they cannot be consistently separated as in the case of perfect markets. Since operational decisions on the scale and scope of production directly affect all firm risk, which then determines the available forms and cost of financing, the presence of any frictions creates interdependence of the two functions of operations and finance. In the model in §3, both taxes and financial distress costs from debt lower production quantities or capacity investments, but the greater impact appears in the other direction where firm's operational decisions have a first-order impact on the cost of financial distress and hence the firm's debt decision. Balancing production and inventory in the presence of financial markets for commodity inputs and outputs as, for example, in Secomandi and Kekre (2014) and Kouvelis et al. (2013), also creates direct connections between financial and operational activities.

These observations did not include a number of other operations-finance interaction effects, such as the use of financial instruments to control firm risk (i.e., financial hedging; see, e.g., Caldentey and Haugh 2006), other uses of operational flexibility options to improve firm value (e.g., Boyabatlı and Toktay 2011, Chod et al. 2010, Ding et al. 2007, Kazaz et al. 2005), the use of operations to address agency issues (e.g., Babich and Tang 2012, Chod and Zhou 2014), and forms of financing that depend directly on firm assets (e.g., Buzacott and Zhang 2004, Alan and Gaur 2012). The use of financial instruments and lending based on assets generally requires some other form of friction, such as information asymmetry or agency costs, to motivate their use and relationship to operational actions. Competitive effects (as, e.g., in the model of Brander and Lewis 1986) can also play a role in linking firms' operational and financial decisions.

Each of these areas of interactions provides new opportunities for research that explores how firms can, should, and have made operational and financial decisions. The research to date represents only the beginning of investigation into the effects of finance on operations and vice versa. Opportunities for new insights exist in a wide variety of areas from purely theoretical models to specific empirical tests. In terms of theory, many issues such as the impact of asymmetric information, the combined roles of operations and finance in controlling agency issues, and the effects of competition, firm entry, and supply chain network structure on operations-finance interactions could all provide insights into the analysis and design of firms' operational and financial activity. These models could then help expand and explain the impacts of different organizational and systemic mechanisms.

The model also raise questions about the operational decision-making mechanisms within firms and across levels of their supply chain networks. Firm-level studies can examine specific decision environments to identify specific interactions such as the relationships between operational investments and financial condition, the relationship between product market activity such as production and pricing policy with financial activity, and the role of incentives and financial market activity in operational decision making.

Broader empirical studies that compare firms cross-sectionally can also test proposed relationships and the implications of structural models. These studies can also elucidate the role of operational signals such as inventory turns, sales growth, and the dynamics of costs and investments on the overall valuation of firms. Work on these topics combining operations and finance can help demonstrate, as seen in so many other fields, that the greatest opportunities for innovation are often at the interfaces of disciplines.

Acknowledgments

This work was supported by the University of Chicago Booth School of Business.

Appendix A. The CAPM as an Optimization Model

Suppose there are a total of n possible investments available to all investors over a fixed time period and that each has some random return $\tilde{r}_i$, $i = 1, \ldots, n$. An investor would put a fraction x_i of total wealth into each asset and, assuming the market has a risk-free investment source with return r_f, the remainder $1 - \mathbf{1}^T x$ (where $\mathbf{1}$ is a column vector of ones, $\mathbf{1}^T$ indicates its transpose, and $x = (x_1, \ldots, x_n)^T$) is placed in the risk-free asset (which could result in a positive or negative amount for lending or borrowing, respectively, in this idealized situation). If n is large and the variations in the returns correspond to sequences of additive shocks with appropriate mixing properties, then we might also conclude from a central limit theorem that the return on a portfolio $(\tilde{r} - r_f)^T x + r_f$ could be approximately normally distributed (although clearly this requires some additional assumptions). In this case, investors would only have a choice of the two moments to describe the portfolio distribution. Assuming investors prefer more return (mean) and less risk (variance), each investor would choose some portfolio that maximizes return for a given amount σ^2 of risk, solving a problem of the form

$$\begin{aligned} \max_x \quad & (\bar{r} - r_f)^T x + r_f \\ \text{s.t.} \quad & x^T V x \le \sigma^2, \end{aligned} \tag{A1}$$

where $\bar{r} = \mathbb{E}(\tilde{r})$ is the mean and $V = \mathbb{V}\mathrm{ar}(\tilde{r})$ is the variance-covariance matrix of $\tilde{r}$. We can write optimality conditions for (A1) for a solution $x(\sigma)$ and associated dual multipliers $\lambda(\sigma)$ as follows:

$$(\bar{r} - r_f) - \lambda(\sigma) V x(\sigma) = 0, \tag{A2}$$

$$\lambda(\sigma)(x(\sigma)^T V x(\sigma) - \sigma^2) = 0, \tag{A3}$$

where, if we assume $\bar{r}_i > r_f$ for any i, then $\lambda(\sigma) \neq 0$ and $x(\sigma)^T V x(\sigma) = \sigma^2$. We can also observe that

$$(\bar{r}_i - r_f) = \lambda(\sigma) V_{i\cdot} x(\sigma) = \lambda(\sigma) \mathbb{C}\mathrm{ov}(\tilde{r}_i, \tilde{r}^T x(\sigma)), \tag{A4}$$

where the last equality follows from $V_{i\cdot} x = \sum_{j=1}^n V_{ij} x_j = \sum_{j=1}^n \mathbb{C}\mathrm{ov}(\tilde{r}_i, \tilde{r}_j) x_j = \mathbb{C}\mathrm{ov}(\tilde{r}_i, \sum_{j=1}^n \tilde{r}_j x_j)$. Equation (A4) then states that the expected excess (above risk-free) return on any investment is proportional to the covariance of that asset's return with the investor's full portfolio return. Now, if we consider the market as a whole with investments x_m (with subscript m denoting *market*) as a fraction of all risky assets, then there is a σ_m^2 where $x_m = x(\sigma_m)$ so that, with $\lambda_m = \lambda(\sigma_m)$ and assuming V has full rank, from (A2),

$$1 = \mathbf{1}^T x_m = \mathbf{1}^T V^{-1} (\bar{r} - r_f)/\lambda_m, \tag{A5}$$

or $\lambda_m = \mathbf{1}^T V^{-1} (\bar{r} - r_f)$, and, for each asset i,

$$(\bar{r}_i - r_f) = \lambda_m V_{i\cdot} x_m = \lambda_m \mathbb{C}\mathrm{ov}(\tilde{r}_i, \tilde{r}_m), \tag{A6}$$

which is the fundamental relationship in the CAPM; every asset's excess return is proportional to its covariance with the market where λ_m gives the constant of proportionality.

Note that multiplying (A6) by $x_m(i)$ for each i and adding also implies

$$\lambda_m = \frac{\bar{r}_m - r_f}{\sigma_m^2}, \tag{A7}$$

so that λ_m represents the market price of risk, the return required in compensation for the risk of the market.

We can recover another form of CAPM by substituting for λ_m as

$$(\bar{r}_i - r_f) = \beta_i(\bar{r}_m - r_f), \tag{A8}$$

where $\beta_i = \mathbb{C}\mathrm{ov}(\tilde{r}_i, \tilde{r}_m)/\sigma_m^2$. For an asset with a future value $\tilde{f}_i$ with expectation $\bar{f}_i = \mathbb{E}[\tilde{f}_i]$, current price s_i, and $\tilde{r}_i = \tilde{f}_i/s_i - 1$, we can use (A8) to write

$$s_i = \frac{\bar{f}_i}{1+\bar{r}_i} = \frac{\bar{f}_i}{1+r_f+\beta_i(\bar{r}_m - r_f)}. \tag{A9}$$

Substituting in (A6) also yields

$$\left(\frac{\bar{f}_i}{s_i} - 1 - r_f\right) = \lambda_m \mathbb{C}\mathrm{ov}\left(\frac{\tilde{f}_i}{s_i} - 1, \tilde{r}_m\right) = \frac{\lambda_m}{s_i}\mathbb{C}\mathrm{ov}(\tilde{f}_i, \tilde{r}_m), \tag{A10}$$

or

$$s_i = \frac{1}{1+r_f}(\bar{f}_i - \lambda_m \mathbb{C}\mathrm{ov}(\tilde{f}_i, \tilde{r}_m)), \tag{A11}$$

which states that finding the present value of any uncertain cash flow in this setting involves an adjustment for the cash flow's covariance with the market and then discounting with the risk-free rate. The idiosyncratic risk then plays no role in finding the present value. An implication of this observation is that a model that includes the optimization of a risk averse utility function applied to a future cash flow that includes both idiosyncratic and systematic or market risk is not consistent with market valuation. Consistency requires separate treatment of the market risk, such as adjusting distributions for the market's risk premium as discussed in §2.

Appendix B. Equivalent Risk-Neutral Distributions

The result here considers a simple single-period case with a finite distribution that readily extends to multiple periods and continuous distributions. A set of uncertain future cash flows is given by $\tilde{f}_i, i = 0, 1, \ldots, k$ where $i = 0$ corresponds to a risk-free investment with the same value $f_0 = f_{01} = \cdots = f_{0n}$ in all future states and all other cash flows have n possible values $f_{ij}, j = 1, \ldots, n$ which occur with probabilities $p_j, j = 1, \ldots, n$, and current market values s_i. We can then use the risk-free investment to define the rate r_f so that $s_0 = f_0/(1+r_f)$.

In the absence of arbitrage, the following optimal model must have a value of zero:

$$\max_x \quad \sum_{j=1}^{n}\sum_{i=0}^{m} p_j f_{ij} x_i \tag{B1}$$

$$\text{s.t.} \quad \sum_{i=0}^{m} s_i x_i = 0, \tag{B2}$$

$$\sum_{i=0}^{m} f_{ij} x_i \geq 0, \quad j = 1, \ldots, n; \tag{B3}$$

where $x_i, i = 0, \ldots, n$, corresponds to the units of positions in each of the alternative traded assets. The first constraint (B2) ensures that these investments are self-financing. The second set of constraints (B3) ensures that no losses occur in any of the future states of the world. Bounding the maximum at zero is the no-arbitrage condition that the market cannot allow for infinite profits (since a feasible solution with strictly positive objective value would then yield an unbounded solution).

If (B1) has an upper bound at zero, then the following dual to (B1)–(B3) has a feasible solution (ρ, π) with $\pi = (\pi_1, \ldots, \pi_n)$.

$$\min_{\pi, \rho} \quad \mathbf{0}^{\mathrm{T}}\pi \tag{B4}$$

$$\text{s.t.} \quad \sum_{j=1}^{n} p_j f_{ij} - \rho s_i - \sum_{j=1}^{n} f_{ij}\pi_j = 0, \quad i = 0, \ldots, k; \tag{B5}$$

$$\pi_j \geq 0, \quad j = 1, \ldots, n, \tag{B6}$$

where $\mathbf{0}$ is a vector of zeroes. From (B5),

$$\rho s_i = \sum_{j=1}^{n} p_j(1+\pi_j')f_{ij}, \tag{B7}$$

where $p_j\pi_j' = \pi_j$ and $\rho > 0$ from $p_j > 0$, $\pi \geq 0$, and $f_{ij} > 0$ for some i and j. We can then define

$$q_j = \frac{p_j(1+\pi_j')}{\rho}(1+r_f), \tag{B8}$$

yielding

$$s_i = \left(\frac{1}{1+r_f}\right)\sum_{j=1}^{n} q_j f_{ij}. \tag{B9}$$

Next, for $i = 0$, we have $f_{0j} = f_0$ for all j, so that substituting for s_0 yields

$$1 = \sum_{j=1}^{n} q_j, \tag{B10}$$

implying q_j defines a probability distribution $\mathcal{Q}$ over events j known as an *equivalent martingale measure* since it ensures that the present value of all market instruments can be found by expectation with respect to $\mathcal{Q}$ and discounting at the risk-free rate, allowing risk-neutral valuation under $\mathcal{Q}$ of all cash flows from the market perspective.

References

Alan Y, Gaur V (2012) Operational investment and capital structure under asset based lending: A one period model. Research paper, Johnson School, Cornell University, Ithaca, NY. http://ssrn.com/abstract=1716925.

Andrade G, Kaplan SN (1998) How costly is financial (not economic) distress? Evidence from highly leveraged transactions that became distressed. *J. Finance* 53:1443–1493.

Ang A, Hodrick R, Xing Y, Zhang X (2006) The cross-section of volatility and expected returns. *J. Finance* 61:259–299.

Aytekin A, Birge JR (2009) Optimal investement and production across markets with stochastic exchange rates. Technical report, The University of Chicago Booth School of Business, Chicago. http://ssrn.com/abstract=652561.

Babich V, Tang CS (2012) Managing opportunistic supplier product adulteration: Deferred payments, inspection, and combined mechanisms. *Manufacturing Service Oper. Management* 14: 301–314.

Basel Committee on Banking Supervision (2005) An explanatory note on the Basel II IRB risk weight functions. Consultative document, Bank for International Settlements, Basel, Switzerland. http://www.bis.org/bcbs/irbriskweight.pdf.

Berling P, Rosling K (2005) The effects of financial risks on inventory policy. *Management Sci.* 51:1804–1815.

Birge JR (2000) Option methods for incorporating risk into linear capacity planning models. *Manufacturing Service Oper. Management* 2:19–31.

Birge JR, Louveaux FV (2011) *Introduction to Stochastic Programming*, second ed. (Springer, New York).

Birge JR, Xu X (2011) Firm profitability, inventory volatility, and capital structure. Working paper, The University of Chicago Booth School of Business, Chicago. http://ssrn.com/abstract=1914690.

Birge JR, Yang SA (2007) A model for tax advantages of portfolios with many assets. *J. Banking and Finance* 31:3269–3290.

Birge JR, Zhang RQ (1999) Risk-neutral option pricing methods for adjusting constrained cash flows. *Engrg. Econom.* 44:36–49.

Boyabatlı O, Toktay LB (2011) Stochastic capacity investment and flexible vs. dedicated technology choice in imperfect capital markets. *Management Sci.* 57:2163–2179.

Brander JA, Lewis TR (1986) Oligopoly and financial structure: The limited liability effect. *Amer. Econom. Rev.* 76:956–970.

Brander JA, Lewis TR (1988) Bankruptcy costs and the theory of oligopoly. *Canadian J. Econom.* 21:221–243.

Bray RL, Mendelson H (2012) Information transmission and the bullwhip effect: An empirical investigation. *Management Sci.* 58:860–875.

Buzacott JA, Zhang RQ (2004) Inventory management with asset-based financing. *Management Sci.* 24:1274–1292.

Caldentey R, Haugh MB (2006) Optimal control and hedging of operations in the presence of financial markets. *Math. Oper. Res.* 31:285–304.

Campbell JY, Giglio S, Pathak P (2011) Forced sales and house prices. *Amer. Econom. Rev.* 101:2108–2131.

Chod J, Zhou J (2014) Resource flexibility and capital structure. *Management Sci.* 60:708–729.

Chod J, Rudi N, Van Mieghem JA (2010) Operational flexibility and financial hedging: Complements or substitutes? *Management Sci.* 56:1030–1045.

Devalkar SK, Anupindi R, Sinha A (2011) Integrated optimization of procurement, processing, and trade of commodities. *Oper. Res.* 59:1369–1381.

Ding Q, Dong L, Kouvelis P (2007) On the integration of production and financial hedging decision in global markets. *Oper. Res.* 55:470–489.

Dotan A, Ravid SA (1985) On the interaction of real and financial decisions of the firm under uncertainty. *J. Finance* 40:501–517.

Fama EF, French KR (1992) The cross-section of expected stock returns. *J. Finance* 47:427–465.

Fama EF, French KR (1993) Common risk factors in the returns on stocks and bonds. *J. Financial Econom.* 33:3–56.

Gaur V, Seshadri S (2005) Hedging inventory risk through market instruments. *Manufacturing Service Oper. Management* 7:103–120.

Goel A, Gutierrez GJ (2011) Multiechelon procurement and distribution policies for traded commodities. *Management Sci.* 57:2228–2244.

Harris M, Raviv A (1991) The theory of capital structure. *J. Finance* 46:297–355.

Harrison JM, Kreps DM (1979) Martingales and arbitrage in multiperiod securities markets. *J. Econom. Theory* 20:381–408.

Hennessy CA, Whited TM (2005) Debt dynamics. *J. Finance* 60: 1129–1165.

Hull JC (2009) *Options, Futures, and Other Derivatives*, 7th ed. (Pearson Prentice Hall, Upper Saddle River, NJ).

Jensen MC, Meckling WH (1976) Theory of the firm: Managerial behavior, agency costs and ownership structure. *J. Financial Econom.* 4:305–360.

Kashyap A, Lamont O, Stein JC (1994) Credit conditions and the cyclical behavior of inventories. *Quart. J. Econom.* 109:565–592.

Kazaz B, Dada M, Moskowitz H (2005) Global production planning under exchange-rate uncertainty. *Management Sci.* 51:1101–1119.

Kogut B, Kulatilaka N (1994) Operating flexibility, global manufacturing, and the option value of a multinational network. *Management Sci.* 40:123–139.

Kouvelis P, Li R, Ding Q (2013) Managing storable commodity risks: The role of inventory and financial hedges. *Manufacturing Service Oper. Management* 15:507–521.

Lai G, Margot F, Secomandi N (2010) An approximate dynamic programming approach to benchmark practice-based heuristics for natural gas storage valuation. *Oper. Res.* 58:564–582.

Lai G, Wang MX, Kekre S, Scheller-Wolf A, Secomandi N (2011) Valuation of storage at a liquefied natural gas terminal. *Oper. Res.* 59:602–616.

Lederer PJ, Singhal VR (1994) The effect of financing decisions of the choice of manufacturing technologies. *Internat. J. Flexible Manufacturing Systems* 6:333–360.

Leland HE (1994) Corporate debt value, bond convenants, and optimal capital structure. *J. Finance* 49:1213–1252.

Lintner J (1965) The valuation of risk assets and the selection of risky investments in stock portfolios and capital budgets. *Rev. Econom. Statist.* 47:13–37.

Martin I (2013) Simple variance swaps. Working paper, Stanford University, Stanford, CA. http://web.stanford.edu/~iwrm/simple%20variance%20swaps%20latest.pdf.

Mehran H (1992) Executive incentive plans, corporate control, and capital structure. *J. Financial Quant. Anal.* 27:539–560.

Modigliani F, Miller MH (1958) The cost of capital, corporation finance, and the theory of investment. *Amer. Econom. Rev.* 48:261–297.

Ross SA (1976) The arbitrage theory of capital asset pricing. *J. Econom. Theory* 13:341–360.

Secomandi N (2010a) On the pricing of natural gas pipeline capacity. *Manufacturing Service Oper. Management* 12:393–408.

Secomandi N (2010b) Optimal commodity trading with a capacitated storage asset. *Management Sci.* 56:449–467.

Secomandi N, Kekre S (2014) Optimal energy procurement in spot and forward markets. *Manufacturing Service Oper. Management* 16:270–282.

Secomandi N, Wang MX (2012) A computational approach to the real option management of network contracts for natural gas pipeline transport capacity. *Manufacturing Service Oper. Management* 14:441–454.

Sharpe WF (1964) Capital asset prices: A theory of market equilibrium under conditions of risk. *J. Finance* 19:425–442.

Singhal VR (1988) Inventories, risk, and the value of the firm. *J. Manufacturing Oper. Management* 1:4–43.

Smith JE, Nau RF (1995) Valuing risky projects: Option pricing theory and decision analysis. *Management Sci.* 41:795–816.

Trigeorgis L (1996) *Real Options: Managerial Flexibility and Strategy in Resource Allocation* (MIT Press, Cambridge, MA).

Van Mieghem JA (2003) Capacity management, investment and hedging: review and recent developments. *Manufacturing Service Oper. Management* 5:269–302.

Vasiček O (2002) Loan portfolio value. *Risk* 15(12):160–162.

WardsAuto Group (2014) U.S. car and truck sales 1931–2013. http://wardsauto.com/keydata/historical/UsaSa01summary.

Wu O, Wang D, Qin Z (2012) Seasonal energy storage operations with limited flexibility: The price-adjusted rolling intrinsic policy. *Manufacturing Service Oper. Management* 14:455–471.

Xu X, Birge JR (2004) Joint production and financing decisions: modeling and analysis. Technical report, The University of Chicago Booth School of Business, Chicago. http://ssrn.com/abstract=652562.

Xu X, Birge JR (2006) Equity valuation, production, and financial planning: A stochastic programming approach. *Naval Res. Logist.* 43:641–655.

Xu X, Birge JR (2008) Operational decisions, capital structure, and managerial compensation: A news vendor perspective. *Engrg. Econom.* 53:173–196.

Yahoo! Finance (2014) ˆGSPC historical prices. http://finance.yahoo.com/q?s=ˆGSPC.

Yang SA, Birge JR (2011) How inventory is (should be) financed: Trade credit in supply chains with demand uncertainty and costs of financial distress. Technical report, The University of Chicago Booth School of Business, Chicago. http://ssrn.com/abstract=1734682.