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The Design of Incentives for the Management of Supply and Demand

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by

Matthew J. Drake

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The Design of Incentives for the Management of Supply and Demand

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The only thing that will redeem mankind is cooperation.

Bertrand Russell

I am not trying to relieve others by putting a burden on you; but since you have plenty at this time, it is only fair that you should help those who are in need. Then, when you are in need and they have plenty, they will help you. In this way both are treated equally.

2 Corinthians 8: 13–14

For my parents, Stanley and Christine Drake, for their love and encouragement

and

For Sydney Davis Magidson (1915–1987) for laying the groundwork.
The conversation goes on.

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As I look at the calendar, I see that I am writing these acknowledgments almost four years to the day after I moved to Atlanta to attend Georgia Tech. I attended the graduate-student orientation along with fifty-one of my new colleagues a few days later, and I remember being told that fewer than half of us in that room would actually finish our dissertations and graduate with a Ph.D. from the School of Industrial and Systems Engineering. Boy, that's great! I definitely didn't need another reason to doubt myself at that point. I was a twenty-one-year-old, business-school graduate from a Pennsylvania university that no one here had ever heard of, and I was entering a program in which I couldn't even understand the notation on the chalkboard in my first class. How was I going to hold my own in a group of people who were much more prepared for this journey than I was?

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SUMMARY

This dissertation analyzes the economic incentives involved in three distinct supply chain and revenue management decision environments. The first study examines the adoption of the percent deviation contract in a supply chain to induce the buyer to share some of the demand risk in an environment in which the buyer would typically place her order when she has full knowledge of the customer demand levels. The subgame-perfect Nash Equilibrium decisions are characterized, and the percent deviation is shown to achieve full supply chain channel coordination in cases where a simpler contract cannot. Pareto-improving examples based on industry demand data are presented and discussed. The second section considers a revenue management problem for sports and entertainment organizations. Given that the organization starts the selling season by offering ticket packages exclusively, the optimal time during the selling season for the organization to begin selling individual-event tickets is derived. Extensions of the base model are developed to include multiple ticket packages and heterogeneous ticket packages. The model is illustrated using empirical data sets obtained from the Georgia Tech Athletic Department and the Atlanta Symphony Orchestra. The third section develops a model of vendor-controlled category management in which vendors are in charge of the stocking and assortment decisions for a given amount of shelf space at a vendor when the retailer retains control over the retail price. The subgame-perfect Nash Equilibrium strategies for two vendors and a single retailer are analyzed, and a revenue-sharing contract is shown to coordinate the channel when the vendors can produce multiple brands in a given product category and shelf space is sufficiently large or small.

CHAPTER I

INTRODUCTION

The study of the economic incentives faced by decision makers rests at the intersection of several traditional industrial engineering and management science disciplines. Models of incentive structures often incorporate optimization in the context of game theory because the decision maker's benefit or cost is not simply a function of her own actions but also depends on the actions of other entities in the decision environment. Game theory provides a framework to capture the interdependence between decisions and payoffs as well as the sequential nature of the decision making process. Optimization is also requisite in any incentive analysis; the decision maker must be able to determine the best course of action in order to maximize her benefit or minimize her cost.

Incentive problems appear in every discipline that is in any way affected by the actions of rational decision makers. This dissertation focuses on the specific economic incentives and decision environments that arise when organizations seek to improve the effectiveness of their supply and demand management practices. Many firms have been able to reap substantial benefits by improving their supply chain operations—such as procurement, inventory control, production, warehousing, and distribution—and by partnering with strategic suppliers and customers. In some scenarios, though, an organization may have a fixed quantity of perishable inventory that she wants to utilize in the most effective manner. Since the short-term supply is fixed, she can turn to actions and policies that affect the demand for these goods in order to maximize revenue. Models that establish these policies fall under the broad category of revenue management. Game theory and optimization models can provide guidance in designing the terms of these relationships in order to improve the performance of the entire supply chain, while ensuring that the gains are not realized at the expense of one of the channel members.

This dissertation is comprised of three main chapters, each of which develops a mathematical model for a specific decision environment. Each of these models isolates the tradeoffs that a decision maker must balance in order to obtain the maximum benefit while accounting for the strategic decisions of other stakeholders. The first main chapter studies the incentives generated by a new type of contract that originated in the truckload transportation industry. We analyze the structure and decisions of the percent deviation contract, a supply chain contract that encourages the sharing of information and demand risk between a single supplier and buyer. This contract induces a dynamic game of perfect information, and we characterize the subgame-perfect Nash Equilibria under various contract scenarios. We establish ways to set the contract parameters to coordinate the supply chain and show that the percent deviation contract is able to achieve channel coordination in some cases where the quantity flexibility contract fails. In order to aid the implementation of the percent deviation contract in practice, we develop ways to set the parameters to satisfy both parties' individual-rationality constraints. We conclude with numerical examples based on industry data that highlight the important results by illustrating the channel gains in each case over a traditional contracting arrangement.

The second major chapter considers a revenue management problem faced by sports teams and entertainment venues. Like airlines and hotels, sports teams and entertainment venues can benefit from revenue management efforts for their ticket sales. Demand for these tickets is such that some consumers are willing to purchase a package of tickets for multiple events in advance instead of buying single tickets as they are needed. Teams and entertainment venues usually offer bundles of tickets early in their selling horizon and put single-event tickets on sale at a later date. We model the seller's optimal *a priori* timing decision for offering individual tickets in order to maximize revenue when bundle and single-ticket customers each arrive according to a linear, Markovian death process. When the marginal benefit of selling tickets in the bundle is less than that obtained from selling them individually, we find that the seller should never practice mixed bundling. When the reverse is true, however, we show that it may be optimal to offer both bundles and individual tickets. We find that the timing decision is independent of the initial inventory level and establish comparative statics for the optimal timing decision as model parameters such as bundle size, marginal revenues, and customer arrival rates vary. We extend our results to find the optimal time for offering multiple bundle sizes or nonhomogeneous products.

The final major chapter presents a decentralized model of category management in a retail environment. Category management is a popular retail practice in which pricing, assortment, and stocking decisions are coordinated across products within a particular retail category such as laundry detergent or toothpaste. Recently some retailers have been delegating this assortment decision to their vendors, but it is not known how well this approach performs. We analyze an industry-motivated model of category management in which the retailer allows each vendor to make stocking and assortment decisions for a given amount of shelf space. We determine the optimal pricing policies for the retailer and the best stocking and assortment policies for each vendor in a two-stage decentralized system. We find that when the vendors' stocking incentives run contrary to the retailer's preferences, the retailer can be considerably worse off (i.e., experience profit losses as high as 40%) by delegating these responsibilities to the vendors. We compare the delegated system to a retailer-controlled channel and a centralized supply chain and demonstrate how a minimum-profit constraint can induce the vendors to achieve the total profit of a retailer-controlled channel but it may not induce centralized performance. To improve the performance of the decentralized, vendor-controlled channel, we show that a revenue-sharing arrangement with a discounted wholesale price is guaranteed to achieve full supply chain coordination in a vendor-controlled channel when the vendors produce multiple substitutable products and shelf space is limited or ample. Revenue sharing may not coordinate a vendor-controlled channel with medium levels of shelf space, but we characterize the difference in the decisions compared with the centralized channel's decisions, which is small for most parameter realizations. Through our analysis of revenue sharing, we establish that a revenue-sharing contract can coordinate stocking levels in a general, uncapacitated supply chain consisting of multiple vendors setting stocking levels for multiple substitutable products.

CHAPTER II

FACILITATING DEMAND RISK-SHARING WITH THE PERCENT DEVIATION CONTRACT

2.1 Introduction

The proliferation of computerized information systems in the 1990s facilitated the establishment of supply chain partnerships in which demand information is shared between firms. The upstream firms can use this information to reduce the traditional demand distortion due to the bullwhip effect (Lee et al., 1997). Some firms have also incorporated this information into contracts that induce their supply chain partners to share demand risk, thereby improving supply chain efficiency. Many researchers and practitioners (e.g. Lee (2004) and Finley and Srikanth (2005)) have advocated demand risk-sharing as a necessary condition for supply chain collaboration efforts to be successful in practice. In this chapter we analyze one such contracting mechanism, which we denote as the *percent deviation* contract.

One industry that stands to benefit from application of the percent deviation contract is truckload transportation. While these carriers generally have standing weekly orders for loads with their bigger customers, most shippers call dispatch requesting a pickup in a few hours. Current legislation limiting driver hours has brought the efficiency of operations into the forefront of truckload carriers' concerns. A survey by the American Trucking Association estimates that trucking companies can expect a 17 percent productivity drop as a result of the new restrictions (Strong, 2004). In July 2004 a U.S. federal appeals court overturned these new regulations, but it is likely that some of the restrictions on driver hours will remain (Machalaba, 2004).

Trucking companies have employed a variety of actions to account for the loss of efficiency. Many carriers have sharply increased their rates or accessorial charges to attain their profitability goals, but this increase has caused some shippers to switch to regional less-than-truckload (LTL) carriers (Schulz, 2004). Other carriers have begun charging their shippers for excess loading time, since now these delays are counting against the time that drivers can be on the road (Strong, 2004). The percent deviation contract offers carriers an alternative method of improving efficiency by allocating some demand risk to the shippers. A large truckload carrier originally proposed the idea for this contract but did not know how to set the parameters or whether or not the contract would be beneficial.

The percent deviation mechanism is applicable in traditional manufacturer-retailer channels as well, especially those in which one party currently bears the weight of demand risk. One obvious application would be an industry where the retailer places an order only when he receives an order from his customer, such as home construction, equipment integrators, window replacement, or door-to-door sales.

We analyze the strategic properties of the percent deviation contract in which the buyer gives an initial order estimate and the supplier pre-acquires inventory. Once the buyer's customer demand is realized, she places her final order, and the supplier fulfills all or a portion of the order, possibly by expediting. We characterize the subgame-perfect Nash Equilibria decisions when the supplier has a fixed expediting capacity and in the special case of infinite capacity. We discuss methods of channel coordination to optimize the performance of the entire system. Since the buyer assumes some demand risk under the percent deviation contract, her expected profit may be less than that under a traditional contracting structure; therefore, we develop two methods that the supplier can use to satisfy the buyer's individual-rationality constraint. Numerical examples utilizing demand distributions estimated from industry shipping data illustrate how the percent deviation contract can be used to create a Pareto-improving system for each party.

2.2 Literature Review

The breadth of supply chain contracting literature has grown significantly over the last two decades as researchers and practitioners have examined strategic relationships between supply chain partners. (See Tsay et al. (1998) for a review of traditional contracting mechanisms.) One stream of supply chain contracting literature has proposed and analyzed methods of coordinating decentralized decisions to attain the optimal supply chain profit. Examples of these studies include Weng (1997). Parlar and Weng (1997). Taylor (2002). and Huggins and Olsen (2003). We discuss below the most relevant contracting references, which model a system with multiple, sequential decisions.

Tsay (1999) analyzes a quantity flexibility contract in which the retailer commits to purchasing no less than a certain percentage of the initial forecast while the supplier agrees to fulfill up to a certain percentage above the forecast. He also evaluates the sharing of demand risk that produces the coordinated channel. Tsay and Lovejoy (1999) extend these results to a rolling horizon decision environment. In contrast to quantity flexibility, the percent deviation contract places no limits on the buyer's final order, although it adds complexity to the decision environment by including additional contract parameters. We show in Section 2.4.4 that this added complexity can be justified because the percent deviation contract succeeds in coordinating the supply chain in several cases where the quantity flexibility contract is known to be unable to coordinate the channel.

Donohue (2000) and Cachon (2004) analyze contracts with two-tier pricing structure that induce early commitment from buyers. In both of these contracts the buyer is bound to her order in both periods, whereas in our contract the first order is only an estimate of demand and can be freely adjusted once demand is known. These two papers only consider the full compliance contract regime where the supplier must fulfill the entire order; whereas, we model the supplier's compliance decision explicitly.

Several contracts employ an options framework where the buyer makes a firm order commitment and purchases options for additional goods to be exercised if demand is high. Cachon and Lariviere (2001) consider a single period model with options and forecast sharing. Since the buyer has an incentive to provide a biased forecast. they develop conditions that facilitate the credible sharing of forecasts under both full and voluntary compliance. They also analyze information asymmetry in which the manufacturer has some private information about demand. They conclude by showing that this options framework is a general model that encompasses other contract structures such as returns and additional sources of supply. However, in our case. we have an additional parameter (the deviation range).

no firm commitment, and no upper bound on the final order amount, so the contract we study cannot be reduced to their model. Barnes-Schuster et al. (2002) extend the options framework using a two-period model with correlated demand between periods.

A recent series of studies (see, for example, Jin and Wu (2001) and Erkoc and Wu (2005)) have analyzed reservation fee supply contracts in which the buyer pays a (usually) deductible fee to reserve capacity along with an exercise fee for the final order quantity. The manufacturer builds capacity based on the reservations made, but they can also build excess capacity to offer at a higher spot rate once demand is realized. The aforementioned studies only consider *linear* reservation fee contracts—where each unit ordered is charged the same prices. The percent deviation contract is a special case of a *piecewise-linear* reservation fee contract in which the reservation and exercise prices differ for various portions of the order.

In addition to contracting, several papers (e.g. Lee et al. (2000), Cachon and Fisher (2000), and Balakrishnan et al. (2004)) have examined various ways of reducing the bullwhip effect through information sharing in decentralized supply chains. Kulp et al. (2004) study the benefits the manufacturer gains under different degrees of information sharing and collaboration. They find that most of the manufacturers' benefit from information integration comes from collaborative activities such as vendor-managed inventory and collaborative forecasting instead of simply sharing information. On the contrary, our results suggest that the information sharing induced by the percent deviation contract enable the supplier to attain a higher expected profit through increased efficiency and the sharing of demand risk with his customers.

Another stream of literature analyzes the effect of supply chain information asymmetry and forecast updating. Corbett et al. (2004) compare various contract structures under full and asymmetric information. Fisher and Raman (1996) and Iyer and Bergen (1997) evaluate the benefits of Quick Response manufacturing. Ferguson et al. (2005) develop a structure for analyzing supply chains under information updating where the final demand is the sum of two independent random variables; we introduce a similar form of information updating into an infinite capacity scenario in Section 2.4.3.

Our contribution includes analysis of a risk-sharing contract where decisions made by the buyer and supplier explicitly depend on each other and are solvable in the framework of a dynamic, extensive form game. This dynamic game necessarily results in a more complex contract, but we also show that this contract can be strictly Pareto-improving for both parties. Our contract is most similar to the quantity flexibility contract, but ours does not enforce limits on the buyer's final behavior, so we show that this contract can coordinate the supply chain in some cases where quantity flexibility cannot. Our analysis focuses on the buyer's assumption of some demand risk unlike traditional relationships in this decision environment where she places an order when demand is known with certainty and experiences no loss when the realized demand is especially high or low. Because of this increased demand risk and because the purchase is often of a commodity good, we incorporate individual-rationality constraints to ensure buyer participation.

The next section develops the model for the general case where the supplier has an expediting capacity constraint as well as the special case of infinite capacity. Section 2.4 develops conditions on the contract parameters that satisfy each party's participation constraints, details ways to coordinate the channel in each decentralized scenario, and compares the percent deviation contract with the well-known quantity flexibility contract. Section 2.5 provides the results of several numerical examples under various contract conditions based on demand distributions estimated from a major manufacturer's weekly shipping activity. Conclusions and suggestions of future research are given in Section 2.6.

2.3 Models and Scenarios

The percent deviation contract accommodates the following sequence of decisions. The buyer provides an initial estimate of its final-order demand that will be placed at a later date. The seller can then use this information to acquire goods in advance (e.g., a truckload carrier can preposition trucks or coordinate backhauls to optimize his transportation network) at a low cost in anticipation of this demand. When the buyer's demand is known with certainty, she places her actual order with the supplier. Depending on the contract parameters, the seller can choose to satisfy additional demand by expediting or subcontracting at a high cost or can choose to fulfill only the demand equal to the number of previously-acquired goods.

The percent deviation penalty is the mechanism that punishes the buyer for unrealistic estimates. If the buyer's final order is within a certain percentage above or below her initial estimate, no penalty is charged. If the order exceeds the limits, the supplier charges a penalty on all goods ordered outside of the tolerable range.

2.3.1 Notation and Assumptions

We employ notation adapted from Donohue (2000). The buyer receives r dollars in revenue for each unit, and she pays a wholesale price, w, to the supplier. We assume that the buyer earns a positive gross margin from these transactions (i.e., $r > w$). Consumer demand for a period is given by the random variable X, which has a continuous, differentiable probability distribution function, $f(x)$. If the buyer cannot satisfy her customers' demand (due to lack of product availability), she incurs a customer penalty of 3 per unit. This 3 could also be viewed as the higher cost from using an alternative supplier not under long-term contract.

The seller faces a cost of c_1 dollars to acquire goods in anticipation of demand and must pay c_2 dollars to satisfy demand after the firm order has been placed. We assume that $c_2 > c_1$, so the c_2 can be thought of as an expediting or subcontracting cost. If the supplier has excess inventory at the end of the period, he receives a unit salvage value of v. It is natural to assume that $w > v$ and $c_1 > v$, which ensure that the supplier does not receive too much of a benefit from selling goods for salvage. Since the seller may choose not to satisfy the buyer's entire order, he must pay the buyer α for each unit ordered but not delivered. We assume that $\alpha < 3$, which signifies that lost customers are more costly for the buyer than for the supplier.

The per-unit penalty that the buyer must pay the supplier for orders outside of the allowable deviation range is denoted by p, while $d \in [0, 1]$ is the percentage that defines the range. We assume that the buyer only pays the deviation penalty on units ordered and ultimately provided by the supplier. The buyer's initial forecast of her order is given by q_1, and the actual order is q_2. The number of units the supplier acquires in advance of demand is t_1, and the additional goods expedited or subcontracted are denoted by t_2. The supplier has a maximum expediting capacity of M units. (In Section 2.3.2.3 we consider a special case where the supplier has unlimited expediting capacity.)

This particular way of modeling the supplier's capacity bears further consideration. It is important to note that the capacity for the supplier's pre-acquisition decision is infinite. By setting the t_1 value, the supplier is *de facto* determining the capacity of the system as a whole, which is equal to $t_1 + M$. This structure is appropriate for buyer-supplier transactions in which the supplier has a lot of capacity in his system, but he must make the allocation decisions over many customers before production occurs. Therefore, if the supplier knows that a particular buyer will require many units in a given period, he can plan his production to satisfy the large order; closer to the purchase date, however, he can only provide a limited amount of excess capacity if necessary because the rest of his system is dedicated to fulfilling orders from other customers.

We make the following assumptions that improve tractability but are not likely to impede the application of the results. The first assumption is that all costs are linear per unit of demand for a single product line because we are interested in the structure of the incentives. Another assumption is the existence of complete, symmetric cost, capacity, and demand information between the two parties. (We relax this assumption in Section 2.4.3 by allowing the buyer to have a private demand forecast; the supplier constructs a conditional distribution of demand based on the buyer's initial order estimate.) When the buyer places her final order, she knows the exact demand as is usual in truckload transportation and the other relevant channels discussed in Section 2.1.

If the actual demand amount exceeds the upper limit of the deviation range, the cost and penalty parameters determine whether or not the buyer's order equals the full demand. In order for the buyer to order above the deviation threshold, the net cash flow from satisfying the demand must exceed the penalty that she must pay her customer for not satisfying demand. If the inequality

$$r - w - p > -\beta \tag{1}$$

holds, then $q_2 = X$, or the actual customer demand. If this inequality is not satisfied (for instance, if the penalty for ordering outside of the deviation range is too high), $q_2 = min\{X, (1+d)q_1\}$. The additional assumption $w > p$ assures that if the actual demand is below the lower limit of the deviation range, $(1-d)q_1$, the buyer orders the actual demand amount.

2.3.2 General Model with Finite Expediting Capacity

We begin our analysis with the decentralized structure in which each party makes decisions to optimize his individual expected profit. Even though the supplier has an expediting capacity of M units, the cost of expediting these units, c_2, might be too high for him to choose to do so. In order for the supplier to use any of this expediting capacity, the cash flow from expediting must be higher than the cost of failing to expedite. These flows are dependent on whether or not the supplier will receive the deviation penalty on some or all of these units. The two buyer scenarios discussed above, which are dependent on whether or not the the buyer is willing to place orders above the upper limit of the deviation range, generate different parameter conditions dictating the supplier's expediting decision; therefore, we must consider each of these buyer scenarios independently.

2.3.2.1 Buyer Orders Entire Demand

In the following two instances, the supplier's expediting decision can be determined *a priori*, without knowledge of how many units for which the buyer will pay the deviation penalty. If $w - c_2 > -\alpha$, then the supplier finds it beneficial to expedite whether or not he receives the deviation penalty on any units; consequently, $t_2^* = (\min\{q_2 - t_1, M\})^+$. We will denote this case as I.A. Similarly, if $w - c_2 + p < -\alpha$, the supplier would not choose to expedite any units even if he were receiving the deviation penalty on all of the units; and thus, $t_2^* = 0$. This will be scenario I.B.

We will use backward induction to solve for the subgame-perfect Nash Equilibria in each scenario. We now formulate the expected profit functions for the buyer and supplier in case I.A., where $q_2^* = X$ and $t_2^* = (\min\{q_2^* - t_1, 0\})^+$. The supplier chooses t_1 to maximize his expected profit function:

$$\begin{aligned}\Pi^S_{I.A.} \;=\;& w\left[\int_0^{t_1+M} x f(x)dx + (t_1+M)\left(1-F(t_1+M)\right)\right] + v\int_0^{t_1}(t_1-x)f(x)dx\\ & p\int_0^{\min\{t_1+M,(1-d)q_1\}}\left(\min\{t_1+M,(1-d)q_1\}-x\right)f(x)dx +\end{aligned}$$