Strategic Customer Behavior and the Benefit of Decentralization

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Abstract

In the operations management literature, decentralization is often associated with the double marginalization problem. However, in this chapter, we review several existing papers that demonstrate how decentralization can be beneficial to supply chain performance. A key premise in this literature is that consumers are *strategic*: They rationally anticipate and respond to future market conditions. We consider two broad classes of products, durable goods and perishable goods. In both cases, when facing strategic consumers, firms are typically better off if they can commit to future actions. When operating in a decentralized supply chain, contractual mechanisms can help firms achieve commitment power and increase profits. In this way, decentralized systems can outperform a centralized organization.

Keywords: strategic customer behavior, supply chain, decentralization, durable goods, newsvendor

1 Introduction

Conventional wisdom in the operations management literature suggests that decentralized supply chains are inefficient. Under decentralization, individual firms in the supply chain (such as manufacturers, distributors, wholesalers, and retailers) make operational decisions with different and possibly conflicting objectives. In particular, double marginalization is a well-known problem that arises in decentralized supply chains. Much work has been done to rectify the double marginalization problem and to "coordinate" the supply chain. One major goal of contemporary supply chain research has been to design economic mechanisms in order to achieve the benchmark performance of a centralized system. When all decision rights are concentrated in the hands of a single party, there is no incentive misalignment, and economic inefficiencies can be reduced or even eliminated. It is thus no wonder that centralized systems have served as gold standard for many research studies, while decentralization has been associated with a myriad of coordination problems. In this chapter, we wish to present a different perspective. We will show, through some specific settings, that decentralization can sometimes enhance supply chain performance.

One fundamental premise in this chapter is that consumers are strategic. In particular, we will consider dynamic settings (in their simplest form, two-period models) where consumers are capable of rationally anticipating future market conditions, such as prices. Interestingly, modeling such strategic consumer behavior often adds a novel twist to existing operations models. These new models generate new insights – specifically, in this chapter, we will see that decentralization (such as selling through an intermediary) can be beneficial when facing strategic consumers.

We will focus on two broad classes of products: durable goods and perishable goods. Durable goods refer to products whose consumption value persist over long time horizons. Examples include automobiles, furniture, and TV sets. In some cases, there are well-established secondary markets with used products that compete with the supply chain's new products. Such cannibalization is particularly severe when consumers are strategic and can optimally choose whether to purchase a new product or to wait for a used product from the secondary market. We shall see in this chapter that for durable goods, decentralization can be a useful supply chain strategy.

The second class of products that we will consider is perishable goods. They refer to items that have a short product life cycle and have little to no value afterward. Examples include fashion items (which become out-of-date quickly) as well as hi-tech products (which become obsolete quickly). In these cases, retailers and manufacturers have an incentive to offer deep discounts toward the end of the selling season in order to sell off excess inventory. While perfectly legitimate from an operational standpoint, price markdowns inevitably train consumers to wait for sales and have a negative impact on demand. When facing such strategic consumer behavior, decentralization again serves a useful purpose that we shall explore in this chapter.

In today's markets, durable goods and perishable goods are everywhere. Further, consumers are becoming increasingly sophisticated as they enjoy access to better information and decision aids over the internet. In such settings, strategic decentralization will be a useful concept for operations management.

2 Durable goods

The essence of most durable goods models can be captured using a simple two-period model. The analysis in this section is based on the papers by Bulow (1982), Desai, Koenigsberg, Purohit (2004) and Arya and Mittendorf (2006), which also contain some generalizations and more details. Here we make a number of simplifying assumptions to make the key insights more transparent. We begin with a centralized system before moving on to consider a decentralized system consisting of a manufacturer and a retailer.

2.1 Centralized system

2.1.1 Benchmark model

Consider a centralized seller who operates over two time periods. The seller sells a durable good over both periods. The durable good lasts for both periods and provides consumption value in both periods. In each period $t = 1, 2$, the consumption value (for that period) is given by the following linear demand curve:

$$V_t = \alpha - \beta Q_t, \tag{1}$$

where Q_t is the total available quantity in that period. There is a perfect secondary market. We assume that old products are indistinguishable from and thus compete perfectly with new products. We use q_t to denote the number of new units produced in period t, so the cumulative available quantities Q_t satisfies $Q_1 = q_1$ and $Q_2 = q_1 + q_2$. In other words, the consumer who buys the product in period 2 earns utility V_2 and is thus willing to pay $p_2 = V_2$ as given by

$$p_2 = \alpha - \beta(q_1 + q_2), \tag{2}$$

while the consumer who buys in period 1 earns total utility $V_1 + V_2$ and is thus willing to pay $p_1 = V_1 + V_2$ as given by

$$p_1 = [\alpha - \beta q_1] + [\alpha - \beta(q_1 + q_2)]. \tag{3}$$

Then, normalizing production costs to zero, the seller's profit function can be written as

$$\begin{aligned} \Pi(q_1, q_2) &= p_1 q_1 + p_2 q_2 && (4)\\ &= \{[\alpha - \beta q_1] + [\alpha - \beta(q_1 + q_2)]\}q_1 + [\alpha - \beta(q_1 + q_2)]q_2, && (5) \end{aligned}$$

which attains the maximum at

$$q_1^* = \frac{\alpha}{2\beta}, \qquad q_2^* = 0. \tag{6}$$

In this benchmark scenario, the centralized seller's optimal profit is

$$\Pi^* = \frac{\alpha^2}{2\beta}. \tag{7}$$

2.1.2 Strategic consumers and the lack of commitment

Unfortunately, in the presence of so-called strategic consumers, the benchmark profit level above can not be attained. This is because consumers are able to look ahead and anticipate all occurrences on the equilibrium path. We first explain why the benchmark solution above is not subgame perfect, and then proceed to derive the subgame perfect outcome.

In the benchmark scenario above, the seller maximizes total profit $\Pi(q_1, q_2)$ by setting $q_1^* = \frac{\alpha}{2\beta}$ and $q_2^* = 0$. However, these actions are not subgame perfect. At the end of period 1, if q_1^* units have indeed been sold, then the seller's period 2 profit function becomes

$$\Pi_2(q_2) = [\alpha - \beta(q_1^* + q_2)]q_2, \tag{8}$$

which is maximized at $q_2 = \frac{\alpha}{2\beta} - \frac{q_1^*}{2} = \frac{\alpha}{4\beta} > 0$. In other words, when period 2 arrives, the seller has the incentive to sell additional units, which decreases the consumption value in period 2. Recognizing such behavior, consumers' willingness to pay in period 1 will be decreased. The benchmark outcome is thus not attainable.

However, if the seller were able to commit to period 2 production quantity q_2 in advance (i.e., in period 1), then the analysis in the previous subsection holds and the benchmark profit is attainable. For this reason, we may also refer to the benchmark scenario as the "commitment scenario".

Next, we proceed to analyze the subgame perfect equilibrium when the seller is unable to commit and consumers are strategic. We use backward induction. Suppose that q_1 units were sold in period 1. Then, following the logic leading to the profit function in (8), we know that the seller's optimal period 2 response is to sell

$$q_2(q_1) = \frac{\alpha}{2\beta} - \frac{q_1}{2}. \tag{9}$$

Along the equilibrium path, q_1 and q_2 can not be chosen freely; rather, choosing q_1 necessarily leads to $q_2(q_1)$ in period 2. Therefore, the seller's profit function (5) can be written in terms of q_1 only. After some calculations, we obtain the subgame perfect equilibrium

$$q_1^* = \frac{2\alpha}{5\beta}, \qquad q_2^* = \frac{3\alpha}{10\beta}. \tag{10}$$

In this case, the seller's total equilibrium profit is

$$\Pi^* = \frac{9\alpha^2}{20\beta}. \tag{11}$$

Notice that this equilibrium profit is lower than the benchmark case where either the seller can commit or consumers are not strategic. This is precisely the durability problem first discussed by Coase (1972), who observed that durable goods monopolies, through competition with their future selves, lose market power and may even be forced to price at marginal cost in some extreme cases.

2.2 Decentralized system

2.2.1 Wholesale price contract

Next, we turn attention to a decentralized system consisting of a manufacturer and a retailer. As in the previous case, we assume that consumers are strategic and firms are unable to commit to future actions. Our goal is to set up the analytical framework to study equilibrium actions of all players over the two time periods. Here, we first focus on the wholesale price contract. That is, the manufacturer sells to the retailer at a per unit wholesale price, and the retailer then sells to consumers. As before, the manufacturer's production cost is normalized to zero.

To use the backward induction approach, we first suppose that q_1 units were produced in period 1 and the manufacturer sets the period 2 wholesale price to be w_2. Given these inputs, the retailer chooses quantity q_2 to maximize his period 2 profits

$$\Pi_2(q_2) = [\alpha - \beta(q_1 + q_2)]q_2 - w_2 q_2. \tag{12}$$

The optimal choice of q_2 is

$$q_2(q_1, w_2) = \frac{\alpha}{2\beta} - \frac{q_1}{2} - \frac{w_2}{2\beta}. \tag{13}$$

Anticipating this response, the manufacturer chooses the period 2 wholesale price w_2 to maximize his own period 2 profits $w_2 \cdot q_2(q_1, w_2)$. The manufacturer's optimal wholesale price w_2 and the retailer's corresponding production quantity q_2 in period 2, given q_1, turn out to be

$$w_2(q_1) = \frac{\alpha}{2} - \frac{\beta q_1}{2}, \qquad q_2(q_1) = \frac{\alpha}{4\beta} - \frac{q_1}{4}. \tag{14}$$

Next, we consider period 1. Suppose the manufacturer sets the wholesale price w_1. Then, the retailer's total profit function, similar to (5), is

$$\Pi(q_1) = \{[\alpha - \beta q_1] + [\alpha - \beta(q_1 + q_2)]\}q_1 + [\alpha - \beta(q_1 + q_2)]q_2 - w_1 q_1 - w_2 q_2, \tag{15}$$

where q_2 and w_2 depend on q_1 as given above. The retailer's optimal period 1 response is

$$q_1(w_1) = \frac{13\alpha}{27\beta} - \frac{8w_1}{27\beta}. \tag{16}$$

Anticipating this response, the manufacturer sets the optimal w_1 to maximize his total profits $w_1 q_1 + w_2 q_2$. It can be shown that the equilibrium wholesale prices and production quantities are

$$q_1^* = \frac{11\alpha}{52\beta}, \qquad q_2^* = \frac{41\alpha}{208\beta}, \tag{17}$$

$$w_1^* = \frac{379\alpha}{416}, \qquad w_2^* = \frac{41\alpha}{104}. \tag{18}$$

The corresponding total supply chain profit is

$$\Pi^* = \frac{17,671\alpha^2}{43,264\beta} \approx 0.408\frac{\alpha^2}{\beta}. \tag{19}$$

Notice that the total system profit here is lower compared to that of the centralized case, even when the seller is unable to commit. In other words, the double marginalization problem is in effect here. For the case of durable goods, under a simple wholesale price contract, decentralization involves economic inefficiencies.

2.2.2 Two part tariffs

It is well-known that two-part tariffs can rectify the double marginalization problem. Now, we consider the same decentralized system as above, but we allow the manufacturer to charge the retailer a two-part tariff. In other words, apart from a fixed fee, the manufacturer also charges the retailer a fixed per unit wholesale price.

We first consider period 2. Suppose that q_1 units were already sold in period 1. Let us denote the wholesale price by w_2 and the fixed fee by F_2. Since the fixed fee does not influence the retailer's actions, the retailer's optimal choice of $q_2 = \frac{\alpha}{2\beta} - \frac{q_1}{2} - \frac{w_2}{2\beta}$ remains unchanged, as given in (13). Now, the manufacturer can set the fixed fee high enough to extract the entire channel profit. In other words, the manufacturer would like to set w_2 to maximize

$$\Pi_2(w_2) = [\alpha - \beta(q_1 + q_2)]q_2. \tag{20}$$

The total channel profits for period 2 is maximized when the retailer is induced to choose $q_2 = \frac{\alpha}{2\beta} - \frac{q_1}{2}$. This corresponds to $w_2 = 0$, which is thus the manufacturer's optimal choice.

Next, we consider period 1. Suppose the manufacturer offers a wholesale price w_1 and fixed fee F_1 to the retailer. Since the retailer anticipates zero period 2 surplus, he will choose q_1 to maximize his period 1 profit given by

$$\Pi_1(q_1) = \{[\alpha - \beta q_1] + [\alpha - \beta(q_1 + q_2)]\}q_1 - w_1 q_1. \tag{21}$$

The optimal choice of q_1 is $q_1(w_1) = \frac{\alpha}{2\beta} - \frac{w_1}{3\beta}$. Recognizing this response and using the fixed fee to extract the total supply chain profit in both periods, the manufacturer will then choose the wholesale price w_1 to maximize

$$\Pi(w_1) = \{[\alpha - \beta q_1] + [\alpha - \beta(q_1 + q_2)]\}q_1 + [\alpha - \beta(q_1 + q_2)]q_2. \tag{22}$$

Since $q_2 = \frac{\alpha}{2\beta} - \frac{q_1}{2}$, this becomes

$$\Pi(w_1) = \frac{3}{2}(\alpha - \beta q_1)q_1 + \frac{1}{4\beta}(\alpha - \beta q_1)^2, \tag{23}$$

where $q_1(w_1) = \frac{\alpha}{2\beta} - \frac{w_1}{3\beta}$. Consistent with (10), this is maximized at $q_1 = \frac{2\alpha}{5\beta}$, which corresponds to an optimal period 1 wholesale price of $w_1 = \frac{3\alpha}{10}$. In summary, with two-part tariffs, the equilibrium wholesale prices and quantities are

$$q_1^* = \frac{2\alpha}{5\beta}, \qquad q_2^* = \frac{3\alpha}{10\beta}, \tag{24}$$

$$w_1^* = \frac{3\alpha}{10}, \qquad w_2^* = 0. \tag{25}$$

The total supply chain profit is given by

$$\Pi^* = \frac{9\alpha^2}{20\beta}.$$

This analysis shows that with two-part tariffs, a decentralized system can attain the performance of a centralized system, as in (11). In familiar terminology, the system is coordinated. However, since the equilibrium profit is still below the benchmark profit (7), we conclude that two part tariffs do not solve durability problem (Coase problem). In other words, when firms face strategic consumers and are unable to commit to future courses of action, two-part tariffs are inadequate. More needs to be done to solve the durability problem and achieve the benchmark profit.

2.2.3 Two part tariffs: long term contracts

We now show that the key to solving both the coordination problem and the durability problem is to establish long-term contracts. Specifically, we consider a long-term two-part tariff between the manufacturer and the retailer. That is, the manufacturer specifies the wholesale prices w_1, w_2 for both periods as well as a fixed fee F at the start of the game.

Under the long term contract, the retailer's optimal period 2 choices remain unchanged since he still wishes to maximize period 2 profit then. This optimal choice, as given above, is $q_2 = \frac{\alpha}{2\beta} - \frac{q_1}{2} - \frac{w_2}{2\beta}$. In period 1, however, the retailer wishes to maximize his total profit given by

$$\Pi(q_1) = \{[\alpha - \beta q_1] + [\alpha - \beta(q_1 + q_2)]\}q_1 + [\alpha - \beta(q_1 + q_2)]q_2 - w_1 q_1 - w_2 q_2, \tag{26}$$

where q_2 depends on q_1 as above. With some manipulation, the retailer's optimal choice is $q_1 = \frac{2\alpha}{5\beta} - \frac{2w_1}{5\beta} + \frac{2w_2}{5\beta}$.

Now, we consider the manufacturer's optimal choice of wholesale prices. Since he can extract the entire profit share using the fixed fee, the manufacturer will choose w_1, w_2 such that the induced actions (by the retailer) will maximize total supply chain profit given by

$$\Pi(q_1, q_2) = \{[\alpha - \beta q_1] + [\alpha - \beta(q_1 + q_2)]\}q_1 + [\alpha - \beta(q_1 + q_2)]q_2. \tag{27}$$

Similar to the calculations in the benchmark case, the manufacturer wishes the retailer to choose $q_1 = \frac{\alpha}{2\beta}$ and $q_2 = 0$, as in (6). Observe that these actions can be induced using the wholesale prices $w_1 = \frac{\alpha}{4}, w_2 = \frac{\alpha}{2}$. In summary, with a long term contract of two-part tariffs, the equilibrium wholesale prices and quantities are

$$q_1^* = \frac{\alpha}{2\beta}, \qquad q_2^* = 0, \tag{28}$$

$$w_1^* = \frac{\alpha}{4}, \qquad w_2^* = \frac{\alpha}{2}. \tag{29}$$

The total supply chain profit is then

$$\Pi^* = \frac{\alpha^2}{2\beta}.$$

Since this matches the optimal centralized benchmark profit (7), we conclude that a long term two-part tariff can solve both the coordination problem and the durability problem.

This analysis highlights the strategic role of decentralization. A centralized seller that is unable to commit to future actions will be plagued by the Coase problem, as shown in Section 2.1.2. The highest possible benchmark profit can not be attained. On the other hand, the situation is different under decentralization. Although the introduction of an intermediary may generate double marginalization problems as in Section 2.2.1, standard contractual mechanisms (such as a two-part tariff) can resolve coordination issues easily, as shown in Section 2.2.2. Further, when long term contracts are feasible, a decentralized system can even attain the benchmark profit, as shown in Section 2.2.3. This is an important message to supply chain managers. While firms often find it difficult to commit to consumers in the market, it may be feasible for them to commit to other firms within the supply chain (through appropriate contractual mechanisms). Bringing into the supply chain an intermediary to whom one can commit to is thus a useful strategy to adopt. Such strategic decentralization effectively solves the Coase problem that is central to many durable goods markets.

2.3 Longer time horizons

Although we have so far focussed on two-period models, similar reasoning also applies to longer time horizons. With three or even more time periods, the same backward induction approach can be used to derive the subgame perfect equilibrium. One can then obtain the equilibrium quantities and prices.

For a three-period model, Arya and Mittendorf (2006) analyze the centralized system as well as a decentralized system operating under the simple wholesale price contract. In other words, they provide analysis analogous to Sections 2.1.2 and 2.2.1 above. They obtain the following results. Details are omitted.

For the centralized seller who is unable to commit to future actions, the equilibrium production quantities are

$$q_1^* = \frac{10\alpha}{29\beta}, \qquad q_2^* = \frac{38\alpha}{145\beta}, \qquad q_3^* = \frac{57\alpha}{290\beta}, \tag{30}$$

and total equilibrium profit level is

$$\Pi^* = \frac{361\alpha^2}{580\beta} \approx 0.622\frac{\alpha^2}{\beta}. \tag{31}$$

For the decentralized system operating under a wholesale price contract, the equilibrium wholesale prices and quantities are

$$q_1^* \approx 0.19\frac{\alpha}{\beta}, \qquad q_2^* \approx 0.17\frac{\alpha}{\beta}, \qquad q_3^* \approx 0.16\frac{\alpha}{\beta}, \tag{32}$$

$$w_1^* \approx 1.27\alpha, \qquad w_2^* \approx 0.74\alpha, \qquad w_3^* \approx 0.32\alpha. \tag{33}$$

The total system profit, in equilibrium, is

$$\Pi^* \approx 0.631\frac{\alpha^2}{\beta}. \tag{34}$$

The key observation here is that, with a longer time horizon, a decentralized channel may perform better than a centralized channel. Observe that the three-period decentralized profit (34) exceeds the three-period centralized profit (31). Recall that the decentralized system is operating under the simple per unit wholesale price contract. This suggests that even in the absence of complex contractual arrangements (such as long term contracts), decentralization can be a useful strategy in its own right. With longer time horizons, simply introducing an intermediary into the supply chain can improve system performance.

Before concluding this section, we emphasize two points concerning time horizons.

1. We first clarify the interpretation of longer time horizons. Moving away from a two-period model, what does three time periods mean? One interpretation is that, longer time horizons implies higher durability. With two periods, the durable good lasts for two periods. With three periods, the durable good lasts for three periods. In fact, in the classic model of Coase (1972), there are infinitely many periods, so the good is infinitely durable. In such cases, the durability problem is at its extreme severity and the monopoly seller makes zero profit. Therefore, longer time horizons are more applicable to goods that have higher durability. Next, a second interpretation is that time periods refer to time points during which the seller can change prices. With two time periods, the seller can change prices once during the season; with three time periods, the seller can change prices twice. In our opinion, with improving technology and increasing industry clockspeed, longer time horizons will become more and more relevant.

2. An implicit assumption in many durable goods models is that all consumers are present at the start of the time horizon. In the models discussed above, whether we have two, three, or even more time periods, the consumer pool is exogenously fixed at the outset. This is not an innocuous assumption. In many practical settings, new consumers may arrive to the market within the selling season, so longer time horizons may imply higher customer traffic. An influx of strategic consumers during the selling season creates analytical difficulties that require different solution approaches. Such problems have recently been addressed in the revenue management literature; see Shen and Su (2007) for a review. In this chapter, we focus on a static consumer pool and short time horizons (e.g., two or three periods), and discuss the benefits of decentralization in such settings. More generally, with longer time horizons and dynamic consumer arrivals, the effect of decentralization on supply chain performance remains an open question.

3 Perishable Goods

We proceed in this section to study the second class of products: perishable goods. In contrast to durable goods, perishable goods exhibit characteristics on the other extreme: the life-cycle is relatively short either due to the perishability of the goods in nature (e.g., food and newspaper) or due to frequent new product introductions (e.g., fashion and high tech goods). Since most perishable goods possess more or less innovative elements and they are valuable only for a single, short selling season, market demand for perishable goods is usually highly uncertain. For these reasons, sellers of perishable goods face a remarkable challenge of matching their supply to market demand. Although many sellers have adopted various operational strategies (e.g., collaborative forecasting and quick response), completely eliminating the mismatch between supply and demand is not feasible. Therefore, perishable goods sellers actively seek remedies to minimize the consequences of demand-supply imbalances. A commonly used strategy is price markdown in which a seller clears excess inventory and garner additional revenue by dramatically dropping the product price at the end of a selling season. According to recent media reports, such a practice has been increasingly used both in terms of broadness and depth (see Merrick, 2001 and Byrnes and Zellner, 2004). However, this strategy trains consumers to wait for the after-season sales, which may affect the seller's profit in the regular season. How should a seller deal with this kind of strategic consumer behavior? Does strategic decentralization help as in the case of durable goods? In this section we present a modeling framework to investigate the role of strategic consumer behavior in supply chain management for perishable goods.

3.1 Model Setting

Consider a seller who sells a product in a single selling season. Demand for this product is uncertain and is denoted by a random variable X. One may interpret X as the total mass of infinitesimal consumers in the market. Let F and f denote the distribution and density functions of X. For technical reasons, we assume that f is continuous, $f(0) > 0$, and F has an increasing failure rate (i.e., $f(x)/(1 - F(x))$ is increasing in x). Most of the commonly used distributions satisfy this assumption. Each unit of the product costs c and has a salvage value of s at the end of the selling season. All consumers value the product at v, which is equivalent to the maximal willingness to pay. To avoid trivial solutions, assume $s < c < v$.

The above setup is exactly the classic newsvendor problem. Given a price p and a stocking quantity Q, we know the newsvendor profit is given by

$$\Pi(Q, p) = (p - s)E(X \wedge Q) - (c - s)Q, \tag{35}$$

where $\wedge$ represents the minimum operation. The newsvendor model has been widely studied in the operations management literature and regarded as a building-block for supply chain management research. The twist we add here is strategic consumer behavior. To explain, each consumer may choose to either buy the product during the regular selling season (i.e., pay a full price) or wait for sales at the end of the season (i.e., pay a lower price). However, there is a risk associated with waiting because the product may not be available anymore. Basically, each consumer needs to weigh the two options and choose the timing of purchase accordingly. In particular, the consumers can observe the price announced by the seller, but not the stocking quantity.

The seller's decisions include stocking quantity Q and price p for the selling season, while the consumers choose to buy immediately or wait. From the seller's standpoint, this setting resembles the newsvendor model with pricing (see Petruzzi and Dada, 1999). Further, to study the interaction between the seller and the consumers, we need to examine the beliefs formed by the two parties: First, the seller has to form expectations about the consumers' reservation prices in the regular season (i.e., the maximum price at which the consumers are willing to buy immediately). Second, since the consumers cannot observe the actual stocking quantity at the seller, they need to form expectations about the likelihood of product availability at the end of the season. To maintain tractability and make explicit the deliberations of the two parties, we utilize the Rational Expectations (RE) equilibrium concept to characterize the outcome of the game between the seller and the consumers. The rational expectations hypothesis, first proposed by Muth (1961), states that economic outcomes do not differ systematically from what people expect them to be.

This model is identical to the RE game studied in Su and Zhang (2008). For consistency, we follow their notations as well. We briefly outline the equilibrium analysis and highlight the major insights in this chapter. More details can be found in Su and Zhang, where they also check the robustness of results in several extensions of the basic model.

For ease of exposition, we adopt the following sequence of events. First, the seller forms a belief ξ_r of the consumers' reservation price, and then choose the optimal price p and quantity Q to maximize the newsvendor profit $\Pi(Q, p)$. Then, the consumers privately form a belief ξ_{prob} over the availability probability in the salvage market, and determine a reservation price r for immediate purchase. Next, the random demand X is realized. Then sales occur at the full price p in the regular season, provided that p does not exceed r. Finally, unsold units are salvaged at price s after the selling season ends. Two additional assumptions are made in the basic model to facilitate analysis. First, we consider equilibrium outcomes where all consumers share the same belief ξ_{prob} and the same reservation price r. Second, all parties are risk neutral and there is no discounting of money over time. The following definition introduces the RE equilibrium concept.

Definition 1 *A rational-expectations (RE) equilibrium* $(p, Q, r, \xi_{prob}, \xi_r)$ *must satisfy the following five conditions:*
(i) $r = v - (v-s)\xi_{prob}$, *(ii)* $p = \xi_r$, *(iii)* $Q = \arg\max_Q \Pi(Q,p)$, *(iv)* $\xi_{prob} = F(Q)$, *(v)* $\xi_r = r$.

The above equilibrium conditions deserve some explanation. A consumer's surplus is $v - p$ if she buys immediately, and the expected surplus is $(v-s)\xi_{prob}$ if she waits. Thus the maximal price a consumer is willing to pay in the regular season is $r = p = v - (v-s)\xi_{prob}$, which is condition (i). Conditions (ii) and (iii) assert that under expectations ξ_{prob} and ξ_r, the seller will take the profit-maximizing actions. The last two conditions require that expectations must be consistent with outcomes. Condition (iv) is about the consistence on the availability probability. We know ξ_{prob} is the belief on availability probability. The actual probability can be calculated as follows. In equilibrium, the seller prices the product at consumers' reservation price, so all consumers will buy the product. Consider an individual consumer who deviates and waits instead. Since this customer is infinitesimally small, the mass of remaining consumers is X. Hence, this individual will face a stockout later if $X > Q$. On the other hand, if $X \leq Q$, this individual consumer will get the product at the salvage price. Therefore, when an individual consumer waits, she will obtain the product with probability $F(Q)$, which must be consistent with her beliefs ξ_{prob}, as shown in (iv). An implicit assumption here is that consumers who wait for the sale have the highest priority to receive the product in the salvage market. This is reasonable because consumers who are interested in a particular product and eagerly waiting for a sale are also the ones who are more likely to get the product when the sale actually takes place. Finally, in (v), the seller's belief over the reservation price should be consistent with the consumers' actual reservation price.

3.2 Centralized System

3.2.1 RE equilibrium outcome

We first present the outcome of the RE equilibrium. Manipulation of the five conditions shows that the RE equilibrium in Definition 1 can be characterized by a pair of equations in p and Q only: $p = v - (v-s)F(Q)$, and $Q = \arg\max_Q \Pi(Q,p)$. Thus we have the following result.

Proposition 1 *There is a unique RE equilibrium. In the equilibrium, the seller's price* p *and quantity* Q *are characterized by*

$$p_c = s + \sqrt{(v-s)(c-s)} \text{ and } \bar{F}(Q_c) = \sqrt{\frac{c-s}{v-s}},$$

and all consumers will buy immediately.

We use subscript c for a centralized seller (later we will consider a decentralized supply chain with a manufacturer and a retailer). For concision, we use $\bar{F}$ for $1 - F$. The proofs are presented in the appendix at the end of the chapter. Under such a RE equilibrium, the centralized seller's profit can be written as

$$\Pi_c = (p_c - s)E(X \wedge Q_c) - (c-s)Q_c, \tag{36}$$

which will serve as a benchmark in future comparisons.

3.2.2 Two types of commitment

The seller receives a profit Π_c in the RE equilibrium. In this subsection we show that the seller's profit can be improved with two types of commitments: quantity-commitment (keeping quantities low) and price-commitment (keeping prices high). The rationale under both strategies is to guarantee customers that the product is sufficiently exclusive: it is not available in large quantities and it cannot be purchased at low prices. Practical examples of quantity-commitment include limited editions of cars, furniture, and collectors' items, while price-commitment may arise in the form of "one-price" or "no-haggle" policies.

We begin with quantity-commitment. Suppose the seller is able to convince the consumers that exactly Q units of the product will be available for the entire problem horizon. Or equivalently, the customers can observe the actual stocking quantity. Knowing the stocking quantity Q, customers no longer need to form rational expectations ξ_{prob} because if they wait for the sale (while all other customers buy), their chances of getting the product on the salvage market is $\Pr(X \le Q) = F(Q)$. In other words, when the seller commits to sell Q units, customers are willing to pay (and the seller also charges) price $p(Q) = v - (v-s)F(Q)$. The seller's profits, as a function of price p and quantity Q, is

$$\Pi_q(Q) = (p(Q) - s)E(X \wedge Q) - (c-s)Q = (v-s)\overline{F}(Q)E(X \wedge Q) - (c-s)Q. \tag{37}$$

We use the subscript q for quantity-commitment. Let $Q_q^* = \arg\max_Q \Pi_q(Q)$ be the seller's optimal quantity he will commit to. Then the seller charges price $p_q^* = v - (v-s)F(Q_q^*)$. Denote the corresponding optimal profit level under quantity-commitment by Π_q^*. Essentially, quantity-commitment allows the seller to manipulate the selling price $p(Q)$ as a function of the chosen quantity Q; on the other hand, in the absence of quantity-commitment, the price p is determined by the RE equilibrium. We next compare the optimal outcome under quantity commitment with the RE equilibrium outcome.

Proposition 2 *$\Pi_q(Q)$ has a unique maximizer Q_q^*. In addition, $Q_q^* \le Q_c$ and $\Pi_q^* \ge \Pi_c$.*

Proposition 2 confirms that the seller can obtain a higher profit ($\Pi_q^* \ge \Pi_c$) by committing to a lower quantity ($Q_q^* \le Q_c$). The practice of artificially creating the impression of shortages is not uncommon. Zara, one of the largest Spanish fashion retailers, is well-known for limiting production quantities to induce customers to make quick purchases (Ferdows, Lewis, and Machuca, 2005). Now, why cannot the seller achieve Q_q^* in the RE equilibrium? It is because an external commitment device is critical in realizing the quantity Q_q^*. To see this, recall from Definition 1 that in order to sustain Q_q^* in equilibrium, the required expectations are $\xi_{prob} = F(Q_q^*)$ and $\xi_r = r$, and the required selling selling price is $p = r = v - (v-s)F(Q_q^*)$. It can be verified that these values satisfy conditions (i), (ii), (iv), and (v) in Definition 1, but the definition of Q_q^* contradicts condition (iii). Intuitively, under the expectations that only Q_q^* is available, consumers would be willing to pay $p(Q_q^*)$; but once customers are willing to pay this much, the seller has an incentive to raise the stocking quantity above Q_q^* to make higher profit, so the initial expectations of Q_q^* would not have be formed in the first place. Therefore, Q_q^* can not be sustained in the RE equilibrium. However, this problem vanishes if the seller possesses some external commitment device.

Next we discuss price-commitment. Suppose the seller can credibly commit to a high price throughout the entire horizon. It is sufficient to consider the case in which the seller commits to $p = v$ (any other price would not be optimal for the seller). Note that committing to maintain prices at v is equivalent to eliminating the markdown opportunity provided by the salvage market. Given that the price commitment is credible, consumers will be willing to pay v at the start. It can be shown that under price-commitment, we have a standard newsvendor model with zero salvage value. The seller sets $p_p^* = v$ and his profit function is given by

$$\Pi_p(Q) = vE(X \wedge Q) - cQ. \tag{38}$$

The seller's optimal stocking quantity is $Q_p^* = \arg\max_Q \Pi_p(Q)$ with a profit level Π_p^*. The subscript p stands for price-commitment. The following result compares the performance of price commitment to the RE equilibrium outcome.

Proposition 3 *(i) Given s and v, there exists a threshold value c_l such that $\Pi_p^* \geq \Pi_c$ for $c \leq c_l$ and a threshold value c_h such that $\Pi_p^* \leq \Pi_c$ for $c \geq c_h$.*

(ii) Given c and s, there exists a threshold v_l such that $\Pi_p^* \leq \Pi_c$ for $v \leq v_l$ and a threshold value v_h such that $\Pi_p^* \geq \Pi_c$ for $v \geq v_h$.

Proposition 3 shows that under certain conditions, price-commitment may increase the seller's profits above the RE equilibrium level. In particular, the relationship $\Pi_p^* \geq \Pi_c$ holds when the production cost c is relatively low and when the valuation v is relatively high. However, unlike quantity-commitment, price-commitment is not unambiguously beneficial: We have identified examples in which the inequality $\Pi_p^* < \Pi_c$ holds. Proposition 3 also sheds light on when price commitment is valuable: Price commitment tends to be more valuable when the product becomes more profitable (either c decreases or v increases).

From the above analysis, we can see that quantity-commitment and price-commitment are both effective strategies in dealing with strategic consumers. The problem is, in most situations, the seller lacks an appropriate commitment device and the implementation of the strategies is not feasible. If this is indeed the case, our analysis suggests that the seller would have to contend with the RE equilibrium outcome. What can the seller do? Fortunately, this may be true in a centralized system (single seller), but not for decentralized systems. In the following sections, we focus on decentralized supply chains consisting of two independent firms. We examine different contractual arrangements between supply chain parties. It will be shown that these contractual arrangement can serve as a surrogate commitment device, and enable the supply chain to attain the optimal profit benchmarks Π_q^* and Π_p^* with commitment. Therefore, again we can see that a decentralized supply chain may yield higher profits than a centralized supply chain.

3.3 Decentralized System

In the previous analysis, customers purchase the product from a centralized seller. This section extends the newsvendor model to a supply chain setting. Specifically, we consider a manufacturer distributing a product through a retailer. The model setting is the same as before, except that now we interpret c as the manufacturer's production cost. The timing of the model is as follows: First, the contractual agreements between the manufacturer and the retailer are exogenously established; then, the retailer and customers make their pricing, stocking, and purchase decisions according to a RE equilibrium; finally, demand is realized during the selling season and unsold products are salvaged. In this decentralized setting, we assume that the manufacturer and the retailer are risk neutral, independent firms aiming at maximizing their own profits.

3.3.1 Wholesale price contracts

We first consider contracts with the simplest form: wholesale price contracts. In a wholesale price contract, the manufacturer specifies a unit price w ($w \geq c$) for the retailer. Under this contract, the retailer's profit function can be written as

$$\Pi_w^r(Q, p) = (p - s)E(X \wedge Q) - (w - s)Q. \tag{39}$$

Here, the subscript w stands for wholesale price and the superscript r stands for retailer. Later we will use the superscript m to refer to the manufacturer's profit function. The equilibrium analysis under the wholesale price contract can be derived similarly as before. Following the argument of Proposition 1, the retailer's order quantity Q_w and retail price p_w in RE equilibrium are given by

$$\overline{F}(Q_w) = \frac{w-s}{p_w-s} = \sqrt{\frac{w-s}{v-s}}, \tag{40}$$

$$p_w = s + (v-s)\overline{F}(Q_w) = s + \sqrt{(v-s)(w-s)}. \tag{41}$$

In this RE equilibrium, the profits to the retailer, the manufacturer, and the supply chain are given by

$$\Pi_w^r = (p_w-s)E(X \wedge Q_w) - (w-s)Q_w = (v-s)\overline{F}(Q_w)E(X \wedge Q_w) - (v-s)\overline{F}^2(Q_w)Q_w, \tag{42}$$

$$\Pi_w^m = Q_w(w-c) = Q_w[(v-s)\overline{F}^2(Q_w) - (c-s)], \tag{43}$$

$$\Pi_w \equiv \Pi_w^r + \Pi_w^m = (v-s)\overline{F}(Q_w)E(X \wedge Q_w) - (c-s)Q_w, \tag{44}$$

respectively.

It is worth noting that the wholesale price w can be used as a control lever for the supply chain to induce a particular equilibrium stocking quantity. The explanation is as follows. First, there is a one-to-one relationship between $Q_w \in [0, Q_c]$ and $w \in [c, v]$, since the equilibrium quantity Q_w is monotonically decreasing in w. (To highlight the dependence of the equilibrium quantities on the wholesale price w, later we write $Q_w(w)$, and similarly for $p_w(w), \Pi_w^r(w), \Pi_w^m(w)$, and $\Pi_w(w)$). Second, recall that Q_c is the RE equilibrium quantity in the centralized system. Then, by varying w between c and v, the supply chain can realize any equilibrium quantity within the range $[Q_w(v), Q_w(c)]$. Therefore, it is as if the supply chain could choose a desired quantity at the outset (though this particular quantity has to conform to the requirements of an RE equilibrium). In this sense, a pure wholesale price contract provides the supply chain with certain degree of quantity-commitment power. Actually, it turns out that quantity-commitment power can significantly enhance supply chain profits. The next proposition formalizes this observation.

Proposition 4 *There exists a $w^* \in (c, v)$ such that:*
(i) $\Pi_w(w) \geq \Pi_c$ for every $w \in (c, w^*]$, i.e., the equilibrium profit in the decentralized system under the wholesale price contract w exceeds the equilibrium profit in the centralized system.
(ii) The decentralized system achieves the optimal profit Π_q^* under quantity commitment at $w = w^*$.

Proposition 4(i) states that the profit of a centralized supply chain is dominated by the profit of a decentralized supply chain, under an array of wholesale price contracts. This is a surprising result. A customary practice in operations management research is to use the centralized scheme as a benchmark to study supply chain efficiency. Proposition 4(i) delivers a message that the centralized optimal profit may not always be the highest possible profit that a supply chain can achieve. In particular, there have been numerous studies addressing the inefficiency caused by double marginalization. That is, when $w > c$, the retailer orders less than the optimal quantity for the entire supply chain. In contrast, here we show that increasing the wholesale price beyond c actually improves the supply chain's profit. The reason is that a higher wholesale price will enable the retailer to credibly stock a lower quantity (recall $Q_w(w)$ is a decreasing function of w), and hence charge a higher retail price to forward-looking consumers in equilibrium. Meanwhile, varying the wholesale price would not affect the supply chain profit since it only alters the transfer payment between the two parties.

Proposition 4(ii) further states that a decentralized supply chain can achieve Π_q^*, the optimal profit under the quantity commitment, by using a wholesale price contract $w = w^*$. That is, the wholesale price induces the optimal quantity Q_q^* in equilibrium and "coordinates" the supply chain.

A similar situation where a wholesale price contract can coordinate a supply chain is when horizontal competition is present. For example, Netessine and Zhang (2005) demonstrate that in a distribution channel with a manufacturer and multiple retailers, the substitution effect among the retailers can offset the double marginalization effect and thus retain the supply chain optimal outcome. But here the underlying reason is different: There are strategic consumers on top of double marginalization, and therefore a wholesale price contract can serve as a coordination device to balance these two opposite forces.

We proceed by asking the following two questions. First, if given the choice, what wholesale price would the retailer and the manufacturer select? In other words, how are the quantities $w^r \in \arg\max_w \Pi_w^r(w)$ and $w^m \in \arg\max_w \Pi_w^m(w)$ characterized, and are they unique? Second, how do these unilaterally-preferred wholesale prices w^r and w^m compare with the system-optimal wholesale price w^*? These questions are important, since although the wholesale price w^* allows the supply chain to attain the profit benchmark Π_q^*, it specifies a particular division of profits between the retailer and the manufacturer (their shares are $\Pi_w^r(w^*)$ and $\Pi_w^m(w^*)$, respectively). However, each individual party may prefer some wholesale price other than w^* and may negotiate for their preferences. The following proposition deals with these questions.

Proposition 5 *The profit-maximizers w^r (for the retailer) and w^m (for the manufacturer) are unique. Moreover, they satisfy $w^r < w^* < w^m$.*

To further understand each party's preferences over wholesale prices, it would be useful to characterize the set of Pareto optimal wholesale price contracts. A contract is Pareto optimal if there exists no alternative such that some firm is strictly better off and no firm is worse off. Any wholesale price in the Pareto set is a possible choice both parties agree upon. The next proposition presents the set of Pareto wholesale price contracts.

Proposition 6 *The Pareto optimal wholesale price set is given by $w \in [w^r, w^m]$. In particular, if $w^r > c$, then the wholesale price $w = c$ is Pareto dominated by any $w \in [c, w^r]$.*

From the above two propositions we can see how the allocation of bargaining power affects supply chain efficiency (one may view the wholesale price as a proxy of the bargaining power of the two parties): Since $w^r < w^* < w^m$, the supply chain achieves its optimum when the wholesale price lies in the middle. This suggests that an extreme allocation of bargaining power may reduce the supply chain profit. Now, consider the retailer's profit. Intuitively, a retailer would prefer to have a lower wholesale price. But this is not necessarily true in our problem setting. In fact, even if the retailer has absolute bargaining power, it may not ask for a wholesale price $w = c$ to squeeze the manufacturer's profit to zero. The explanation is as follows. Note that the problem of choosing the wholesale price w faced by the retailer is equivalent to the problem of choosing the production cost c faced by the single seller in Section 3.2. In other words, one may view the seller's profit Π_c as a function of c, and then w^r is essentially the production cost that maximizes the seller's profit. Therefore, if $w^r > c$ (i.e., the profit-maximizing production cost is greater than the actual cost), then according to Proposition 6, the contract with $w = c$ is Pareto dominated by any $w \in [c, w^r]$. That is, under certain conditions, both the retailer and the manufacturer prefer a wholesale price higher than the production cost c. This is an interesting result because it implies that the retailer may increase his own profit by voluntarily inviting a higher wholesale price.

3.3.2 Buyback contracts

So far we have explained that wholesale price contracts can achieve quantity commitment for a decentralized supply chain. Next, we show that decentralized supply chains can attain the price-commitment benchmark profit Π_p^* using buyback contracts. In a buyback contract, the manufacturer sells to the retailer at wholesale price w_b and agrees to buy back unsold items at b per unit after demand is realized. There are two separate cases to consider. When $b < s$, the retailer would prefer to salvage the excess inventory rather than selling them back to the manufacturer. The (w_b, b) contract essentially reduces to a pure wholesale price contract, which has already been studied above. For this reason, we will focus on the case $b \geq s$. In this case, the option of selling excess inventory back to the manufacturer becomes more attractive than marking down the price. More importantly, this buyback arrangement eliminates the salvage market, thereby inducing all customers to pay the maximum regular price $p = v$. We emphasize that the buyback contract requires the retailer to physically return the unsold products to the manufacturer (or the retailer "destroys" the leftover inventory by himself). Mere monetary transfers are insufficient because the retailer has to "burn his own bridge" in order to convince consumers that he is unable to activate the salvage market after all intra-supply-chain transactions have occurred.

We start the analysis by assuming that a buyback contract (w_b, b) with $b \geq s$ has been established at the outset. In this environment, the RE equilibrium (between the retailer and the strategic customers) dictates that prices (selling price, reservation price, anticipated reservation price) are all $p = r = \xi_r = v$ and the anticipated probability of low-price availability is $\xi_{prob} = 0$. Then, the retailer has a profit function

$$\Pi_b^r(Q) = (v - b)E(X \wedge Q) - (w_b - b)Q \tag{45}$$

and chooses the quantity Q_b^r characterized by $\overline{F}(Q_b^r) = \frac{w_b - b}{v - b}$. We use the subscript b for buyback. We also define $\Pi_b^m(Q)$ and $\Pi_b(Q) = \Pi_b^r(Q) + \Pi_b^m(Q)$ as the manufacturer's profits and total supply chain profits (under the buyback contract), as a function of the retailer's order quantity Q. These profit functions, respectively, can be written as

$$\Pi_b^m(Q) = bE(X \wedge Q) + (w_b - c - b)Q \tag{46}$$

and

$$\Pi_b(Q) = vE(X \wedge Q) - cQ. \tag{47}$$

Total supply chain profit $\Pi_b(Q)$ is maximized at Q_b satisfying $\overline{F}(Q_b) = \frac{c}{v}$. Observe that total supply chain profit under the buyback contract $\Pi_b(Q)$ coincides with the profit function of the centralized system with price-commitment, $\Pi_p(Q)$, so their maximizers also coincide. Therefore, if the supply chain can be coordinated to produce and stock the optimal quantity Q_b, the price-commitment profit benchmark Π_p^* can be attained. The next proposition shows that this can indeed be done, but only for a certain range of profit allocations.

Proposition 7 *Let $\lambda \in [0, 1 - \frac{s}{v}]$ be the retailer's profit share in a buyback contract. Then under the parameter values $w_b = \lambda c + (1 - \lambda)v$ and $b = (1 - \lambda)v$, the RE equilibrium outcome attains the price-commitment profit benchmark Π_p^* for the system. The retailer's and the manufacturer's profits are, respectively, $\lambda \Pi_p^*$ and $(1 - \lambda)\Pi_p^*$.*

It is well-known that buyback contracts can coordinate a decentralized supply chain and arbitrarily divide the profit between supply chain members (see Cachon, 2003). Our results identify a new role that buyback contracts play when customers are strategic: They serve as a commitment device. The ability to commit to strategic customers, combined with the ability to coordinate on mutually beneficial actions, allows supply chains to attain the profit levels of a centralized system with price-commitment. This may not even be an alternative when a centralized seller operates in isolation. Industry evidence seems to be consistent with the above analysis. For example, buyback or return policies are widely used in the book industry. Instead of marking down prices, major retailers such as Barnes & Noble return the unsold books to their publishers when the selling season ends. The returned copies are then sold to companies specializing in bargain books, or, books that cannot be sold are simply pulped for a total loss. There is an on-going debate in the book industry over whether returns should be eliminated: while some retailers claim that they are willing to mark down books and sell them on spot, most publishers are leery of the change (see Trachtenberg, 2005). In fact, one major concern is that readers may learn to wait until books are cheaper. We suspect that the book industry, in spite of losses due to returns, may still be using such a practice as a price-commitment device in order to extract higher profits.

Another observation from Proposition 7 is that there is an upper bound $1 - \frac{s}{v}$ on the retailer's profit share λ. In general, the ability to allocate profits arbitrarily between parties is a desirable property in evaluating different contractual formats. This is because with such a property, we can separate the coordination process from the allocation process: The supply chain can concentrate on maximizing the size of the pie before negotiating over individual shares. In the current situation, the upper bound on retailer share may create problems, especially when the retailer is powerful relative to the manufacturer. This suggests that using buyback contracts as a price-commitment device may face implementation challenges. Note that $\lambda \leq 1 - \frac{s}{v}$ follows directly from the condition $b \geq s$. Thus, ironically, it is precisely these profit caps (due to the upper bound on profit share) that make buybacks effective in providing price-commitment. This is different from the situations without the presence of strategic consumers, where buyback contracts can achieve arbitrary profit allocation through the manipulation of the contract parameters, w_b and b.

4 Conclusion and Future Research

The main theme of this chapter is to demonstrate that decentralized supply chains may perform better than centralized systems. This claim may appear to challenge conventional wisdom in operations management since decentralization is often associated with double marginalization problems. However, in this chapter, we first show that decentralization can indeed be a beneficial strategy in durable goods supply chains. Decentralization can be particularly useful in durable goods supply chains in the following two scenarios:

1. The first scenario is when firms are able to write long-term contracts. In such cases, long-term contracts allow firms to commit to one another, and this serves as a proxy for commitment to consumers (which firms are unable to achieve). Thus, through long-term contracts, durable goods supply chains are able to mitigate the Coase problem and improve profits.

2. The second scenario is when firms are selling over long time horizons. In such cases, we see that even in the absence of complex contractual arrangements, simply introducing an intermediary can increase supply chain profits. This is because double marginalization leads to lower future quantities and higher consumer willingness to pay. In this sense, double marginalization is no longer a "problem" but rather, it helps to sustain higher prices over longer time horizons for durable goods.

We also show that decentralization can be beneficial to perishable goods supply chains since it can serve as a commitment device to convince consumers of certain actions taken by firms. Two types of commitment that may help enhance a seller's profit have been studied:

1. The first type is quantity commitment. In quantity commitment, the seller promises that the quantity will be low and thus induces the consumers to buy at a relatively high price in the

regular season. While a centralized system may lack such a commitment power, a decentralized system under the simplest wholesale price contracts can credibly commit to a desirable quantity due to the double marginalization effect.

2. The second type is price commitment. A consumer may choose to wait simply because she anticipates a lower price in the salvage market. This opportunistic behavior will not exist any more if a seller can credibly commit to a high price throughout the entire horizon. A buyback contract, which removes any leftover inventory of the product from the market, can clearly achieve the effect of price commitment.

It can be seen in this chapter that for both durable goods and perishable goods models, commitment power is the key. Essentially, both models involve the dynamic inconsistency (also known as time inconsistency) problem recognized in the economics literature. That is, a firm competes against his future self when making managerial decisions at multiple time points. (The only exception is the model of quantity commitment for perishable goods supply chains, where the seller makes a single-shot decision at the beginning of the selling season). Under these circumstances, a firm may be better off if he possesses commitment power to convince other game players that certain actions will be taken.

We emphasize that strategic consumers are also critical for the results. We believe that modeling individual consumer behavior in various operations problems is a fruitful topic for future research. The majority of supply chain management literature study isolated operational systems by treating the demand as an exogenous random variable or a fixed downward-sloping curve. However, individual consumers may take strategic actions that in turn affect the performance of the operational system. In fact, modeling customer behavior explicitly has been quite common in service contexts (e.g., queueing analysis and revenue management), probably because consumers are more tangible in service than in other settings. Nevertheless, we hope this chapter can inspire more research in different operational settings.

All the analysis in this chapter requires that consumers act perfectly rational in response to firms' strategies and market conditions. That is, consumers are not myopic and possess unlimited information processing capability. Although this assumption is understandable from a research point of view, apparently, it may not hold in reality. Consumers are human beings and they are not necessarily always, perfectly rational. Thus another direction for future research is to investigate the impact of bounded rationality in consumer behavior on firms' operational strategies.

Finally, the message that strategic decentralization could benefit a firm has been reported in other studies. In these studies, a firm competes against other independent competitors rather than his future self. McGuire and Staelin (1983) consider two manufacturers selling substitutable products. Each manufacturer may sell his product through a manufacturer-owned outlet or an independent retailer. They find that both manufacturers may choose to distribute the products through a decentralized channel in equilibrium, depending on product substitutability. Cachon and Harker (2002) study two competitive service providers that have the option to outsource the service to a third party. It has been shown that both firms outsourcing could be an equilibrium since adding an upstream stage in the service supply chain can reduce the intensity of competition at the downstream stage. A recent paper by Liu and Tyagi (2007) shows that strategic decentralization could also be useful when two firms compete on horizontally differentiated products. Since production/service outsourcing is an important operational strategy that has gained tremendous popularity, it would be interesting to identify new driving forces underlying the industry trend.

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Appendix

Proof of Proposition 1 The RE equilibrium conditions

$$
\begin{aligned}
p &= v-(v-s)F(Q), &(48)\\
Q &= \arg\max_Q \Pi(Q,p), &(49)
\end{aligned}
$$

reduce to

$$
\begin{aligned}
p &= s+(v-s)\overline{F}(Q), &(50)\\
\overline{F}(Q) &= \frac{c-s}{p-s}, &(51)
\end{aligned}
$$

respectively. Solving these equations yields the desired results. ■

Proof of Proposition 2 The first-order-condition $\Pi_q'(Q)=0$ yields

$$
\frac{c-s}{\overline{F}(Q)}+(v-s)\frac{f(Q)}{\overline{F}(Q)}E(X\wedge Q)=(v-s)\overline{F}(Q). \tag{52}
$$

The left-hand-side is increasing (because F has an increasing failure rate), and the right-hand-side is decreasing in Q, so the first-order-condition has a unique solution. Further, we know that $\Pi_q'(0)=v-c>0$ and $\lim_{Q\to\infty}\Pi_q'(Q)=-(c-s)<0$. Therefore, $\Pi_q(Q)$ is quasi-concave and has a unique maximizer.

The derivative of $\Pi_q(Q)$ at $Q=Q_c$ is:

$$
\begin{aligned}
\Pi_q'(Q_c) &= (v-s)\overline{F}^2(Q_c)-(c-s)-(v-s)E(X\wedge Q_c)f(Q_c)\\
&= -(v-s)E(X\wedge Q_c)f(Q_c)\\
&< 0,
\end{aligned}
$$

where the second equality follows from $(v-s)\overline{F}^2(Q)-(c-s)=0$. From the previous proposition we know that $\Pi_q(Q)$ is increasing first and then decreasing in Q. Hence there must be $Q_q^*<Q_c$ and $\Pi_q^*\geq\Pi_c$. ■

Proof of Proposition 3 The proof is similar to that of Proposition 2 and omitted. ■

Proof of Proposition 4 The proof follows directly from Proposition 2. ■

Proof of Proposition 5 Consider the equilibrium profits $\Pi_w^r(Q)$ and $\Pi_w^m(Q)$ as a function of equilibrium quantities Q. Denote the maximizers of these functions $Q_w^r\in\arg\max_Q\Pi_w^r(Q)$ and $Q_w^m\in\arg\max_Q\Pi_w^m(Q)$. It suffices to show that (i) Q_w^r and Q_w^m are unique, and (ii) $Q_w^m<Q_q^*<Q_w^r$.

(i) Taking derivative of $\Pi_w^r(Q)$ gives

$$
\frac{d}{dQ}\Pi_w^r(Q)=(v-s)f(Q)[-E(X\wedge Q)+2Q\overline{F}(Q)]. \tag{53}
$$

Let

$$
g(Q)=-E(X\wedge Q)+2Q\overline{F}(Q)=-\int_0^Q xf(x)dx+Q\overline{F}(Q), \tag{54}
$$

then

$$g'(Q) = \overline{F}(Q) - 2Qf(Q). \tag{55}$$

Since F has an increasing failure rate, we know $g'(Q)$ starts at $g'(0) = 1$ and then decreases to the negative domain. Thus, $g(Q)$ starts at $g(0) = 0$, increases first, and then decreases to the negative domain. Let Q_w^r be the unique solution to $g(Q) = 0$, then $\Pi_w^r(Q)$ is increasing for $Q < Q_w^r$ and decreasing for $Q > Q_w^r$. That is, $\Pi_w^r(Q)$ is quasi-concave and has a unique maximizer.

The proof for $\Pi_w^m(Q)$ is similar and omitted.

(ii) Consider the first-order conditions for Q_w^r, Q_w^m, and Q_q^*:

$$Q_w^r \quad : \quad \frac{d}{dQ}\Pi_w^r(Q) = (v-s)f(Q)[E(X \wedge Q) - 2Q\overline{F}(Q)] = 0, \tag{56}$$

$$Q_w^m \quad : \quad \frac{d}{dQ}\Pi_w^m(Q) = (v-s)\overline{F}^2(Q) - (c-s) - (v-s)2Q\overline{F}(Q)f(Q) = 0, \tag{57}$$

$$Q_q^* \quad : \quad \frac{d}{dQ}\Pi_q(Q) = (v-s)\overline{F}^2(Q) - (c-s) - (v-s)E(X \wedge Q)f(Q) = 0. \tag{58}$$

Since $E(X \wedge Q_w^r) = 2Q_w^r\overline{F}(Q_w^r)$ and $\Pi_w^r(Q)$ is quasi-concave, we have $\frac{d}{dQ}\Pi_w^m(Q) \leq \frac{d}{dQ}\Pi_q(Q)$ for $Q < Q_w^r$ and the opposite holds for $Q > Q_w^r$. Therefore, the only possible orderings for Q_w^r, Q_w^m, Q_q^* are $Q_w^r < Q_q^* < Q_w^m$ and $Q_w^m < Q_q^* < Q_w^r$.

Next we show $Q_q^* < Q_w^r$. The retailer's optimal quantity Q_w^r is given by $E(X \wedge Q_w^r) = 2Q_w^r\overline{F}(Q_w^r)$ and is determined only by the distribution function. Define $\beta \equiv \frac{c-s}{v-s}$ $(0 < \beta < 1)$. Then, the first-order condition for Q_q^* can be written as

$$\beta + f(Q)E(X \wedge Q) = \overline{F}^2(Q). \tag{59}$$

If $\beta + f(Q_w^r)E(X \wedge Q_w^r) > \overline{F}^2(Q_w^r)$, then we know $Q_q^* < Q_w^r$. Since $\beta > 0$, it suffices to show $f(Q_w^r)E(X \wedge Q_w^r) > \overline{F}^2(Q_w^r)$. Plugging $E(X \wedge Q_w^r) = 2Q_w^r\overline{F}(Q_w^r)$ into the inequality, we only need to show

$$\overline{F}(Q_w^r) - 2Q_w^r f(Q_w^r) < 0. \tag{60}$$

Recall from (i) that $g'(Q) = \overline{F}(Q) - 2Qf(Q) = 0$ has a unique solution. Let $\hat{Q}$ be this solution. In addition, Q_w^r is the unique solution to $g(Q) = 0$. This implies that $\hat{Q} < Q_w^r$, so we have

$$g'(Q_w^r) = \overline{F}(Q_w^r) - 2Q_w^r f(Q_w^r) < g'(\hat{Q}) = 0. \tag{61}$$

The desired result follows. ■

Proof of Proposition 6 The proof follows directly from Proposition 2 and Proposition 5. ■

Proof of Proposition 7 Recall that the retailer faces the profit function

$$\Pi_b^r(Q) = (v-b)E(X \wedge Q) - (w_b - b)Q, \tag{62}$$

so the optimal stocking quantity is

$$\overline{F}(Q_b^r) = (w_b - b)/(v-b). \tag{63}$$

Recall also that the supply chain profit function is

$$\Pi_b(Q) = vE(X \wedge Q) - cQ, \tag{64}$$

which is maximized at Q_b, as characterized by

$$\overline{F}(Q_b) = c/v. \tag{65}$$

The proof follows the standard approach in the supply chain contracting literature, so we shall keep it brief. The appropriate buyback contract has two objectives: (i) to induce $Q_b^r = Q_b$ (coordination) and (ii) to yield a $(\lambda, 1-\lambda)$ division of profits (allocation). The two conditions $v - b = \lambda v$ and $w_b - b = \lambda c$ together achieve both objectives because: (i) $\frac{w_b - b}{v - b} = \frac{\lambda c}{\lambda v} = \frac{c}{v}$, so from (63) and (65), we have $Q_b^r = Q_b$, and (ii) from (62) and (64), we have $\Pi_b^r(Q) = (v-b)E(X \wedge Q) - (w_b - b)Q = \lambda v E(X \wedge Q) - \lambda c Q = \lambda \Pi_b(Q)$. Solving these two equations yields the desired contract parameters. Finally, since $b = (1-\lambda)v$, the condition $b \geq s$ yields the upper bound of $1 - \frac{s}{v}$ on the retailer's share λ. ■