Price Protection in the Personal Computer Industry

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Price protection is a commonly used practice between manufacturers and retailers in the personal computer (PC) industry, motivated by drastic declines of product values during the product life cycle. It is a form of rebate given by the manufacturer to the retailer for units unsold at the retailer when the price drops during the product life cycle. It is a controversial policy in the PC industry because it is not clear how such a policy benefits the supply chain and its participants. We show that price protection is an instrument for channel coordination. For products with long manufacturing lead times, so the retailer has a single buying opportunity, a properly chosen price protection credit coordinates the channel. For products with shorter manufacturing lead times, so the retailer has two buying opportunities, price protection alone cannot guarantee channel coordination when wholesale prices are exogenous. However, when the price protection credit is set endogenously together with the wholesale prices, channel coordination is restored. In the two-buying-opportunity setting with fixed wholesale prices, we show that price protection has two primary impacts: (1) shifting sales forward in time and (2) increasing total sales. Finally, we present a simple numerical example that suggests, given the current economics of the PC industry, that price protection under fixed wholesale prices may benefit the total chain and the retailer but hurt the manufacturer.
(*Channel Coordination*; *Supply Chain Management*; *Computer Industry*; *Incentives*; *Inventory Management*)

1. Introduction

The personal computer (PC) industry is marked by rapid product obsolescence, significant price declines over the product life cycle, and high demand uncertainty. Over the first year of a product life cycle, the average retail price of a desktop PC system declines 50%–58% (*PC Today* 1996, 1997, 1998). The decline in retail price for the Pentium 200-Mhz desktop PC system is shown in Figure 1. The prospect of decreased future prices can create an incentive for retailers to postpone purchases rather than face the prospect of "buying high and selling low." In addition, high demand uncertainty leads retailers to reduce the stock level. In such environments, suppliers may offer price protection policies that grant retailers credits applied to the retailers' unsold inventories when prices drop during the product life cycle.

In practice, the timing and magnitude of price protection credits is based on the decline in wholesale price. The most generous policies—termed *full price*

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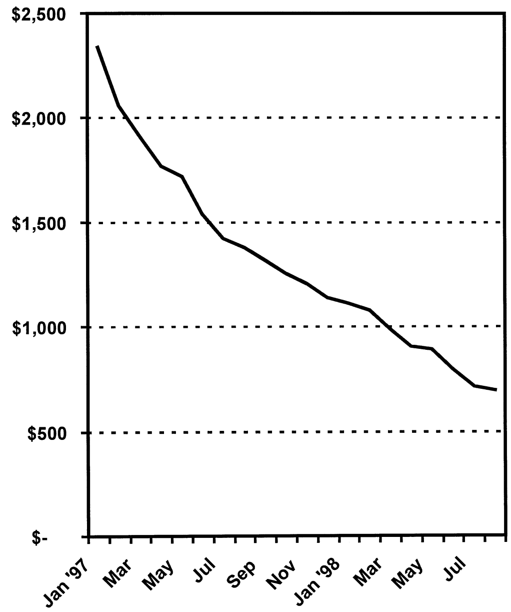
Figure 1 **Pentium 200-MHz Desktop System Price**



Source: *PC Today*

protection policies—offer a credit on all unsold inventory for the full amount of the wholesale price drop without restriction on when the inventory was originally purchased. Less generous policies—termed *partial price protection policies*—place a time restriction on the inventory eligible for price protection (e.g., only products purchased within the last 30 days) or limit the magnitude of the price protection credit (e.g., 70% of the price drop is credited). Industry interviews indicate that time restrictions are the primary type of policy observed in practice.

Price protection is a controversial issue in the PC industry. Opinion is divided among manufacturers, wholesalers, and retailers on its merits/demerits. Consequently, there have been dramatic changes in such policies in the PC industry. For instance Compaq, which never offered price protection to its distributors, extended full price protection to them beginning in autumn 1993 (Graziose 1994). Apple announced in late 1993 that it was limiting price protection to its dealers to 30 days. The ensuing debate and pressure drove Apple to rescind this policy and reinstitute full price protection in January 1994 (Zarley 1994). Other manufacturers extended price protection, so for a while the industry was content with almost full price protection (Bakar et al. 1998). In July 1997, Compaq announced that it would restrict its price protection to 15 days (Zarley and Bliss 1997). Over the next five months IBM, Hewlett-Packard (HP), and Apple followed suit, announcing 30-day, 14-day, and 4-week price protection policies, respectively (O'Heir 1997, Schick 1997, Pereira and Zarley 1997). However, the channel has resisted these tighter price protection terms, and manufacturers' enforcement of them has been "lax at best" (Bakar et al. 1998).

Much of the confusion surrounding price protection comes from a poor understanding of its role. Why have these policies changed, and can such changes be justified on the grounds of economic efficiency? What is the impact of price protection on the behavior and performance of the firms in the supply chain?

We attempt to lend some clarity to this debate by carefully examining the role of price protection in the supply chain and presenting a rationale for its use. We show that there is more to price protection than a simple transfer of money between business partners: Price protection is an instrument for channel coordination (i.e., for arriving at the maximum efficiency for the total supply chain of both the manufacturer and the retailer). If products have long manufacturing lead times so that the retailer has a single buying opportunity, a properly chosen price protection credit coordinates the channel. If, contrarily, products have shorter manufacturing lead times so that the retailer has multiple (or two, for simplicity) buying opportunities, price protection alone cannot guarantee channel coordination when wholesale prices are exogenous. However, when the price protection credit is set endogenously together with the wholesale prices, channel coordination is restored. In the two-buying-opportunity setting with fixed wholesale prices, we show that price protection has two primary impacts: (1) shifting sales forward in time and (2) increasing total sales. Finally, we present a simple numerical example that suggests, given the current economics of the PC industry, that price protection under fixed wholesale prices may benefit the total chain and the retailer but hurt the manufacturer.

The paper is organized as follows. Section 2 provides a survey of related research. Section 3 introduces a simple two-period model to analyze the obsolescence-prone market. We examine a supply chain consisting of one manufacturer and one retailer in which the retailer has a single buying opportunity. In §4 we extend this model to consider the situation in which the retailer has a second buying opportunity (at a lower price). This model is used to explore the declining wholesale price market. In §5 we offer concluding remarks as well as suggestions for future research.

2. Literature Survey

There is considerable research on why manufacturers might accept returns from retailers. The context for most of this research is perishable products. The primary argument for returns is based on insurance (e.g., Lin 1993, Marvel and Peck 1995), the point being that returns insure retailers against the inventory risk posed by uncertain demand for a perishable product. Pellegrini (1986) shows that a returns policy can encourage retailers to order excess stocks and thereby improve sales of a firm's product relative to its competitors by reducing the probability of stock-out. Padmanabhan and Png (1997) demonstrate that a returns policy can improve manufacturer profitability by intensifying retail price competition.

Pasternack (1985) examines the pricing decision of a manufacturer of a product with a limited shelf life. His focus is on channel coordination. He shows that policies such as full credit for unsold goods or no credit for unsold goods are suboptimal. In contrast, a policy whereby the manufacturer offers partial credit for all unsold goods can achieve channel coordination. He also shows that limiting returns to a fixed percentage of sales may be an optimal policy in a single-retailer setting but is suboptimal in a multiretailer setting. Kandel (1996) extends Pasternack (1985) by modeling price sensitivity in end consumer demand. He explores ways to coordinate the channel when either the manufacturer or the retailer specifies the terms of the returns agreement.

There is much economics, marketing, and management science literature on channel coordination. Channel coordination seeks to optimize the joint performance of the supply chain and split the gain between the parties. Jeuland and Shugan (1983) study coordination issues in a bilateral monopoly and derive the optimal discount pricing policy. Zusman and Etgar (1981) investigate pricing policies and monitoring schemes in the context of a three-level supply chain. McGuire and Staelin (1983) investigate the optimality of forward integration in a duopolistic retail market. This literature concentrates on deriving the terms of trade that generate channel coordination.

Our work is closest in spirit and structure to Pasternack (1985), who searches for the optimal returns policy in the context of a perishable product. We look at the optimal price protection policy in the context of product markets faced with obsolescence. Pasternack uses a newsboy model to derive the optimal pricing policy, and we use a similar model here. However, this work differs from Pasternack (1985) in that we consider a dynamic model of buyer–seller interaction. Our interest is in the implications of a pricing policy for channel coordination as markets evolve over time.

3. The Single-Buying-Opportunity Model

To examine the obsolescence-prone market, consider a two-period model of a computer product market. In this section we assume that products have long lead times, so the retailer has a single buying opportunity at the beginning of the product life cycle. The retailer chooses an order quantity at the beginning of Period 1, and the units are delivered ready for sale in Period 1 at full price. Unmet demand is lost. At the beginning of Period 2, another new product is introduced to the market. The launch of the new product reduces the attractiveness of the existing product. Consumers react to the introduction of the new product in one of two ways. Some consumers prefer to purchase the existing product at a discount; perhaps their needs do not require the technological sophistication of the new product. Other consumers prefer to buy the new product. The important point is that there still exists a demand for the old product in Period 2 at a lower price. This characterization of product adoption in markets for successive generation of product advances is borne out by the empirical results in Norton and Bass (1987).

Our interest is in the channel coordination implications of product obsolescence. To better understand the effects of price protection, we begin by examining the issue in a simple setting before proceeding to a more general analysis. The benchmark setting is the case where the manufacturer owns its retail channel. We next consider the setting where the retailer is an independent entity and chooses an order quantity to maximize her own expected profit. Within this setting we investigate the impact of price protection by considering two polar cases. First, we look at the situation where the retailer is offered no price protection. In other words, there is no rebate for unsold units. We show that this leads to a suboptimal order quantity for the supply chain. Second, we consider the situation where the manufacturer allows the possibility of price protection. This implies that for each unit left unsold by the end of Period 1, the retailer is paid a fixed credit. We show that this price protection (if the credit is properly chosen) can result in the optimal order quantity, thereby achieving channel coordination.

We assume that the manufacturer moves first as the Stackelberg leader setting the terms of the price protection policy, and the retailer follows by choosing the order quantity. The retail market is very competitive so that the retailer faces fixed market/retail prices in both periods. The objective of the manufacturer is to maximize the profit of the entire supply chain. Why might such an objective be appropriate? As competition intensifies, companies are increasingly realizing that competitiveness lies beyond a single firm's ability to execute and its performance in isolation. In the global marketplace firm-to-firm competition is being replaced by supply-chain-to-supply-chain competition, and companies are coming to view their competitors not as individual firms but as supply chains. In the PC industry, direct to consumer vendors such as Dell have emerged with a cost structure that is significantly lower than that of the indirect vendors (i.e., companies like Compaq, IBM, and HP, which have multifirm distribution channels). Competitors like Dell have leveraged their cost advantage into a price advantage and have taken away significant market share from the indirect incumbents. As indirect vendors compete against more fully integrated supply chains, they may need to focus on maximizing the efficiency of their *entire* supply chain to ensure their long-term profitability and survival as manufacturers (Fortuna et al. 1997). In our model we use the integrated supply chain as a benchmark for the decentralized supply chain; we do not model the competitive dynamics of supply-chain-to-supply-chain competition.

Channel coordination can be achieved if the manufacturer can replicate the performance of the fully integrated company. To do so, the manufacturer has to use some pricing structure or policies to induce the retailer to choose the "right" order quantity (or stock level) that is optimal for the integrated firm. First, we introduce the following notation:

p_i = selling price at the market per unit in period $i = 1, 2$ (i.e., retail price);
w_1 = manufacturer's price to the retailer per unit in Period 1 (i.e., wholesale price);
c_1 = manufacturing cost per unit in Period 1 (i.e., marginal cost);
$\hat{c}_i$ = retailer's cost per unit in period $i = 1, 2$ (e.g., handling, administrative, and sales effort cost);
g_i = stock-out cost due to loss of good will per unit in period $i = 1, 2$;
h_i = holding cost at retailer per unit in period $i = 1, 2$ (h_2 can be negative, denoting salvage value);
ξ_i = random variable denoting the demand in period $i = 1, 2$;
$\Phi_i(\cdot)$ = distribution function of demand in period $i = 1, 2$;
μ_i = mean demand in period $i = 1, 2$;
Q = order quantity by the retailer at the beginning of Period 1;
x = quantity left for sales in Period 2;
γ = rebate per unit left unsold at the end of Period 1;
α = discount factor for costs in Period 2, $0 < \alpha \le 1$

We make the following assumptions.

Assumption A1. *$0 < c_1 < w_1 < p_1$, $0 \le h_1$, $0 \le g_2 \le g_1$, and $-(g_2 + h_2) < p_2 < p_1$.*

Assumption A2. *p_i, w_1, c_1, $\hat{c}_i$, g_i, h_i, $\Phi_i(\cdot)$, and α are exogenous; γ and Q are endogenous.*

Assumption A3. *$\phi_i(\cdot) > 0$ for its support $[0, \infty)$.*

Assumption A4. *No lump sum side payment is allowed.*

Further, order setup cost is negligible. All retailer orders can be filled (i.e., manufacturer capacity is infinite). Goodwill cost to the manufacturer of demand unmet by the retailer is negligible. Taken together, these assumptions restrict the analysis to the area of interest. They require that prices exceed cost (i.e., marginal cost as well as salvage value), the game clears at the end of the second period, demand distributions are exogenously determined, and two-part tariffs are not permitted. These assumptions are common in this literature (e.g., Pasternack 1985).

3.1. The Integrated Channel

We begin the analysis by considering an integrated channel. To solve the decision problem for the integrated company, we work backward starting with Period 2. At the end of Period 1, if the leftover stock is x, the company's expected profit $\pi_2(x)$ in the second period is given by

$$\begin{aligned}\pi_2(x) = {} & -\hat{c}_2 x + \int_0^x [p_2\xi_2 - h_2(x - \xi_2)]d\Phi_2(\xi_2) \\ & + \int_x^\infty [p_2 x - g_2(\xi_2 - x)]d\Phi_2(\xi_2) \\ = {} & -g_2\mu_2 + (p_2 + g_2 - \hat{c}_2)x \\ & - \int_0^x [(p_2 + g_2 + h_2)(x - \xi_2)]d\Phi_2(\xi_2).\end{aligned}$$

Define $\Gamma_i(x) := \int_0^x \xi_i d\Phi_i(\xi_i)$. Moving back to the first period, the expected profit to the integrated company when she orders Q is given by

$$\begin{aligned}\pi_1(Q) = {} & -(c_1 + \hat{c}_1)Q + \int_0^Q [p_1\xi_1 - h_1(Q - \xi_1) \\ & + \alpha\pi_2(Q - \xi_1)]d\Phi_1(\xi_1) \\ & + \int_Q^\infty [p_1 Q - g_1(\xi_1 - Q) + \alpha\pi_2(0)]d\Phi_1(\xi_1) \\ = {} & [p_1 + g_1 - c_1 - \hat{c}_1 \\ & - [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Phi_1(Q) \\ & - \alpha(p_2 + g_2 + h_2)\Phi_3(Q)]Q - g_1\mu_1 - \alpha g_2\mu_2 \\ & + [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Gamma_1(Q) \\ & + \alpha(p_2 + g_2 + h_2)\Gamma_3(Q), \qquad (1)\end{aligned}$$

where $\Phi_3(\cdot)$ is the distribution function of $\xi_3 = \xi_1 + \xi_2$, i.e., the convolution of $\phi_1(\cdot)$ and $\phi_2(\cdot)$. The first-order condition of the first-period optimization is given by

$$\begin{aligned}(d/dQ)\pi_1(Q) = {} & p_1 + g_1 - c_1 - \hat{c}_1 \\ & - [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Phi_1(Q) \\ & - \alpha(p_2 + g_2 + h_2)\Phi_3(Q) = 0. \qquad (2)\end{aligned}$$

It is easy to verify that the second-order condition is satisfied. Let $\bar{Q}$ be the Q that satisfies Equation (2), i.e., the optimal order quantity for the integrated company. Applying Equation (2) to (1), we have the expected profit to the integrated company as follows:

$$\begin{aligned}\pi_1(\bar{Q}) = {} & -g_1\mu_1 - \alpha g_2\mu_2 \\ & + [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Gamma_1(\bar{Q}) \\ & + \alpha(p_2 + g_2 + h_2)\Gamma_3(\bar{Q}).\end{aligned}$$

3.2. Independent Retailer with No Price Protection

We next consider the situation in which the manufacturer offers no price protection to the independent retailer. The manufacturer's wholesale price to the retailer is w_1 with $c_1 < w_1 < p_1$. The retailer orders Q and receives the amount in time for sales in Period 1. The retailer's expected profit $r_2(x)$ in the second period starting with the leftover stock x is

$$r_2(x) = -g_2\mu_2 + (p_2 + g_2 - \hat{c}_2)x - \int_0^x [(p_2 + g_2 + h_2)(x - \xi_2)]d\Phi_2(\xi_2).$$

Then, the first-period expected profit to the retailer is given by

$$\begin{aligned} r_1(Q) = [&p_1 + g_1 - w_1 - \hat{c}_1 \\ &- [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Phi_1(Q) \\ &- \alpha(p_2 + g_2 + h_2)\Phi_3(Q)]Q - g_1\mu_1 - \alpha g_2\mu_2 \\ &+ [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Gamma_1(Q) \\ &+ \alpha(p_2 + g_2 + h_2)\Gamma_3(Q). \end{aligned}$$

As in the case of the integrated channel, the retailer's optimal order quantity Q satisfies

$$\begin{aligned} &p_1 + g_1 - w_1 - \hat{c}_1 \\ &\quad - [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Phi_1(Q) \\ &\quad - \alpha(p_2 + g_2 + h_2)\Phi_3(Q) = 0. \end{aligned} \tag{3}$$

It is easy to show that the expected profit to the retailer without price protection is given by

$$\begin{aligned} r_1(Q) = &-g_1\mu_1 - \alpha g_2\mu_2 \\ &+ [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Gamma_1(Q) \\ &+ \alpha(p_2 + g_2 + h_2)\Gamma_3(Q). \end{aligned}$$

Then, we have the following theorem.

THEOREM 1. $Q < \bar{Q}$.

In other words, without price protection, the retailer's optimal order quantity is strictly less than the optimal quantity corresponding to the integrated solution. Note that this is a form of quantity distortion driven by double marginalization (Spengler 1950, Hirshleifer 1964). The proof of Theorem 1, as well as those of the other theorems and lemmas in the paper, is given in the appendix.

3.3. Independent Retailer with Price Protection

While in practice price protection is based on a decline in the wholesale price, in this section we consider a variant of price protection that is based on a decline in the retail price. Because there is only a single buying opportunity, a wholesale price decline does not exist, so it is not possible for the manufacturer to offer price protection in the normal sense. We mimic such a practice by allowing the manufacturer to offer price protection based on a retail price decline as a way for the manufacturer to subsidize the retailer when the retail price drops.

We consider the same setting as in §3.2, except that the manufacturer specifies a positive rebate γ per each unit that is unsold at the end of Period 1. We introduce a bounded rebate condition on the magnitude of this rebate: $\alpha\gamma \le p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)$. Consider an item that the retailer could have sold in Period 1. If the retailer did not sell the unit, but rather deliberately held on to it and sold it in the next period, then the loss to this retailer is $p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)$. Clearly, it would not be reasonable if the return from the rebate, $\alpha\gamma$, was greater than this cost from deliberately holding off the sale of an item by the retailer in Period 1. If this were the case, the retailer would gain from postponing sales deliberately. Hence, the bounded rebate condition should hold for reasonable levels of the rebate. We note that if $p_1 - p_2 \ge \gamma$, then the bounded rebate condition is automatically satisfied.

The second-period expected profit to the retailer with x in stock is

$$r_2'(x) = -g_2\mu_2 + (p_2 + g_2 + \gamma - \hat{c}_2)x + \int_0^x [(p_2 + g_2 + h_2)(x - \xi_2)]d\Phi_2(\xi_2).$$

The first-period expected profit to the retailer is

$$\begin{aligned} r_1'(Q) = &-(c_1 + \hat{c}_1)Q + \int_0^Q [p_1\xi_1 - h_1(Q - \xi_1) \\ &+ \alpha r_2'(Q - \xi_1)]d\Phi_1(\xi_1) \\ &+ \int_Q^\infty [p_1 Q - g_1(\xi_1 - Q) + \alpha r_2'(0)]d\Phi_1(\xi_1) \\ = [&p_1 + g_1 - c_1 - \hat{c}_1 - [p_1 + g_1 + h_1 \\ &- \alpha(p_2 + g_2 + \gamma - \hat{c}_2)]\Phi_1(Q) \end{aligned}$$

$$- \alpha(p_2 + g_2 + h_2)\Phi_3(Q)]Q - g_1\mu_1 - \alpha g_2\mu_2$$
$$+ [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 + \gamma - \hat{c}_2)]\Gamma_1(Q)$$
$$+ \alpha(p_2 + g_2 + h_2)\Gamma_3(Q).$$

As before, the optimal order quantity Q' satisfies

$$(d/dQ)r_1'(Q) = p_1 + g_1 - w_1 - \hat{c}_1 - [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 + \gamma - \hat{c}_2)]\Phi_1(Q') - \alpha(p_2 + g_2 + h_2)\Phi_3(Q') = 0. \tag{4}$$

Note that the second-order condition is guaranteed by the bounded rebate condition.

THEOREM 2. *Let*

$$\gamma^* = \frac{w_1^* - c_1}{\alpha\Phi_1(\bar{Q})}. \tag{5}$$

If γ^* satisfies the bounded rebate condition, then channel coordination is achieved.

Because $\bar{Q}$ is a function of both Period 1 and 2 parameters, γ^* is determined by parameters from both periods. Note from Theorem 2 that the amount of the rebate for channel coordination will be greater than or equal to the manufacturer's margin in Period 1. Note also that there exists a continuum of price/rebate pairs that achieve channel coordination. For a given w_1, there is a corresponding rebate γ^* that satisfies (5). If this γ^* satisfies the bounded rebate condition, then this (w_1, γ^*) pair achieves channel coordination. If w_1 is large compared to production cost c_1, the gap between $\bar{Q}$ and Q will be large, so a large rebate will be required for channel coordination. On the other hand, if w_1 is close to c_1, then the gap between $\bar{Q}$ and Q is small, and a small rebate will be sufficient. In the extreme case, if $w_1 = c_1$, the retailer's problem collapses to that of the integrated company, so no rebate is needed.

If channel coordination is achieved, the expected profits to the supply chain (π), the retailer (r^*), and the manufacturer (m^*) are, respectively, given by

$$\pi = -g_1\mu_1 - \alpha g_2\mu_2 + [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Gamma_1(\bar{Q}) + \alpha(p_2 + g_2 + h_2)\Gamma_3(\bar{Q}), \tag{6}$$

$$r^* = -g_1\mu_1 - \alpha g_2\mu_2 + [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 + \gamma^* - \hat{c}_2)]\Gamma_1(\bar{Q}) + \alpha(p_2 + g_2 + h_2)\Gamma_3(\bar{Q}), \tag{7}$$

$$m^* = \alpha\gamma^*\Gamma_1(\bar{Q}). \tag{8}$$

Equations (6) to (8) demonstrate how the total profit is split between the two parties. Note first that total supply chain profit and order quantity $\bar{Q}$ are fixed and independent of w_1 and γ^*, as far as channel coordination is achieved. As w_1 increases, the optimal rebate γ^* for channel coordination increases, and so does the manufacturer's share of the profit at the expense of the retailer's profit share. Rather ironically, therefore, the higher the rebate, the higher the profit to the manufacturer (from Equation (8)). Let $\bar{\gamma}^*$ be the value of γ^* such that $m^* = \pi$. Then, values of w_1 beyond $\bar{w}_1$ (the wholesale price corresponding to $\bar{\gamma}^*$) would be difficult to implement because they will make the retailer worse off as a result of coordination. If the manufacturer has monopoly power over the retailer, $\bar{\gamma}^*$ satisfies the bounded rebate condition, and $\bar{w}_1 < p_1$, then channel coordination will be achieved, and the manufacturer will take all the supply chain profit equivalent to the integrated channel while the retailer will get zero profit. This represents the first-best solution $(\bar{w}_1, \bar{\gamma}^*)$ to the manufacturer. On the other extreme, if w_1 is equal to c_1, then $\gamma^* = 0$ and the manufacturer will make zero profit. This will be a plausible scenario to the monopolistic manufacturer only if the manufacturer can "sell the company" to the retailer at a fixed lump sum—i.e., a franchise arrangement.

4. The Two-Buying-Opportunity Model

In this section we consider a situation in which the retailer has *two* buying opportunities, and the *wholesale* price and manufacturing cost are both declining in time. The retailer's problem is how much to order at the two buying opportunities, when the retailer has the option to buy later at a lower unit cost.

We first assume that wholesale prices are given exogenously. In addition to the notation from §3, let w_2 and c_2 be the second period analogs of w_1 and c_1.

We modify the assumptions in §3 by replacing Assumption A1 with Assumption A1′.

ASSUMPTION A1′. *$0 < c_2 < c_1 < w_1 < p_1$, $0 \le g_1$, $0 \le h_1$, $-(g_2 + h_2) < c_2 < w_2 < p_2$, and $w_2 < w_1$.*

In Assumption A1′ we restrict our attention to situations in which the wholesale price is declining over time because price protection is meaningful only in this context. The assumption of decreasing manufacturing cost is reasonable because of decreasing material costs (wholesale prices of components are likely to decrease) and potential learning effects. Both of these assumptions are borne out empirically in the PC industry where microprocessors, memory chips, and hard disk prices all decline over time (Gotlieb 1985).

Let $L_i(y)$ = expected retailer penalty and holding cost in period i ($i = 1, 2$), given that y is available to satisfy demand in that period. Hence,

$$L_i(y) = (p_i + g_i)E[(\xi_i - y)^+] + h_iE[(y - \xi_i)^+].$$

Clearly $L_i(y)$ is convex in y. As in §3, we assume the retailer's initial stock is zero.

4.1. The Integrated Channel

Let Π_1 = the integrated channel's total expected profit over the two periods; and $\Pi_2(x)$ = the integrated channel's expected profit in Period 2, given that the retailer's initial stock (before purchase) in Period 2 is x. The integrated channel's problem is described in the following dynamic program:

$$\Pi_1 = \operatorname*{Max}_{y\ge 0}\{p_1\mu_1 - (c_1 + \hat{c}_1)y - L_1(y) + \alpha E[\Pi_2((y - \xi_1)^+)]\}, \tag{9}$$

$$\Pi_2(x) = \operatorname*{Max}_{y\ge x}\{p_2\mu_2 - c_2(y - x) - \hat{c}_2 y - L_2(y)\}.$$

It is well-known that an order-up-to policy is optimal for (9). Let

$$\bar{H}_1(y) = p_1\mu_1 - (c_1 + \hat{c}_1)y - L_1(y) + \alpha E[\Pi_2((y - \xi_1)^+)]$$

and

$$\bar{H}_2(y) = -(c_2 + \hat{c}_2)y - L_2(y).$$

Let $\bar{S}_1$ and $\bar{S}_2$ be the values that maximize $\bar{H}_1$ and $\bar{H}_2$ respectively. Then the optimal order-up-to quantities for the integrated company in the first and second periods are $\bar{S}_1$ and $\bar{S}_2$, respectively. Solving the Period 2 problem gives

$$\bar{S}_2 = \Phi_2^{-1}\left(\frac{p_2 + g_2 - c_2 - \hat{c}_2}{p_2 + g_2 + h_2}\right).$$

Define

$$\bar{S}_0 := \Phi_1^{-1}\left(\frac{p_1 + g_1 - c_1 - \hat{c}_1}{p_1 + g_1 + h_1 - \alpha c_2}\right).$$

The quantity $\bar{S}_0$ is the myopic order-up-to quantity in Period 1 when each unit unsold at the end of Period 1 has value αc_2. This holds, for example, when each unit ordered and sold in Period 1 will be "replaced" by a unit ordered in Period 2.

LEMMA 1. *The optimal order-up-to quantity $\bar{S}_1$ for the integrated company in Period 1 is given by the following: If $\bar{S}_2 \ge \bar{S}_0$, then $\bar{S}_1 = \bar{S}_0$; if $\bar{S}_2 < \bar{S}_0$, then $\bar{S}_1$ satisfies*

$$p_1 + g_1 - c_1 - \hat{c}_1 - (p_1 + g_1 + h_1 - \alpha c_2)\Phi_1(\bar{S}_1) + \alpha\left[(p_2 + g_2 - c_2 - \hat{c}_2)\Phi_1(\bar{S}_1 - \bar{S}_2) - (p_2 + g_2 + h_2)\int_0^{\bar{S}_1-\bar{S}_2}\Phi_2(\bar{S}_1 - \xi_1)\,d\Phi_1(\xi_1)\right] = 0, \tag{10}$$

and it holds that $\bar{S}_2 < \bar{S}_1 < \bar{S}_0$.

Applying (10) to (9), the expected profit to the integrated company is

$$\Pi_1 = \begin{cases} -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + (p_1 + g_1 + h_1 - \alpha c_2)\Gamma_1(\bar{S}_0) \\ \quad + \alpha(p_2 + g_2 + h_2)\Gamma_2(\bar{S}_2) & \text{if } \bar{S}_2 \ge \bar{S}_0, \\ -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + (p_1 + g_1 + h_1 - \alpha c_2)\Gamma_1(\bar{S}_1) \\ \quad - \alpha(p_2 + g_2 - c_2 - \hat{c}_2)\Gamma_1(\bar{S}_1 - \bar{S}_2) \\ \quad + \alpha(p_2 + g_2 + h_2) \\ \quad \times \left[\Gamma_2(\bar{S}_2) + \int_0^{\bar{S}_1\bar{S}_2}\xi_1\Phi_2(\bar{S}_1 - \xi_1)\,d\Phi_1(\xi_1) \right. \\ \quad \left. + \int_{\bar{S}_2}^{\bar{S}_1}\xi_2\Phi_1(\bar{S}_1 - \xi_2)\,d\Phi_2(\xi_2)\right] & \text{if } \bar{S}_2 < \bar{S}_0. \end{cases}$$

4.2. Independent Retailer with No Price Protection The retailer's problem with no price protection is described in the following dynamic program:

$$R_1 = \operatorname*{Max}_{y \geq 0}\{p_1\mu_1 - (w_1 + \hat{c}_1)y - L_1(y) + \alpha E[R_2((y - \xi_1)^+)]\}, \tag{11}$$

$$R_2(x) = \operatorname*{Max}_{y \geq x}\{p_2\mu_2 - w_2(y - x) - \hat{c}_2 y - L_2(y)\}.$$

Again, an order-up-to policy is optimal for (11). Let

$$H_1(y) = p_1\mu_1 - (w_1 + \hat{c}_1)y - L_1(y) + \alpha E[R_2((y - \xi_1)^+)]$$

and

$$H_2(y) = -(w_2 + \hat{c}_2)y - L_2(y).$$

Let S_1 and S_2 be the values that maximize H_1 and H_2, respectively, which gives the optimal order-up-to quantities for the retailer with no price protection in the first and second periods, respectively. In §4.3 we observe that the optimal order-up-to quantity for the retailer in the second period with price protection is also S_2. Maximizing H_2 gives

$$S_2 = \Phi_2^{-1}\left(\frac{p_2 + g_2 - w_2 - \hat{c}_2}{p_2 + g_2 + h_2}\right).$$

Because $w_2 > c_2$, therefore $\bar{S}_2 > S_2$, i.e., the optimal order-up-to quantity for the integrated company in Period 2 is strictly greater than the optimal order-up-to quantity for the retailer in Period 2 with price protection or with no price protection.

The analogous result to Lemma 1 for the retailer with no price protection is given in Lemma 2. Define

$$S_0 := \Phi_1^{-1}\left(\frac{p_1 + g_1 - w_1 - \hat{c}_1}{p_1 + g_1 + h_1 - \alpha w_2}\right).$$

LEMMA 2. *The optimal order-up-to quantity S_1 for the retailer in Period* 1 *under no price protection is given by the following*: *If $S_2 \geq S_0$, then $S_1 = S_0$; if $S_2 < S_0$, then S_1 satisfies*

$$p_1 + g_1 - w_1 - \hat{c}_1 - (p_1 + g_1 + h_1 - \alpha w_2)\Phi_1(S_1) + \alpha\left[(p_2 + g_2 - w_2 - \hat{c}_2)\Phi_1(S_1 - S_2) - (p_2 + g_2 + h_2)\int_0^{S_1 - S_2}\Phi_2(S_1 - \xi_1)\,d\Phi_1(\xi_1)\right] = 0,$$

and it also holds that $S_2 < S_1 < S_0$.

It is easy to show that the expected profit to the retailer without price protection is given by

$$R_1 = \begin{cases} -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + (p_1 + g_1 + h_1 - \alpha w_2)\Gamma_1(S_0) \\ \quad + \alpha(p_2 + g_2 + h_2)\Gamma_2(S_2) & \text{if } S_2 \geq S_0, \\ -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + (p_1 + g_1 + h_1 - \alpha w_2)\Gamma_1(S_1) \\ \quad - \alpha(p_2 + g_2 - w_2 - \hat{c}_2)\Gamma_1(S_1 - S_2) \\ \quad + \alpha(p_2 + g_2 + h_2) \\ \quad \times \left[\Gamma_2(S_2) + \displaystyle\int_0^{S_1 - S_2}\xi_1\Phi_2(S_1 - \xi_1)\,d\Phi_1(\xi_1)\right. \\ \quad \left. + \displaystyle\int_{S_2}^{S_1}\xi_2\Phi_1(S_1 - \xi_2)\,d\Phi_2(\xi_2)\right] & \text{if } S_2 < S_0. \end{cases}$$

The expected manufacturer profit with no price protection is

$$M = (w_1 - c_1)S_1 + \alpha(w_2 - c_2)E[(S_2 - (S_1 - \xi_1)^+)^+].$$

4.3. Independent Retailer with Price Protection In §3 we explored the use of price protection initiated by a decline in the retail price. If retail prices are declining, in the two-buying-opportunity context we could construct a price protection policy where the payment is a function of the decline in the retail price. However, in practice, price protection is a payment based on a decline in the *wholesale* price, so we model the policy accordingly.

Specifically, at the end of the first period, the retailer receives a price protection credit given by the amount of the wholesale price drop multiplied by the price protection magnitude parameter β for each unit of unsold inventory on hand. Thus, after discounting, the present value of the credit is $\alpha\beta(w_1 - w_2)$. Hence, price protection policies have the effect of lowering the retailer's overage cost in the first period. We assume that the price protection magnitude parameter satisfies $0 < \beta \leq 1$. If $\beta = 1$, the policy is full price protection; if $0 < \beta < 1$, the policy is partial price protection, while $\beta = 0$ corresponds to the case of no price protection.

Let $L'_1(y)$ = expected retailer penalty cost, holding cost, and *price protection credit* "cost" with magnitude parameter β in Period 1, given that y is available to satisfy demand in that period. Hence,

$$L'(y) = (p_1 + g_1)E[(\xi_1 - y)^+] + (h_1 - \alpha\beta(w_1 - w_2))E[(y - \xi_1)^+].$$

Clearly $L'_1(y)$ is convex in y. Note that $L'_1(y) < L_1(y)$ for all y.

The retailer's problem is described in the following dynamic program:

$$R'_1 = \max_{y \geq 0}\{p_1\mu_1 - (w_1 + \hat{c}_1)y - L'_1(y) + \alpha E[R_2((y - \xi_1)^+)]\},$$

$$R_2(x) = \max_{y \geq x}\{p_2\mu_2 - w_2(y - x) - \hat{c}_2 y - L_2(y)\}.$$

Let

$$H'_1(y) = p_1\mu_1 - (w_1 + \hat{c}_1)y - L'_1(y) + \alpha E[R_2((y - \xi_1)^+)].$$

Let S'_1 be the value that maximizes H'_1. The optimal order-up-to quantities for the retailer with price protection in the first and second periods are S'_1 and S_2, respectively. Recall that the optimal order-up-to quantity for the retailer in the second period with price protection is also S_2.

For a fixed set of wholesale prices, the expected retailer profit under price protection is strictly greater than the expected retailer profit under no price protection (i.e., $R'_1 > R_1$). To see this, note $H'_1(y)$ (or $H_1(y)$, respectively) is the retailer's expected profit under price protection (or no price protection, respectively) and order-up-to quantities y and S_2 in the first and second periods, respectively. Thus, $H'_1(S'_1) = R'_1$ and $H_1(S_1) = R_1$. Clearly $H'_1(S'_1) > H'_1(S_1) > H_1(S_1)$.

Lemma 3 presents the analogous result for the first-period order quantity in the price protection case. Define

$$S'_0 := \Phi_1^{-1}\left(\frac{p_1 + g_1 - w_1 - \hat{c}_1}{p_1 + g_1 + h_1 - \alpha(\beta w_1 + (1 - \beta)w_2)}\right).$$

Note that $S'_0 > S_0$.

LEMMA 3. *The optimal order-up-to quantity S'_1 for the retailer in Period 1 under price protection is given by the following: If $S_2 \geq S'_0$, then $S'_1 = S'_0$; if $S_2 < S'_0$, then S'_1 satisfies*

$$p_1 + g_1 - w_1 - \hat{c}_1 - [p_1 + g_1 + h_1 - \alpha(\beta w_1 + (1 - \beta)w_2)]\Phi_1(S'_1) + \alpha\left[(p_2 + g_2 - w_2 - \hat{c}_2)\Phi_1(S'_1 - S_2) - (p_2 + g_2 + h_2)\int_0^{S'_1 - S_2} \Phi_2(S'_1 - \xi_1)\,d\Phi_1(\xi_1)\right] = 0,$$

and it also holds that $S_2 < S'_1 < S'_0$.

THEOREM 3. $S'_1 > S_1$.

In other words, the optimal order-up-to quantity for the retailer in Period 1 under price protection is strictly greater than that under no price protection. Let Q_i and Q'_i denote the order quantity in period i, when the optimal policy is followed by the retailer under no price protection and under price protection, respectively. Note Q_2 and Q'_2 are random variables. We have the following corollary, where relationships (b) and (c) hold pointwise for the same realization of demand in Period 1.

COROLLARY.
(*a*) $Q'_1 > Q_1$.
(*b*) $Q'_2 \leq Q_2$.
(*c*) $Q'_1 + Q'_2 \geq Q_1 + Q_2$.

Hence, while price protection results in a larger order quantity in Period 1 but a smaller (or equal) quantity in Period 2, the overall effect is that the total ordered in both periods is larger (or equal). In summary, price protection policies have two effects on retailer order quantities: (1) They shift orders forward in time, and (2) they increase the total amount ordered. A consequence of the corollary is that Q_2 dominates Q'_2 under first-order stochastic dominance, and $Q'_1 + Q'_2$ dominates $Q_1 + Q_2$

under first-order stochastic dominance. The expected manufacturer profit with price protection is

$$M' = (w_1 - c_1)S'_1 - \alpha[\beta(w_1 - w_2)E[(S'_1 - \xi_1)^+] - (w_2 - c_2)E[(S_2 - (S'_1 - \xi_1)^+)^+]].$$

In the single-buying-opportunity case of §3, we were able to show the optimal order quantity for the integrated company in Period 1 is greater than the optimal order quantity for the retailer in Period 1 under no price protection (i.e., $\bar{Q} > Q$). One might therefore conjecture that, because of double marginalization, an analogous result would hold in Period 1 when we consider the two-buying-opportunity case. This conjecture does not hold: The optimal order-up-to quantity in Period 1 for the integrated company may be less than, greater than, or equal to the optimal order-up-to quantity in Period 1 for the retailer under no price protection (i.e., $\bar{S}_1 < S_1$, $\bar{S}_1 > S_1$, or $\bar{S}_1 = S_1$). The total expected optimal order quantity for the total chain under centralized decision making (sum of both periods) may also be less than, greater than, or equal to the total optimal order quantity for the retailer under no price protection. Examples can easily be constructed for each case. We may have $\bar{S}_1 < S_1$ if, for example, retailer margins are decreasing in time while total chain margins are increasing.

Given an arbitrary fixed set of wholesale prices in the two periods, price protection cannot guarantee channel coordination. This holds for two reasons. First, we have $\bar{S}_2 > S_2$. Because price protection does not influence the second-period order-up-to quantity, price protection cannot guarantee that the optimal system-wide order in Period 2 will be induced. Second, we may have $S_1 > \bar{S}_1$. Because $S'_1 > S_1$, price protection cannot guarantee that the optimal system-wide order in Period 1 will be induced. For either of these two reasons, price protection may fail to achieve channel coordination.

Interestingly, if we allow the manufacturer to set both the price protection credit and the wholesale prices, channel coordination can be restored. We relax the assumption that the wholesale price has to *strictly* exceed the manufacturing cost in Period 2 and assume that the manufacturer commits at the start of Period 1 to his second period wholesale price.

Let

$$\beta_k = \frac{w_1 - c_1}{\alpha(w_1 - c_2)\Phi_1(\bar{S}_k)}, \quad k = 0, 1.$$

If we set $w_2 = c_2$, then $\beta_k > 0$ if and only if $w_1 > c_1$, and $\beta_k \leq 1$ if and only if

$$w_1 \leq \frac{c_1 - \alpha c_2 \Phi_1(\bar{S}_k)}{1 - \alpha\Phi_1(\bar{S}_k)}.$$

Because $c_2 < c_1$, we have

$$c_1 < \frac{c_1 - \alpha c_2 \Phi_1(\bar{S}_k)}{1 - \alpha\Phi_1(\bar{S}_k)}.$$

Thus, it is possible to select w_1 such that

$$c_1 < w_1 \leq \frac{c_1 - \alpha c_2 \Phi_1(\bar{S}_k)}{1 - \alpha\Phi_1(\bar{S}_k)}$$

and $0 < \beta_k \leq 1$.

THEOREM 4. *The following policy of* (β^*, w_1^*, w_2^*) *achieves channel coordination: Set* $w_2^* = c_2$. *If* $\bar{S}_2 \geq \bar{S}_0$, *then set* $\beta^* = \beta_0$ *and set* w_1^* *such that*

$$c_1 < w_1^* \leq \frac{c_1 - \alpha c_2 \Phi_1(\bar{S}_0)}{1 - \alpha\Phi_1(\bar{S}_0)}.$$

If $\bar{S}_2 < \bar{S}_0$, *then set* $\beta^* = \beta_1$ *and set* w_1^* *such that*

$$c_1 < w_1^* \leq \frac{c_1 - \alpha c_2 \Phi_1(\bar{S}_1)}{1 - \alpha\Phi_1(\bar{S}_1)}.$$

The policy in Theorem 4 represents one of a potentially larger set of policies that may achieve channel coordination. Rather than attempt to describe exhaustively all possible policies that may coordinate the channel, we focus on the structural results stemming from this policy. If channel coordination is achieved, the expected profits to the supply chain (Π), the retailer (R^*), and the manufacturer (M^*) are respectively given by:

$$\Pi = \begin{cases} -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + (p_1 + g_1 + h_1 - \alpha c_2)\Gamma_1(\bar{S}_0) \\ \quad + \alpha(p_2 + g_2 + h_2)\Gamma_2(\bar{S}_2) & \text{if } \bar{S}_2 \geq \bar{S}_0, \\ -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + (p_1 + g_1 + h_1 - \alpha c_2)\Gamma_1(\bar{S}_1) \\ \quad - \alpha(p_2 + g_2 - c_2 - \hat{c}_2)\Gamma_1(\bar{S}_1 - \bar{S}_2) \\ \quad + \alpha(p_2 + g_2 + h_2) \\ \quad \times \left[\Gamma_2(\bar{S}_2) + \int_0^{\bar{S}_1 - \bar{S}_2} \xi_1 \Phi_2(\bar{S}_1 - \xi_1) d\Phi_1(\xi_1) \right. \\ \quad \left. + \int_{\bar{S}_2}^{\bar{S}_1} \xi_2 \Phi_1(\bar{S}_1 - \xi_2) d\Phi_2(\xi_2) \right] & \text{if } \bar{S}_2 < \bar{S}_0. \end{cases} \tag{12}$$

$$R^* = \begin{cases} -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + \left(p_1 + g_1 + h_1 - \alpha c_2 - \dfrac{w_1^* - c_1}{\Phi_1(\bar{S}_0)}\right)\Gamma_1(\bar{S}_0) \\ \quad + \alpha(p_2 + g_2 + h_2)\Gamma_2(\bar{S}_2) & \text{if } \bar{S}_2 \geq \bar{S}_0, \\ -g_1\mu_1 - \alpha g_2\mu_2 \\ \quad + \left(p_1 + g_1 + h_1 - \alpha c_2 - \dfrac{w_1^* - c_1}{\Phi_1(\bar{S}_1)}\right)\Gamma_1(\bar{S}_1) \\ \quad - \alpha(p_2 + g_2 - c_2 - \hat{c}_2)\Gamma_1(\bar{S}_1 - \bar{S}_2) \\ \quad + \alpha(p_2 + g_2 + h_2) \\ \quad \times \left[\Gamma_2(\bar{S}_2) + \int_0^{\bar{S}_1 - \bar{S}_2} \xi_1 \Phi_2(\bar{S}_1 - \xi_1) d\Phi_1(\xi_1) \right. \\ \quad \left. + \int_{\bar{S}_1}^{\bar{S}_2} \xi_2 \Phi_1(\bar{S}_1 - \xi_2) d\Phi_2(\xi_2) \right] & \text{if } \bar{S}_2 < \bar{S}_0. \end{cases} \tag{13}$$

$$M^* = \begin{cases} \dfrac{w_1^* - c_1}{\Phi_1(\bar{S}_0)} \Gamma_1(\bar{S}_0) & \text{if } \bar{S}_2 \geq \bar{S}_0, \\ \dfrac{w_1^* - c_1}{\Phi_1(\bar{S}_1)} \Gamma_1(\bar{S}_1) & \text{if } \bar{S}_2 < \bar{S}_0. \end{cases} \tag{14}$$

There exists a continuum of prices/rebate pairs that achieve channel coordination. Each (β^*, w_1^*, w_2^*) triplet achieves channel coordination. Equations (12) to (14) demonstrate how the total profit is split between the two parties. As the manufacturer chooses a large w_1^*, the optimal rebate β^* for channel coordination increases, and so does his share of the profit at the expense of the retailer's profit share. As in the one-buying-opportunity case, the higher the rebate, the higher the profit to the manufacturer. On the other extreme, if w_1^* is chosen to be c_1, then $\beta^* = 0$ and the manufacturer will make zero profit.

To what extent will the channel coordination result hold in the context of multiple retailers? If the retailers are identical, then the channel coordination result will hold trivially: The same channel coordinating policy can be used with each retailer. If retailers are heterogeneous, then a single price protection and wholesale price policy is unlikely to guarantee coordination (because the coordinating price protection credit is a function of each retailer's parameters and demand distribution). It is possible that under certain conditions (e.g., limited heterogeneity of retailers in terms of demand variability, sales effort cost, holding cost, salvage value, etc.) channel coordination could be achieved by a single wholesale price but different price protection credits. Despite price protection policies that officially claim to be the same across retailers, the effective policies in force may in fact differ. Because enforcement of price protection is "lax at best," differential enforcement may effectively result in differing effective price protection policies.

It is also possible that distinct wholesale price and price protection credit combinations would be required to achieve channel coordination. If this were the case, the manufacturer could offer a menu of wholesale price and price protection credit combinations to its retailers. For example, IBM offered a 2.5% reduction in its wholesale price to resellers that accepted 15 rather than 30 days of price protection (O'Heir 1997). Generally, when faced with a menu, retailers who are more efficient—for example in forecasting and marketing (and hence face lower demand variability)—will opt for the price break, while less efficient retailers will opt for more insurance through generous price protection terms. However, incentive compatibility issues may hamper the effectiveness of a menu approach in achieving coordination in a multiretailer environment.

We could consider a setting in which there are multiple manufacturers, each offering its own price protection policy. This is similar to research in which a retailer has a choice of suppliers who differ in lead time and cost (cf. Fisher and Raman 1996). This extension suggests that retailers in declining price environments should evaluate manufacturers not only in terms of factors like cost and lead time, but also in terms of their price protection policies.

Table 1 Benefits and Costs of Price Protection Policies

	Retailer	Manufacturer	Total Chain
Benefits	• Incremental sales • Price protection credit	• Incremental sales • Time value of money from earlier sales of product	• Incremental sales
Costs	• Holding cost for additional unsold units • Time value of money from earlier purchase of product	• Higher production cost from increased production in Period 1 • Price protection credit cost	• Higher production cost from increased production in Period 1 • Holding cost for additional unsold units

4.4. Managerial Implications

The financial effects of price protection on the retailer, manufacturer, and total chain over a two-period time horizon are described in Table 1. Price protection can bring benefits to the retailer by the price protection credit itself as well as the prospect of incremental sales to end customers. If the retailer margin is decreasing over time, then the positive effect of price protection on the retailer's profit will be particularly marked. On the other hand, the retailer incurs the holding cost for the additional unsold units. This is particularly pronounced in the first period, although it may carry over to the second period. The retailer also incurs the cost for the time value of money associated with the incremental order quantity in Period 1; the manufacturer will correspondingly gain the time value of money associated with this amount.

The manufacturer benefits by the incremental sales to the retailer. Because $Q_1' > Q_1$ and $Q_2' \leq Q_2$, the manufacturer will particularly benefit if its margins are decreasing over time. However, if manufacturer margins are increasing over time, then it is not clear whether the manufacturer will benefit from this shift in sales over the two periods. Similarly, if production cost is decreasing in time, then the manufacturer incurs a higher production cost because it has to produce more units at the higher cost and fewer units at the lower cost. In most industry contexts, however, we would expect manufacturer margins to be decreasing over time.

4.5. Numerical Example

In this section we examine the role of price protection in the economics of the current PC market. Over the first year of a product life cycle, the average price of a desktop PC system typically declines 50%–58%. The average selling price in the first nine months of the life cycle is 38%–39% higher than the average selling price in the subsequent nine months (*PC Today* 1996, 1997, 1998). Manufacturer component prices drop 25%–30% per year on average (Fortuna et al. 1997). Component costs account for 80%–90% of all product costs for one PC manufacturer (Kurawarwala and Matsuo 1996). Manufacturer gross margins on PCs are 17%–19% (Zlotnikov et al. 1998). Based on a nine-company industry sample, reseller and distributor gross margins range between 5.2% and 11.4% with an average of 8.1% (Bakar et al. 1998). Standard terms in the PC industry for resellers and distributors are net 30 days. Thus, channel players who carry 30 days of inventory essentially do not bear the financial cost of holding inventory. Estimates of channel players' inventories range from 24 (Hansell 1998) to 30 (Fortuna et al. 1997) to 49 (Bakar et al. 1998) days.

We use the following example to illustrate the impact of price protection. We assume an 18-month product life cycle, a price drop at the mid-life (nine month) mark, 40% of revenues are earned in the first half of a product life cycle, goodwill cost equals half the retail price, retailer cost and holding cost are negligible, inventory can be salvaged at 40% of the second-period wholesale price, and the annual discount rate is 20%. The following parameters are consistent with these assumptions and the economics of the industry as described above: $p_1 = 100$, $g_1 = 50$, $w_1 = 91$, $c_1 = 65.5$, $h_1 = 0$, $p_2 = 62$, $g_2 = 31$, $w_2 = 57.4$, $c_2 = 50.8$, $h_2 = -23$, and $\alpha = 0.87$. Further, let us suppose that demand is normally distributed with mean 40, 60 and variance 50, 150 in the first and second periods, respectively. The assumptions above were validated by executives at a major PC manufacturer (Billington 1998).

In this example, we applied Mathematica to obtain $\bar{S}_1 = 45.9$, $\bar{S}_2 = 63.2$, and $\Pi_1 = 1466.7$. Under no price protection, $S_1 = 41.6$, $S_2 = 60.3$, $R_1 = 27.5$, and $M = 1385.7$. Under full price protection, i.e., $\beta = 1$, S_1'

$= 46.8$, $S_2 = 60.3$, $R'_1 = 177.3$, and $M' = 1279.3$. Thus, in this example, both the retailer and the total chain are better off under full price protection relative to no price protection, but the manufacturer is worse off. An examination of partial price protection policies indicates that for all $0 < \beta \leq 1$, the total chain and retailer always benefit, but the manufacturer is always hurt by price protection. Further, the amount of benefit (cost) to the retailer (manufacturer) is increasing in β. If manufacturers are primarily concerned with maximizing their own profits, this analysis may offer a partial explanation as to why manufacturers have made their price protection policies more restrictive. While a continuum of channel coordinating policies exist, an example channel coordinating policy is $w_1^* = 98$, $w_2^* = 50.8$, and $\beta^* = 0.99$, which leads to profits $R^* = 247.6$ and $M^* = 1219.1$. In this example, the manufacturer and retailer could explore the use of mechanisms, such as a side payment, to ensure that both parties would be better off as a result of price protection.

5. Conclusion

This paper shows that supply chain coordination can be achieved in markets characterized by price declines and product obsolescence. The coordination is achieved through price protection—a practice that is controversial and largely misunderstood. In the long lead time (one-buying-opportunity) case, the basic intuition is that price protection reduces retailer inventory risks in turbulent markets while increasing profit to the manufacturer. In the short lead time (two-buying-opportunities) case, price protection alone is not sufficient to coordinate the channel. However, when the price protection credit is used in conjunction with the appropriate set of wholesale prices, channel coordination is restored. In both cases, the terms of the price protection policy determine the relative sharing of the benefits between the manufacturer and the retailer.

The model we have used in this paper has its limitations. One critical assumption of the model is that the retail market prices are fixed for both periods and independent of the wholesale prices and rebates set by the manufacturer. This assumption may hold only if the retail sector is competitive. The interaction between the wholesale price/rebate and the retail market price is a new dimension that needs a significant new setup, and we hope future work will follow.

Moreover, it is generally perceived that price protection can delay new product introduction. A manufacturer may be pressured to postpone the introduction of the new product to minimize the rebate payment to the retailers. The elimination of such a delay is an important competitive advantage for a manufacturer like Dell, who sells mostly by mail order and thus does not have to worry about retail inventories. Unfortunately, our model is silent about the negative impact of price protection on new product introduction. In particular, as consumer direct sales increasingly becomes a dominant channel of distribution in the PC industry, this consideration may have a different implication to the analysis provided in the paper. We hope that this also will be followed up by future research.

Appendix

Proof of Theorem 1. Compare Equations (2) and (3). These two equations may be rewritten as

$$\psi(\bar{Q}) = p_1 + g_1 - c_1 - \hat{c}_1$$

and

$$\psi(Q) = p_1 + g_1 - w_1 - \hat{c}_1,$$

where

$$\psi(Q) := [p_1 + g_1 + h_1 - \alpha(p_2 + g_2 - \hat{c}_2)]\Phi_1(Q) + \alpha(p_2 + g_2 + h_2)\Phi_3(Q).$$

Because $\psi(\cdot)$ is strictly increasing and $w_1 > c_1$, we have the desired result. □

Proof of Theorem 2. To ensure $Q' = \bar{Q}$, Equations (2) and (4) should coincide. This leads to the theorem. □

Proof of Lemma 1. It is straightforward to show $\bar{H}_1(y)$ is concave. For $y \leq \bar{S}_2$:

$$\begin{aligned}\bar{H}_1(y) = {} & p_1\mu_1 - (c_1 + \hat{c}_1)y - (p_1 + g_1)E[(\xi_1 - y)^+] \\ & - h_1E[(y - \xi_1)^+] + \alpha[p_2\mu_2 - c_2(\bar{S}_2 - E[(y - \xi_1)^+)] \\ & - \hat{c}_2\bar{S}_2 - (p_2 + g_2)E[(\xi_2 - \bar{S}_2)^+] \\ & - h_2E[(\bar{S}_2 - \xi_2)^+]].\end{aligned}$$

The first-order condition is

$$(d/dy)\bar{H}_1(y) = p_1 + g_1 - c_1 - \hat{c}_1 - (p_1 + g_1 + h_1 - \alpha c_2)\Phi_1(y) = 0.$$

For $y > \bar{S}_2$:

$$\bar{H}_1(y) = p_1\mu_1 - (c_1 + \hat{c}_1)y - (p_1 + g_1)E[(\xi_1 - y)^+] - h_1E[(y - \xi_1)^+] + \alpha\Bigg[\int_0^{y-\bar{S}_2}[p_2\mu_2 - \hat{c}_2(y - \xi_1) - (p_2 + g_2)E[(\xi_2 - y + \xi_1)^+] - h_2E[(y - \xi_1 - \xi_2)^+]]d\Phi_1(\xi_1) + \int_{y-\bar{S}_2}^{\infty}[p_2\mu_2 - c_2[\bar{S}_2 - (y - \xi_1)^+] - \hat{c}_2\bar{S}_2 - (p_2 + g_2)E[(\xi_2 - \bar{S}_2)^+] - h_2E[(\bar{S}_2 - \xi_2)^+]]d\Phi_1(\xi_1)\Bigg],$$

and

$$(d/dy)\bar{H}_1(y) = p_1 + g_1 - c_1 - \hat{c}_1 - (p_1 + g_1 + h_1 - \alpha c_2)\Phi_1(y) + \alpha\int_0^{y-\bar{S}_2}[(p_2 + g_2 - c_2 - \hat{c}_2) - (p_2 + g_2 + h_2)\Phi_2(y - \xi_1)]d\Phi_1(\xi_1).$$

Clearly,

$$\int_0^{y-\bar{S}_2}[p_2 + g_2 - c_2 - \hat{c}_2 - (p_2 + g_2 + h_2)\Phi_2(y - \xi_1)]d\Phi_1(\xi_1) < 0.$$

Thus $(d/dy)\bar{H}_1(y) \le 0$ for all $y > \bar{S}_2$ where $\bar{S}_2 \ge \bar{S}_0$. Thus, if $\bar{S}_2 \ge \bar{S}_0$, then $\bar{S}_1 = \bar{S}_0$. Next, suppose $\bar{S}_0 > \bar{S}_2$. Note that $(d/dy)\bar{H}_1(\bar{S}_2) > 0$ and $(d/dy)\bar{H}_1(\bar{S}_0) < 0$. Hence, $\bar{S}_1$ satisfies (10), and $\bar{S}_2 < \bar{S}_1 < \bar{S}_0$. □

Proof of Theorem 3. Note that

$$H_1'(y) = H_1(y) + \alpha\beta(w_1 - w_2)E[(y - \xi_1)^+].$$

Thus,

$$(d/dy)H_1'(y) = (d/dy)H_1(y) + \alpha\beta(w_1 - w_2)\Phi_1(y).$$

Because $(d/dy)H_1(S_1) = 0$, $(d/dy)H_1'(S_1) > 0$. Hence, $S_1 < S_1'$. □

Proof of Corollary.

(a) It is an immediate result of Theorem 3. Because the initial inventory is zero, $Q_1 = S_1$ and $Q_1' = S_1'$.

(b) Because $(S_1' - \xi_1)^+ \ge (S_1 - \xi_1)^+$, we have $S_2 - (S_1' - \xi_1)^+ \le S_2 - (S_1 - \xi_1)^+$.

(c) Because $\mathrm{Min}(S_1', \xi_1) \ge \mathrm{Min}(S_1, \xi_1)$, we have $S_2 + \mathrm{Min}(S_1', \xi_1) \ge S_2 + \mathrm{Min}(S_1, \xi_1)$. □

Proof of Theorem 4. Let $S_i^{\beta k}$ denote S_i' with $\beta = \beta_k$ ($i = 0, 1$). Because $w_2^* = c_2$, $S_2 = \bar{S}_2$. Note that $S_0^{\beta 0} = \bar{S}_0$. Case 1: $\bar{S}_2 \ge \bar{S}_0$. First, $\bar{S}_2 \ge \bar{S}_0$ implies $S_2 \ge S_0^{\beta 0}$, which yields $S_1^{\beta 0} = S_0^{\beta 0}$ by Lemma 3. Since $\bar{S}_2 \ge \bar{S}_0$, $\bar{S}_1 = \bar{S}_0$ by Lemma 1. Thus, $S_1^{\beta 0} = S_0^{\beta 0} = \bar{S}_0 = \bar{S}_1$. Because $\beta^* = \beta_0$, $S_1^{\beta^*} = \bar{S}_1$. Case 2: $\bar{S}_2 < \bar{S}_0$. Note that $S_0^{\beta 0} \le S_0^{\beta 1}$. Thus, $S_2 = \bar{S}_2 < \bar{S}_0 = S_0^{\beta 0} \le S_0^{\beta 1}$. Because $S_2 < S_0^{\beta 1}$, $S_1^{\beta 1}$ satisfies (by Lemma 3)

$$p_1 + g_1 - w_1^* - \hat{c}_1 - [p_1 + g_1 + h_1 - \alpha(\beta_1 w_1^* + (1 - \beta_1)w_2^*)]\Phi_1(S_1^{\beta 1}) + \alpha\Bigg[(p_2 + g_2 - w_2^* - \hat{c}_2)\Phi_1(S_1^{\beta 1} - S_2) - (p_2 + g_2 + h_2) \times \int_0^{S_1^{\beta 1} - S_2}\Phi_2(S_1^{\beta 1} - \xi_1)d\Phi_1(\xi_1)\Bigg] = 0. \tag{A.1}$$

Because $\bar{S}_2 < \bar{S}_0$, $\bar{S}_1$ satisfies (by Lemma 1)

$$p_1 + g_1 - c_1 - \hat{c}_1 - (p_1 + g_1 + h_1 - \alpha c_2)\Phi_1(\bar{S}_1) + \alpha\Bigg[(p_2 + g_2 - c_2 - \hat{c}_2)\Phi_1(\bar{S}_1 - \bar{S}_2) - (p_2 + g_2 + h_2)\int_0^{\bar{S}_1 - \bar{S}_2}\Phi_2(\bar{S}_1 - \xi_1)d\Phi_1(\xi_1)\Bigg] = 0. \tag{A.2}$$

Note that

$$\alpha c_2\Phi_1(\bar{S}_1) = -(w_1^* - c_1) + \alpha(\beta_1 w_1^* + (1 - \beta_1)w_2^*)\Phi_1(\bar{S}_1).$$

Substituting into (A.2), we obtain:

$$p_1 + g_1 - w_1^* - \hat{c}_1 - [p_1 + g_1 + h_1 - \alpha(\beta_1 w_1^* + (1 - \beta)w_2^*)]\Phi_1(\bar{S}_1) + \alpha\Bigg[(p_2 + g_2 - w_2^* - \hat{c}_2)\Phi_1(\bar{S}_1 - \bar{S}_2) - (p_2 + g_2 + h_2) \times \int_0^{\bar{S}_1 - \bar{S}_2}\Phi_2(\bar{S}_1 - \xi_1)d\Phi_1(\xi_1)\Bigg] = 0. \tag{A.3}$$

Because (A.1) and (A.3) coincide, $S_1^{\beta 1} = \bar{S}_1$. Because $\beta^* = \beta_1$, $S_1^{\beta^*} = \bar{S}_1$.

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