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Institut für Weltwirtschaft an der Universität Kiel
Kiel Institute for the World Economy

Kiel Institute for World Economics
Duesternbrooker Weg 120
24105 Kiel (Germany)

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by

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ADJUSTMENT COSTS, INVENTORIES AND OUTPUT

Leif Danziger

Department of Economics, Ben-Gurion University
Beer-Sheva 84105, Israel

Abstract

This paper analyzes the optimal adjustment strategy of an inventory-holding firm facing price- and quantity-adjustment costs in an inflationary environment. The model nests both the original menu-cost model that allows production to be costlessly adjusted, and the later model that includes price- and quantity-adjustment costs, but rules out inventory holdings. The firm's optimal adjustment strategy may involve stockouts. At low inflation rates, output is inversely related to the inflation rate, and the length of time demand is satisfied decreases with the absolute value of the demand elasticity, the storage cost, and the real interest rate.

JEL Classifications: D21; D24; L23
Keywords: Menu costs; Quantity-adjustment costs; Inventories; Output; Inflation

1 Introduction

Fixed price-adjustment costs, often called menu costs, play a central role in many explanations of how monetary changes are transmitted and have real effects. Owing to these costs, it may sometimes be optimal for a monopolistic firm to keep its current nominal price unchanged, even though this price differs from the static profit-maximizing price. The theoretical literature has demonstrated that seemingly minor price-adjustment costs can lead to considerable aggregate price stickiness and cause monetary shocks to have significant welfare implications (Akerlof and Yellen, 1985; Mankiw, 1985; Blanchard and Kiyotaki, 1987; Ball and Romer, 1990). Fully anticipated inflation may increase average output and welfare, and hence be beneficial (Danziger, 1988), or may lead to costly search, which is detrimental (Benabou 1988). Recent contributions consider, among other things, models in which idiosyncratic shocks impinge on price-adjustment costs (Dotsey et al., 1999), and on productivity (Danziger, 1999; Golosov and Lucas, 2006).

There is direct empirical evidence that fixed price-adjustment costs are non-trivial (Levy et al., 1997; Zbaracki et al., 2004). It has also been shown that the nominal prices of various goods are kept unchanged for substantial periods, even in face of high inflation rates when the erosion of real prices can be considerable (Cecchetti, 1986; Danziger, 1987; Kashyap, 1995; Fisher and Konieczny, 2006).[1]

Recognizing the existence of fixed price-adjustment costs does not mean, however, that other adjustment costs can be ignored. One particular shortcoming of most of the theoretical literature is the implicit assumption that while it is costly to adjust the nominal price, it is costless to adjust the production. Such asymmetry between price- and quantity-adjustment costs is not well founded. Due to the loss of organization capital and other internal adjustment costs (Baily et al., 2001; Jovanovic and Rousseau, 2001), sizable fixed costs are often involved in the course of rearranging factor inputs in order to accommodate output changes. Thus, Bresnahan and Ramey (1994) clearly document the existence of fixed costs of quantity adjustment. There is also ample evidence of fixed costs of adjusting labor (Davis and Haltiwanger, 1992; Hamermesh, 1989; Caballero et al., 1997; Abowd and Kramarz, 2003), and of adjusting capital (Doms and Dunne, 1998; Cooper et al. 1999; Nilsen and Schiantarelli,

[1] Needless to say, nominal price stickiness need not originate from fixed price-adjustment costs, but may be caused by other factors, such as signalling and strategic interactions.

2003).

The presence of quantity-adjustment costs in addition to price-adjustment costs significantly changes the response to monetary shocks. Specifically, a small shock may leave output unchanged (Andersen, 1995). In order for a shock to affect output, it must be of intermediate size while price-adjustment costs must be large relative to quantity-adjustment costs (Andersen and Toulemonde, 2004). The effect of a fully anticipated inflation is also very different. If the quantity-adjustment cost at least equals the price-adjustment cost, average output and welfare are lower with a moderate inflation than with full price stability, and inflation is therefore harmful (Danziger, 2001). Furthermore, quantity-adjustment costs amplify the effects of price-adjustment costs (Danziger and Kreiner, 2002). However, while these papers provide a more satisfactory modelling of the adjustment costs facing a typical firm than the earlier literature, they themselves are incomplete since they abstract from inventory holdings by assuming that any unsold output is destroyed. Unless the output is completely perishable, inventories are an inevitable consequence of quantity-adjustment costs. A more realistic assumption would be that firms hold unsold output as inventory for later sale, with the pricing and production decisions naturally taking this into account.

This paper intends to fill the gap in the literature by analyzing the behavior of a firm that produces a storable good and faces fixed price- and quantity-adjustment costs. Keeping goods in inventory may be costly. If the quantity-adjustment cost at least equals the price-adjustment cost, at a constant inflation rate the optimal strategy entails that the firm keeps its nominal price unchanged in periods of equal length and the production at a permanent level. At the beginning of a period, the real price is so high that there is unsold output and the firm accumulates inventory. Later in the period, the real price has fallen enough that demand exceeds current production and the firm runs down the inventory.

It is possible that a firm's inventory may be depleted before the end of a period with a constant nominal price. Stockouts occur, for instance, at low inflation rates. The period with a constant nominal price is then so long that it would be too costly to produce and store enough at the beginning of the period to have sufficient inventory available to satisfy all the demand at the end. Furthermore, production will be shown to decrease with the inflation rate, and the length of time demand is satisfied to decrease with the absolute value of the demand elasticity, the storage cost, and the real interest rate.

The model in this paper nests both the original menu-cost model that allows production to be costlessly adjusted, thereby obviating the need for inventory, and the later model that includes price- and quantity-adjustment costs, but rules out inventory holdings by assumption. Thus, the present model not only remedies the limitations of earlier models, but in addition contains a unifying framework for analyzing the consequences of a firm's optimal pricing and output strategy under all the various alternative assumptions about the cost of adjusting production and the possibility of holding inventory.

The paper also provides a numerical illustration of the output effect of allowing for inventory holdings. Based on realistic parameter values, it is shown that production is considerably higher with inventories than in their absence. This is true even at very high levels of inventory-carrying costs. Accordingly, inventories may play an important role in reducing the output loss from inflation.

2 The Firm

Consider a firm with an elastic demand function $D(z_t)$, where z_t is the real price of the product at time t. The real production cost is $k > 0$ per unit of output.

The rate of inflation is a constant $\mu > 0$. Price and quantity adjustments involve a fixed cost, which prevents the firm from adjusting its nominal price and production continuously. The fixed cost of quantity adjustment at least equals the fixed cost of price adjustment. This implies that the firm's production will remain unchanged at a permanent level while its nominal price will be kept constant in periods of equal length. At the end of each period, the nominal price is increased so that all periods start with the same initial real price.[2] Consequently, when the real price is relatively high at the beginning of a period, the firm

[2] That the firm's adjustment strategy takes this form can be seen by considering a hypothetical case where a quantity adjustment is costless if it takes place at the same time as a price adjustment. Clearly, the nominal price will then be kept unchanged in periods of equal length, while the real price and the production level will be the same at the beginning of each period. Furthermore, the firm would not want to adjust the level of production within a period with a constant nominal price. The reason is that even if it does not cost more to adjust the quantity than to adjust the price, the firm prefers to adjust only the nominal price in order to start each new period with the same initial real price and production level. Accordingly, production always remains unchanged at a permanent level in the hypothetical case that a quantity adjustment is costless if it takes place at the same time as a price adjustment. It follows that production will also always be unchanged at a permanent level if a quantity adjustment is costly whether it takes place by itself or together with a price adjustment.

produces more than it can sell and accumulates inventory. When the real price is relatively low later in the period, demand exceeds production and the inventory helps the firm to postpone and possibly eliminate stockouts.

Let S denote the initial real price of a good in a period with a constant nominal price, T the duration of a period, and Y the production. Accordingly, if the nominal price is adjusted at time zero, it will remain constant in $[0, T)$ and the next adjustment of the nominal price will take place at time T. Inflation reduces the real price of the good to $z_\tau = Se^{-\mu\tau}$ after τ of the period has elapsed, and the terminal real price is $s \equiv Se^{-\mu T}$. Since the real price decreases within a period with a constant nominal price, the initial real price and the production will not be set so low that there is excess demand at the beginning of a period. Neither will the initial real price and the production be set so high, and the period so short, that the firm will hold a positive inventory at the end of the period. If demand exceeds the current production, the firm satisfies demand as long as there is an inventory from which sales can be made. Accordingly, if δ is the depreciation rate of stored goods, there exists a time $T_I \in [0, T]$ that is defined by

$$\int_0^{T_I} e^{-\delta(T_I-\tau)}[Y - D(Se^{-\mu\tau})]d\tau = 0$$

$$\Leftrightarrow \int_0^{T_I} e^{\delta\tau}[Y - D(Se^{-\mu\tau})]d\tau = 0, \qquad (1)$$

at which the inventory is exhausted. It is assumed that $\delta \in (-r, \infty)$, where $r > 0$ is the real interest rate.[3] If $T_I < T$, then demand is satisfied in the first part of the period when $\tau \in [0, T_I)$, while stockouts occur in the second part of the period when $\tau \in [T_I, T)$. If $T_I = T$, then demand is satisfied during the entire period.

When the firm accumulates inventory, it pays the production cost concurrently while receiving the revenue from sales only later. Accordingly, the inventory-carrying cost consists of the storage cost due to the depreciation of goods held in inventory and the real interest on the production cost incurred for later sales.

[3] It is natural to think of δ as being non-negative, but allowing for negative δ's makes the framework more general. In particular, it will be shown later that the extreme case of $\delta = -r$ is equivalent to a model with price-adjustment costs and no quantity-adjustment costs.

3 The Profit Function

Let $z_I \equiv Se^{-\mu T_I}$ denote the real price corresponding to T_I. Demand is satisfied for all real prices above z_I, but not otherwise. Since $T_I < T$ implies that $z_I > s$, it follows that if $s < z_I$, the firm sells $D(z_t)$ when $z_t \in (z_I, S]$, but only sells the current production Y (leaving $D(z_t) - Y$ of demand unsatisfied) when $z_t \in (s, z_I]$. In contrast, if $s = z_I$, the firm always sells $D(z_t)$. Accordingly, the firm's instantaneous real profit is

$$\begin{cases} z_t D(z_t) - kY & \text{if } \; z_t \in (z_I, S], \\ (z_t - k)Y & \text{if } z_t \in (s, z_I]. \end{cases}$$

In Figure 1, the horizontal axis measures the real price and the vertical axis measures the instantaneous real profit. In the absence of fixed costs of quantity adjustment, production would be continuously adjusted to satisfy demand. The instantaneous real profit, stemming solely from the current production, would be $(z_t - k)D(z_t)$, which is shown by the fully drawn grey curve.

In the presence of a fixed cost of quantity adjustment, production remains unchanged at a permanent level. For given S and Y, the instantaneous real profit is shown by the fully drawn black curve.[4] Let z_Y denote the real price at which demand equals production, i.e., $D(z_Y) = Y$. Therefore, $z_Y \in (z_I, S)$ and the instantaneous real profit at z_Y is the same as it would be if production could be continuously adjusted.

At the beginning of a period with a constant nominal price, the real price is so high that $z_t \in (z_Y, S]$. The demand is less than production so that the firm accumulates inventory. Hence, the instantaneous real profit is below that obtained in the absence of a fixed cost of quantity adjustment. Later in the period, the real price falls to $z_t \in (z_I, z_Y)$. The demand exceeds production but the firm satisfies demand by selling from its inventory. The instantaneous real profit is above that obtained in the absence of a fixed cost of quantity adjustment and increases with time.

If $s < z_I$, there is a final part of the period where the real price falls below z_I to $z_t \in (s, z_I]$. The firm has then depleted its inventory and can only sell the current production.

[4] The figure assumes that the production exceeds the initial demand so that $z_I < S$. This is clearly satisfied if the firm's strategy does not involve stockouts, and footnote 5 below verifies that it is also satisfied if the firm's strategy involves stockouts.

Accordingly, the instantaneous real profit drops discontinuously at z_I as the firm stocks out. The instantaneous real profit is linear in the real price and below what it would be in the absence of a fixed cost of quantity adjustment (as long as the real price exceeds k). The instantaneous real profit vanishes as the real price reaches k. On the other hand, if $s = z_I$, then the real price never falls below z_I. The firm always satisfies all demand, since the nominal price is increased at the moment the inventory gets depleted.

The instantaneous real profit at the beginning of the period when the firm has not started to sell from inventory, i.e., when $z_t \in [z_Y, S]$, is the same as it would be if there were no possibility of holding inventory. The instantaneous real profit is, however, higher when the firm sells from inventory, i.e., when $z_t \in (z_I, z_Y)$. The instantaneous real profit would then be only $(z_t - k)Y$ if there were no possibility of holding inventory. This is shown by the dashed grey line in the figure. If $s < z_I$, the instantaneous real profit in the final part of the period when the firm only sells its current production, i.e., when $z_t \in (s, z_I]$, is also the same as it would be if there were no possibility of holding inventory.

4 The Optimal Adjustment Strategy

At the time of a price adjustment, the firm's discounted real profits from the period with a constant nominal price are

$$S\int_0^{T_I} e^{-(\mu+r)\tau} D(Se^{-\mu\tau})d\tau + SY\int_{T_I}^{T} e^{-(\mu+r)\tau}d\tau - kY\int_0^{T} e^{-r\tau}d\tau - c,$$

where $c > 0$ is the fixed real cost of a price adjustment. The first term is the discounted real revenue from the part of the period when the firm satisfies demand and the instantaneous real revenue is $Se^{-\mu\tau}D(Se^{-\mu\tau})$. If $T_I < T$, the second term is the discounted real revenue from the part of the period when the firm stocks out and the instantaneous real revenue is $SYe^{-\mu\tau}$. If $T_I = T$, the second term vanishes since the firm never stocks out. The third term is the discounted real production cost for the entire period.

The total discounted real profits from the current and all future periods with a constant nominal price are

$$V \equiv \frac{1}{1-e^{-rT}}\left[S\int_0^{T_I} e^{-(\mu+r)\tau} D(Se^{-\mu\tau})d\tau + SY\int_{T_I}^{T} e^{-(\mu+r)\tau}d\tau - kY\int_0^{T} e^{-r\tau}d\tau - c\right]. \quad (2)$$

The firm's optimal adjustment strategy consists of a choice of S, T, and Y that maximizes V, given the definition of T_I in the inventory constraint (1) and that $T_I \leq T$. It is assumed that $V \geq 0$ so that the firm remains in business. We will, in turn, analyze the cases in which an optimal adjustment strategy does or does not involve stockouts.

4.1 The Optimal Adjustment Strategy with Stockouts

An optimal adjustment strategy that involves stockouts, $T_I < T$, satisfies (see Appendix A)

$$SD(S) + z_I[Y - D(S)]e^{-(r+\delta)T_I} - sY - rc = 0, \quad (3)$$

$$(s - k)Y - rV = 0, \quad (4)$$

$$z_I e^{-rT_I} \int_0^{T_I} e^{-\delta\tau} d\tau + S \int_{T_I}^{T} e^{-(\mu+r)\tau} d\tau - k \int_0^{T} e^{-r\tau} d\tau = 0. \quad (5)$$

The instantaneous real revenue from the production at the time of price adjustment stems from the sale of $D(S)$ at the initial real price S and the later sale of $[Y - D(S)]e^{-\delta T_I}$ at the real price z_I. Without a price adjustment, the instantaneous real revenue would stem from the sale of Y at the terminal real price s. Condition (3) shows that the initial real price is determined so that the discounted instantaneous real revenue from the production at the time of price adjustment equals what the instantaneous real revenue would be without a price adjustment plus rc, which is the real interest saved by postponing the cost of price adjustment.

According to condition (4), the length of a period with a constant nominal price is such that the instantaneous terminal real profit equals the real interest on V. It entails that at the time of price adjustment the value of the optimal strategy is the same as if the firm would earn the instantaneous terminal real profit at all times; it also entails that the terminal real price at least equals the real production cost, $s \geq k$.

The discounted marginal real revenue from increased production arises partly from the additional production at the beginning of the period sold at time T_I at the real price z_I, i.e., $z_I e^{-rT_I} \int_0^{T_I} e^{-\delta\tau} d\tau$, and partly from the additional production in the final part of the period sold at the contemporaneous real price, i.e., $S \int_{T_I}^{T} e^{-(\mu+r)\tau} d\tau$. Condition (5) expresses that the level of production is such that the discounted marginal real revenue equals the discounted marginal real cost in the entire period, i.e., $k \int_0^{T} e^{-r\tau} d\tau$.[5]

[5] Condition (5) confirms that $z_I < S$, since $s > k$ implies that the left-hand side of the condition would

4.2 The Optimal Adjustment Strategy without Stockouts

An optimal adjustment strategy that does not involve stockouts, $T_I = T$, satisfies (see Appendix A)

$$SD(S) + k_T[Y - D(S)]e^{-(r+\delta)T} - sD(s) + k_T[D(s) - Y] - rc = 0, \quad (6)$$

$$sD(s) - kY - k_T[D(s) - Y] - rV = 0, \quad (7)$$

where $k_T \equiv k \int_0^T e^{r\tau} d\tau / \int_0^T e^{-\delta\tau} d\tau$ is the marginal real cost of a unit, discounted to the end of the period. Clearly, $k_T > k$.

At the time of a price adjustment, the firm sells $D(S)$ from which it obtains the instantaneous real revenue $SD(S)$. Furthermore, the inventoried output $Y - D(S)$ allows the level of production to be reduced, thereby saving the firm $k_T[Y - D(S)]e^{-(r+\delta)T}$ in discounted real production costs in the new period. Had the nominal price been kept unchanged, the firm would have sold $D(s)$ and obtained the instantaneous real revenue $sD(s)$. Since this would have required $D(s) - Y$ of inventoried output, production would have had to be higher in the previous period, and an additional $k_T[Y - D(s)]$ in discounted real production costs would have been incurred in that period. According to condition (6), the initial real price is determined to make the benefit of a price adjustment equal to the benefit of keeping the nominal price unchanged plus the real interest saved by delaying the price adjustment.

The instantaneous real profit attributable to sales at the terminal real price is the difference between the instantaneous real revenue from the sale of $D(s)$ and the total discounted cost of producing enough so that $D(s)$ can be sold. Condition (7) indicates that a price adjustment takes place when the instantaneous real profit attributable to sales at the terminal real price equals the real interest on V.

4.3 Are Stockouts Optimal?

In order to determine whether the optimal adjustment strategy involves stockouts, note that if $T_I < T$ and there are stockouts, then the discounted marginal real revenue from an increase

always be positive for $T_I = 0$.

in production decreases in T_I (for a given S and T).[6] The reason is that the firm has to wait until T_I before it can benefit from selling the last of its inventory and start to benefit from the higher production when there is excess demand. It follows that if T is substituted for T_I, the left-hand side of condition (5) is negative,

$$se^{-rT}\int_0^T e^{-\delta\tau}d\tau - k\int_0^T e^{-r\tau}d\tau < 0$$
$$\Leftrightarrow s < k_T.$$

Accordingly, if the terminal real price is less than the discounted marginal real cost of a unit at the end of the period, $s < k_T$, it does not pay for the firm to produce so much that it avoids stocking out at the end of the period, and $T_I < T$ is optimal. If the terminal real price at least equals the discounted marginal real cost of a unit at the end of the period, $s \geq k_T$, it is profitable for the firm to produce enough to always satisfy demand, and $T_I = T$ is optimal.[7]

5 The Optimal Adjustment Strategy at Low Inflation Rates

This section considers the firm's optimal strategy at low inflation rates. We first establish that $T_I < T$, and then that the firm's production decreases with the inflation rate. We also describe how T_I depends on the demand elasticity, the storage cost, and the real interest rate.

If the inflation rate converges to zero, the initial real price and the production converge to the static monopoly real price Z and output $D(Z)$, where Z is defined by $Z + D(Z)/D'(Z) = k$. The length of a period with a constant nominal price diverges to infinity. Accordingly, condition (4) shows that the terminal real price converges to $Z - rc/D(Z)$, which is finite.[8]

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[6] The partial derivative of the left-hand side of condition (5) with respect to T_I is

$$-(\mu + r + \delta)z_I e^{-rT_I}\int_0^{T_I} e^{-\delta\tau}d\tau < 0.$$

[7] If $T_I = T$ and $s = k_T$, conditions (3)-(4) are identical to conditions (6)-(7). If $s > k_T$, condition (7) shows that the instantaneous real profit from the terminal production is less than the real interest on V, that is, $(s - k)Y < rV$.

The marginal real cost of a unit at the end of a period diverges to infinity. Thus, in the limit the terminal real price is less than the marginal real cost of a unit discounted to the end of a period, $Z - rc/D(Z) < k_\infty$. It follows that $\hat{T}_I \equiv \lim_{\mu \to 0} T_I$ is finite.[9] Since the optimal strategy is continuous in μ, it must be the case that $s < k_T$, and therefore that $T_I < T$, at low inflation rates. It can be concluded that at low inflation rates the nominal price is kept unchanged for so long that the entire inventory is sold and stockouts occur at the end of a period with a constant nominal price.[10] The underlying logic is that at low inflation rates the nominal price is kept constant for long periods. The firm would therefore have to keep inventory for so long that it would be unprofitable to satisfy demand at the end of the period.

Since discounting puts more weight on the real profits at the beginning of a period than on the real profits at the end, at low inflation rates it is particularly important for the firm to increase its instantaneous real profits at the beginning of a period by reducing production and the accumulating inventory. Consequently, the firm produces less than it would under full price stability, and production decreases with the inflation rate.[11]

To further characterize the optimal strategy at low inflation rates, note that condition (5) shows that $\hat{T}_I$ is given by

$$Ze^{-r\hat{T}_I}\left(\int_0^{\hat{T}_I} e^{-\delta\tau} d\tau + \frac{1}{r}\right) - \frac{k}{r} = 0. \tag{8}$$

If the inflation rate approaches zero, the discounted marginal real revenue converges to $Ze^{-r\hat{T}_I}(\int_0^{\hat{T}_I} e^{-\delta\tau} d\tau + 1/r)$, which increases in the monopoly real price Z and decreases in $\hat{T}_I$.

[8] The limit of the terminal real price is less than Z. This is because given the production $D(Z)$, the discounted real profits from charging a real price $z \in (Z - rc/D(Z), Z)$ in perpetuity, exceed the discounted real profits from incurring the price-adjustment cost and then charging Z in perpetuity.

[9] If $\hat{T}_I = \infty$, the discounted marginal real revenue would be zero and less than the discounted marginal real cost k/r. Furthermore, if $\hat{T}_I = 0$, the discounted marginal real revenue would be Z/r and exceed the discounted marginal real cost k/r. Hence, $0 < \hat{T}_I < \infty$.

[10] The lowest real price at which demand is satisfied, i.e., z_I, converges to Z as the inflation rate converges to zero, reflecting that in the limit there is no inventory. The discontinuity of the instantaneous real profit at z_I disappears in the limit.

[11] See Appendix B for a formal proof. In contrast, in a model with price-adjustment costs only, a firm, on average, produces more than under full price stability. The reason is that since the initial real price is close to Z and the periods with a constant nominal price are very lengthy, the real price is below Z most of the time. Hence, the output is above the static monopoly output most of the time (Danziger, 1988).

On the other hand, the discounted marginal real cost converges to k/r, which is independent of Z and $\hat{T}_I$. Hence, $\hat{T}_I$ increases with Z in order for the discounted marginal real revenue to equal the discounted marginal real cost as the inflation rate approaches zero. Since Z decreases with the absolute value of the demand elasticity, a higher absolute value of the demand elasticity is associated with a lower $\hat{T}_I$. At low inflation rates, therefore, the length of time demand is satisfied decreases with the absolute value of the demand elasticity.

The discounted marginal real revenue not only decreases with $\hat{T}_I$, but also with the storage cost, and it decreases faster with the real interest rate than does the discounted marginal real cost.[12] It follows that at low inflation rates, the length of time demand is satisfied also decreases with the storage cost and the real interest rate. This is not surprising: the cost of carrying inventory increases with the storage cost and the real interest rate, and in order to economize on this cost, the inventory, and hence T_I, decreases with the storage cost and the real interest rate.

6 The Optimal Adjustment Strategy at High Inflation Rates

To establish that stockouts occur at high inflation rates, observe that there exists a high inflation rate for which $V = 0$. Condition (4) reveals that at this high inflation rate the terminal real price s equals the production cost k, and hence $s < k_T$.[13] Since the optimal strategy is continuous in μ, it follows that T_I must be less than T at sufficiently high inflation rates. This implies that inventories are exhausted and stockouts occur in the last part of a period with a constant nominal price.

The intuition is that there is only a minor gap between the real price and the production cost towards the end of a period with a constant nominal price. Given the inventory-carrying

[12] The partial derivative of the left-hand side of eq. (8) with respect to r is

$$\frac{Z}{re^{r\hat{T}_I}}\left[(1-r\hat{T}_I)\int_0^{\hat{T}_I} e^{-\delta\tau}d\tau - \hat{T}_I\right],$$

which is negative, since the term in the brackets is negative for $\delta = -r$ and decreases with r.

[13] In order for condition (7) to hold for $V = 0$, it would have to be the case that $s < k_T$, which is inconsistent with $T_I = T$.

cost, it is not profitable for the firm to keep goods in inventory for so long that demand is satisfied until the end of the period.[14]

7 Generality of the Model

Although the model assumes that $\delta \in (-r, \infty)$, the optimality conditions are also valid in the extreme cases where δ equals $-r$ or ∞. These cases are now considered in turn.

If $\delta = -r$, stored goods grow at a rate equal to the real interest rate, so there is no inventory-carrying cost. The discounted production cost is invariant with respect to the time the goods are produced, and it is immaterial when production takes place. Hence, $k_T = k$ so that $s > k_T$ and it is always optimal to satisfy demand to the end of a period. That is, $T_I = T$ for all inflation rates. Since $\int_0^T e^{-r\tau} D(Se^{-\mu\tau}) d\tau = Y \int_0^T e^{-r\tau} d\tau$, the case of $\delta = -r$ is, in terms of the firm's sales and total discounted real profits, equivalent to the absence of quantity-adjustment costs and production being continuously adjusted. Accordingly, conditions (6)-(7) reduce to

$$
\begin{aligned}
(S-k)D(S) - (s-k)D(s) - rc &= 0, \\
(s-k)D(s) - rV &= 0,
\end{aligned}
$$

which are the optimality conditions in the presence of only price-adjustment costs (Sheshinski and Weiss, 1977).

On the other hand, if $\delta = \infty$, the output is completely perishable so that unsold goods are wasted. Since $k_T = \infty$ and therefore $s < k_T$, it is always optimal to stock out at the end of a period. That is, $T_I < T$ for all inflation rates. The case of $\delta = \infty$ is equivalent to not allowing the firm to hold inventory. The second term in condition (3) and the first term in condition (5) vanish, and conditions (3)-(5) therefore reduce to

$$
\begin{aligned}
SD(S) - sY - rc &= 0, \\
(s-k)Y - rV &= 0, \\
S \int_{T_I}^{T} e^{-(\mu+r)\tau} d\tau - k \int_0^T e^{-r\tau} d\tau &= 0,
\end{aligned}
$$

[14] The theoretical conclusion that stockouts are prevalent with high inflation rates is supported by the empirical evidence that stockouts are strongly positively correlated with the inflation rate (Lamont, 1997).

which are the optimality conditions for a non-storable good in the presence of both price- and quantity-adjustment costs (Danziger, 2001).

As a consequence, the present model captures not only the typical inventory-holding circumstances, but nests both the original menu-cost model in which a firm has no need to hold inventory because it can costlessly change production, and the later model in which production changes are costly and a firm cannot hold inventory. Thus, the present model provides a unifying framework for analyzing the optimal adjustment strategy and the effects of inflation in both of these extreme cases considered in the previous models, as well as in all the more realistic, intermediate situations in which a firm faces both price- and quantity-adjustment costs and can hold inventory.

8 A Numerical Illustration

To assess the importance of inventories for the inflation-output relationship, suppose the demand function is $D(z_t) = z_t^{-10}$, the unit production cost is $k = 1$, the real interest rate is $r = 3\%$, and the cost of price adjustment is $c = 9^9/10^{11}$.[15]

Table 1 lists the percentage loss of production (relative to the static monopoly output) due to inflation both when there is no storage cost and at various levels of storage cost.[16] The firm's optimal strategy always involves accumulation of inventory at the beginning of a period with a constant nominal price. For the combinations of inflation rates and storage costs marked by an asterisk, the accumulated inventory is not large enough to satisfy demand until the end of the period and the firm eventually stocks out. For the other combinations of inflation rates and storage costs, the inventory is sufficient to satisfy demand until the end of the period.

The output loss always increases with inflation. A higher storage cost, which increases

[15] The demand function implies a markup (ratio of price to marginal cost) of 10/9, which is consistent with estimated markups that are typically between 1.1 and 1.2 (Rotemberg and Woodford, 1995; Basu and Fernald, 1997). The cost of price adjustment is about 1% of the static monopoly revenue, and between 0.7% found by Levy et al. (1997) and 1.22% found by Zbaracki et al. (2004). Sensitivity analysis (not reported here) shows that broadly similar results would hold with other constant-elasticity demand functions and unit production costs.

[16] Estimated inventory-carrying costs, which include the real interest, are on average 25% (Stock and Lambert, 2001).

the cost of carrying inventory, is associated with a lower production at all levels of inflation. However, the output loss is much reduced compared to what it would be if the firm could not hold inventory (shown in the penultimate column of Table 1). For instance, if there is no storage cost, the loss is only about a third or less of what the loss would be if there were no possibility of holding inventory. At a realistic storage cost of $\delta = 20\%$ and inflation rates of 5% or higher, the loss is less than half of what it would be if the firm could not hold inventory. Even if the storage cost is $\delta = 50\%$ and the inflation rate is 10% or higher, the loss is only a little more than half of what it would be if the firm could not hold inventory.

On the other hand, the output loss is higher than what the loss of average output would be with price-adjustment costs only and production continuously adjusted to satisfy demand (shown in the last column of Table 1). Indeed, in this case, at 1% inflation rate, there would be a minor gain of average output.[17]

9 Conclusion

This paper analyzes the optimal adjustment strategy of a firm faced with fixed costs of adjusting both nominal price and output in an inflationary environment. An important innovation of the model is that the firm may keep its unsold production in inventory for later sales. This makes the framework more realistic than previous models that have abstracted from inventories by assuming that any unsold output is immediately destroyed. In fact, the model is quite general since it nests both the original menu-cost model without costs of quantity adjustment, and the later model that includes costs of quantity adjustment but makes no allowance for inventories.

As long as the cost of quantity adjustment at least equals that of price adjustment, the firm keeps its nominal price unchanged in periods of equal length and its production constant. The firm therefore accumulates inventory at the beginning of a period when its real price is relatively high, and it uses the inventory to augment supply later in the period

[17] See footnote 11. Since sales and consumption with quantity-adjustment costs and the cost of storage given by $\delta = -r$ are the same as with price-adjustment costs only, the last column also shows the loss/gain of average consumption (which is different from output) if there were only price-adjustment costs. The gain of average consumption is made possible by the fact that average sales exceed production if $\delta < 0$. Of course, as proven in Appendix B, the production and the inflation rate are inversely related at low inflation rates also if $\delta < 0$.

when the real price is relatively low and demand exceeds its current production.

The model shows that if the firm's real price at the end of the periods exceeds or equals the discounted marginal real cost, then the firm accumulates enough inventory at the beginning of the period to satisfy demand until the end. However, if the real price at the end of the periods is less than the discounted marginal real cost, then the firm eventually stocks out.

It is also demonstrated that at low inflation rates, the firm chooses to produce less than it would need in order to avoid stockouts at the end of the periods, and that output is inversely related to the inflation rate. Furthermore, the length of time during which the firm's demand is satisfied decreases with the absolute value of the demand elasticity, the storage cost, and the real interest rate. Numerical simulations show that in the presence of fixed price- and quantity-adjustment costs, inventory holdings can significantly reduce the output loss due to inflation.

Appendix A

If Stockouts Are Optimal

Assume that $T_I < T$ and differentiate V totally with respect to S, T, and Y:

$$\begin{aligned}
\frac{\partial V}{\partial S} &= \frac{1}{1-e^{-rT}}\left\{\int_0^{T_I} e^{-(\mu+r)\tau} D(Se^{-\mu\tau})d\tau + S\int_0^{T_I} e^{-(2\mu+r)\tau} D'(Se^{-\mu\tau})d\tau \right. \\
&\quad \left. +Y\int_{T_I}^{T} e^{-(\mu+r)\tau}d\tau + \frac{e^{-(r+\mu)T_I}}{\mu}[D(z_I) - D(S)e^{-\delta T_I} - Y(1-e^{-\delta T_I})]\right\} = 0, \\
\frac{\partial V}{\partial T} &= \frac{1}{e^{rT}-1}[(s-k)Y - rV] = 0, \\
\frac{\partial V}{\partial Y} &= \frac{1}{1-e^{-rT}}\left[z_I e^{-rT_I}\int_0^{T_I} e^{-\delta\tau}d\tau + S\int_{T_I}^{T} e^{-(\mu+r)\tau}d\tau - k\int_0^{T} e^{-r\tau}d\tau\right] = 0,
\end{aligned}$$

using that the definition of T_I in eq. (1) implies

$$\frac{\partial T_I}{\partial S} = \frac{D(z_I) - D(S)e^{-\delta T_I} - Y(1-e^{-\delta T_I})}{\mu S[D(z_I) - Y]}, \tag{A1}$$

$$\frac{\partial T_I}{\partial Y} = \frac{\int_0^{T_1} e^{-\delta\tau}d\tau}{D(z_I) - Y}. \tag{A2}$$

Partially integrating the second integral in $\partial V/\partial S$,

$$S\int_0^{T_I} e^{-(2\mu+r)\tau}D'(Se^{-\mu\tau})d\tau = \frac{D(S) - e^{-(\mu+r)T_I}D(z_I)}{\mu} - \left(\frac{r}{\mu}+1\right)\int_0^{T_I} e^{-(r+\mu)\tau}D(Se^{-\mu\tau})d\tau.$$

Consequently,

$$\begin{aligned}
\frac{\partial V}{\partial S} &= \frac{1}{(1-e^{-rT})\mu S}\left\{SD(S)[1-e^{-(\mu+r+\delta)T_I}] - rS\int_0^{T_I} e^{-(\mu+r)\tau}D(Se^{-\mu\tau})d\tau \right. \\
&\quad \left. +Y\mu S\int_{T_I}^{T} e^{-(\mu+r)\tau}d\tau - z_I e^{-rT_I}(1-e^{-\delta T_I})Y\right\} \\
&= \frac{1}{(1-e^{-rT})\mu S}\left\{SD(S)[1-e^{-(\mu+r+\delta)T_I}] - rS\left[\int_0^{T_I} e^{-(\mu+r)\tau}D(Se^{-\mu\tau})d\tau \right.\right. \\
&\quad \left.\left. +Y\int_{T_I}^{T} e^{-(\mu+r)\tau}d\tau\right] + YS\left[e^{-(\mu+r)T_I} - e^{-(\mu+r)T} - e^{-(\mu+r)T_I}(1-e^{-\delta T_I})\right]\right\},
\end{aligned}$$

which by the definition of V becomes

$$\begin{aligned}
\frac{\partial V}{\partial S} &= \frac{1}{(1-e^{-rT})\mu S}\Big\{SD(S)[1-e^{-(\mu+r+\delta)T_I}] - (rV+kY)(1-e^{-rT}) - rc \\
&\quad +YS\left[e^{-(\mu+r)T_I} - e^{-(\mu+r)T} - e^{-(\mu+r)T_I}(1-e^{-\delta T_I})\right]\Big\} \\
&= \frac{1}{(1-e^{-rT})\mu S}\Big\{SD(S) + z_I[Y-D(S)]e^{-(r+\delta)T_I} - sY - rc \\
&\quad +[(s-k)Y - rV](1-e^{-rT})\Big\}.
\end{aligned}$$

An optimal adjustment strategy with stockouts therefore satisfies

$$\begin{aligned}
SD(S) + z_I[Y-D(S)]e^{-(r+\delta)T_I} - sY - rc &= 0, \\
(s-k)Y - rV &= 0, \\
z_I e^{-rT_I}\int_0^{T_I} e^{-\delta\tau}d\tau + S\int_{T_I}^{T} e^{-(\mu+r)\tau}d\tau - k\int_0^T e^{-r\tau}d\tau &= 0.
\end{aligned}$$

If Stockouts Are Not Optimal

Assume that $T_I = T$ and differentiate V totally with respect to S and T:

$$\begin{aligned}
\frac{\partial V}{\partial S} &= \frac{1}{1-e^{-rT}}\left(\int_0^T e^{-(\mu+r)\tau}D(Se^{-\mu\tau})d\tau + S\int_0^T e^{-(2\mu+r)\tau}D'(Se^{-\mu\tau})d\tau \right.\\
&\quad \left. -k_T\left\{\frac{[D(S)-Y]e^{-\delta T} + Y - D(s)}{\mu S}\right\}e^{-rT}\right) = 0, \\
\frac{\partial V}{\partial T} &= \frac{1}{e^{rT}-1}\left\{sD(s) - kY - k_T[D(s)-Y] - rV\right\} = 0,
\end{aligned}$$

using that eq. (1) for $T_I = T$ implies

$$\begin{aligned}
\frac{\partial Y}{\partial S} &= \frac{\int_0^T e^{(\delta-\mu)\tau}D'(Se^{-\mu\tau})d\tau}{\int_0^T e^{\delta\tau}d\tau} \\
&= \frac{[D(S)-Y]e^{-\delta\tau} + Y - D(s)}{\mu S\int_0^T e^{-\delta\tau}d\tau},
\end{aligned}$$

by partial integration, and

$$\frac{\partial Y}{\partial T} = \frac{D(s)-Y}{\int_0^T e^{-\delta\tau}d\tau}.$$

Partially integrating the second integral in $\partial V/\partial S$,

$$S\int_0^T e^{-(2\mu+r)\tau}D'(Se^{-\mu\tau})d\tau = \frac{D(S) - e^{-(\mu+r)T}D(s)}{\mu} - \left(\frac{r}{\mu}+1\right)\int_0^T e^{-(r+\mu)\tau}D(Se^{-\mu\tau})d\tau.$$

Accordingly, by the definition of V, one obtains

$$\begin{aligned}
\frac{\partial V}{\partial S} &= \frac{1}{(1-e^{-rT})\mu S}\Big\{SD(S) - sD(s)e^{-rT} - rV(1-e^{-rT}) - kY(1-e^{-rT}) - rc \\
&\quad -k_T[D(S)-Y]e^{-(r+\delta)T} - k_T[Y-D(s)]e^{-rT}\Big\} \\
&= \frac{1}{(1-e^{-rT})\mu S}\Big(SD(S) + k_T[Y-D(S)]e^{-(r+\delta)T} - sD(s) + k_T[D(s)-Y] - rc \\
&\quad +\{sD(s) - kY - k_T[D(s)-Y] - rV\}(1-e^{-rT})\Big).
\end{aligned}$$

An optimal adjustment strategy without stockouts therefore satisfies

$$\begin{aligned}
SD(S) + k_T[Y-D(S)]e^{-(r+\delta)T} - sD(s) + k_T[D(s)-Y] - rc &= 0, \\
sD(s) - kY - k_T[D(s)-Y] - rV &= 0.
\end{aligned}$$

Appendix B

It is first established that production decreases with the cost of price adjustment at small inflation rates (where $T_I < T$). Differentiate conditions (3)-(5) totally with respect to c,

$$\frac{dY}{dc} = -\frac{A}{B},$$

where

$$\begin{aligned} A \quad \equiv \quad & (\mu + r + \delta)e^{-\mu T_I}\left[\frac{D(z_I) - D(S)e^{-\delta T_I} - Y(1 - e^{-\delta T_I})}{D(z_I) - Y}\right]\left[\frac{Y - D(S)}{\mu}e^{-\delta T_I}(s - k)\right. \\ & \left. -sY\int_0^{T_I} e^{-\delta\tau}d\tau\right] + \mu k e^{rT_I - \mu T} Y \int_0^{T} e^{-r\tau}d\tau \\ & +(s - k)\left\{Ye^{rT_I - (\mu + r)T} - [D(S) + SD'(S)]\left[e^{rT_I} - e^{-(\mu+\delta)T_I}\right] - Ye^{-(\mu+\delta)T_I}\right\}, \end{aligned}$$

using eq. (A1), and $B < 0$ from the second-order condition for a maximum. Accordingly, dY/dc has the same sign as A. At small inflation rates, therefore, $dY/dc < 0$ if $\lim_{\mu\to 0} A < 0$. Now,

$$\begin{aligned} \lim_{\mu\to 0} A \quad = \quad & (r + \delta)\left\{\lim_{\mu\to 0}\left[\frac{D(z_I) - D(S)e^{-\delta T_I} - Y(1 - e^{-\delta T_I})}{D(z_I) - Y}\right]\right\} \\ & \left(\left\{\lim_{\mu\to 0}\left[\frac{Y - D(S)}{\mu}\right]\right\} e^{-\delta\hat{T}_I}(\hat{s} - k) - \hat{s}D(Z)\int_0^{\hat{T}_I} e^{-\delta\tau}d\tau\right) \\ & -(\hat{s} - k)\left[D(Z)e^{r\hat{T}_I} + ZD'(Z)\left(e^{r\hat{T}_I} - e^{-\delta\hat{T}_I}\right)\right]. \end{aligned}$$

Let T_Y be the time at which demand equals production, and $\hat{T}_Y$ the limit of T_Y as the inflation rate approaches zero. That is, $T_Y \equiv (1/\mu)\ln(S/z_Y)$ and $\hat{T}_Y \equiv \lim_{\mu\to 0} T_Y$. Expand $D(Se^{-\mu T_I})$ and $Y = D(Se^{-\mu T_Y})$ at $\mu = 0$ to obtain

$$\begin{aligned} & \lim_{\mu\to 0}\left[\frac{D(z_I) - D(S)e^{-\delta T_I} - Y(1 - e^{-\delta T_I})}{D(z_I) - Y}\right] \\ = \quad & \lim_{\mu\to 0}\left[\frac{D(Se^{-\mu T_I}) - D(S)e^{-\delta T_I} - D(Se^{-\mu T_Y})(1 - e^{-\delta T_I})}{D(Se^{-\mu T_I}) - D(Se^{-\mu T_Y})}\right] \\ = \quad & \lim_{\mu\to 0}\left[\frac{-D'(Se^{-\mu T_I})Se^{-\mu T_I}\mu T_I + D'(Se^{-\mu T_I})Se^{-\mu T_Y}\mu T_Y(1 - e^{-\delta T_I})}{-D'(Se^{-\mu T_I})Se^{-\mu T_I}\mu T_I + D'(Se^{-\mu T_Y})Se^{-\mu T_Y}\mu T_Y}\right] \\ = \quad & \frac{\hat{T}_I - \hat{T}_Y(1 - e^{-\delta\hat{T}_I})}{\hat{T}_I - \hat{T}_Y}. \end{aligned}$$

Similarly,

$$\begin{aligned}
& \lim_{\mu\to 0}\left[\frac{Y-D(S)}{\mu}\right] \\
= & \lim_{\mu\to 0}\left[\frac{D(Se^{-\mu T_Y})-D(S)}{\mu}\right] \\
= & \lim_{\mu\to 0}\left[\frac{-D'(Se^{-\mu T_Y})Se^{-\mu T_Y}\mu T_Y}{\mu}\right] \\
= & -ZD'(Z)\hat{T}_Y.
\end{aligned}$$

Use eq. (8) to obtain that

$$D(Z)e^{r\hat{T}_I}+ZD'(Z)\left(e^{r\hat{T}_I}-e^{-\delta\hat{T}_I}\right)=(r+\delta)ZD'(Z)\int_0^{\hat{T}_I}e^{-\delta\tau}d\tau.$$

Consequently,

$$\begin{aligned}
\lim_{\mu\to 0}A &= -r\left[\frac{\hat{T}_I-\hat{T}_Y(1-e^{-\delta\hat{T}_I})}{\hat{T}_I-\hat{T}_Y}\right]\left[ZD'(Z)\hat{T}_Ye^{-\delta\hat{T}_I}(\hat{s}-k)+\hat{s}D(Z)\int_0^{\hat{T}_I}e^{-\delta\tau}d\tau\right] \\
& -(\hat{s}-k)(r+\delta)ZD'(Z)\int_0^{\hat{T}_I}e^{-\delta\tau}d\tau \\
&= -\frac{r\hat{T}_I^2[ZD'(Z)(\hat{s}-k)+\hat{s}D(Z)]}{\hat{T}_I-\hat{T}_Y} \\
&= -\frac{r\hat{T}_I^2D(Z)k(Z-\hat{s})}{(\hat{T}_I-\hat{T}_Y)(Z-k)} \\
&< 0,
\end{aligned}$$

where the last equality uses that $D'(Z)=-D(Z)/(Z-k)\Rightarrow ZD'(Z)(\hat{s}-k)+\hat{s}D(Z)=kD(Z)(Z-\hat{s})/(Z-k)$. It can be concluded that $dY/dc<0$ at small inflation rates. Since the production converges to $D(Z)$ as the inflation rate approaches zero, the production is less than the static monopoly output at small inflation rates, $Y<D(Z)$. For this to be the case, the production must decrease with the inflation rate at small inflation rates, $dY/d\mu<0$.

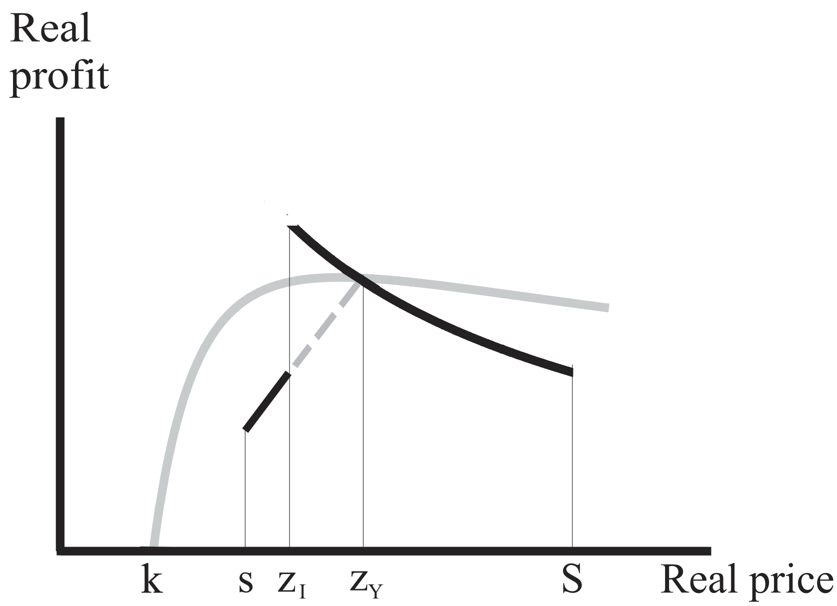

FIGURE 1

TABLE 1 – PERCENTAGE LOSS/GAIN OF OUTPUT

	Price- and quantity-adjustment cost					
		Inventory storage cost				
Inflation rate	No storage cost	5	20	50	No inventory	Price-adjustment cost only
1	– 2.31 *	– 2.80 *	– 4.27 *	– 5.14 *	– 6.71 *	0.10
5	−4.34	−5.07	– 6.88 *	– 9.59 *	– 15.02 *	−2.12
10	−5.99	−6.80	−8.49	−12.22	– 21.26 *	−4.01
15	−7.39	−8.21	−11.02	−14.03	– 26.08 *	−5.55
20	−8.65	−9.47	−11.35	−15.50	– 30.16 *	−6.93

Notes: All numbers are in per cent.

An asterisk indicates that the firm eventually stocks out.

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