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Durable Goods Inventories and the Volatility of Production: A Puzzle

by

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Abstract

A stylized fact associated with inventory behavior is that durable goods production and inventory investment are about 5 times more volatile than those of nondurable goods. This paper shows that the stockout-avoidance theory of inventories (Kahn, AER 1987) featuring demand uncertainty and production lags is inconsistent with this stylized fact. The predicted variance of production is negatively related to the degree of durability of consumption goods. In particular, production is less variable both absolutely and relative to sales when consumption goods are more durable. In addition, durable goods production can be less variable than sales even under serially correlated demand shocks. These predictions run counter to the data.

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1 Introduction

The stockout-avoidance theory of production and inventories is shown by Kahn (1987) to be able to resolve one of the most prominent puzzles in inventory fluctuations, namely, observed production is more variable than sales (e.g., see Blinder 1986 for stylized facts). According to this theory, the major reason that inventories exist in the economy is because of demand uncertainty and production lags. Since production decision must be made before demand uncertainty is resolved, firms have an incentive to keep excess supply of goods (inventories) relative to expected demand to avoid possible stockouts. Thus, if demand shocks are serially correlated, production should move more than one-for-one in response to demand (Kahn, 1987). Kahn (1992) shows that the stockout-avoidance theory is also consistent with many other important features of inventory fluctuations. Recently, Wen (2003) further shows that this theory can also explain the apparent paradoxical behavior of aggregate inventory investment across high- and low-cyclical frequencies observed in major OECD countries, which cannot be explained by the production-smoothing theory nor by the cost-shock theory.[1]

However, the stockout-avoidance theory has so far been applied only to the case of nondurable goods inventories. Surprisingly little attention in the theoretical literature has been paid to durable goods inventories.[2] It is well-known that both production and inventory investment in the durable goods sector not only exhibit similar features

[1] Wen (2003) documents that the correlation between inventory investment and sales is strongly negatively at the high cyclical frequencies (i.e., 2-3 quarters per cycle) but significantly positively at lower cyclical frequencies (such as the business cycle frequencies). Wen (2003) shows that these features are consistent with the prediction of the stockout-avoidance theory of Kahn (1987) and are inconsistent with the production-smoothing theory and the cost-shock theory.

[2] The only theoretical paper I know of tempting to deal with durable goods inventories is Kahn, McConnell and Perez-Quiros (2001). The model they use, however, is not a genuine model for durable goods inventories. Since they put the inventory stock into the utility function, there is consequently no distinction between consumption goods and inventory goods in their model. Because of this, the standard nonnegativity constraint on inventories (which gives rise to the stockout-avoidance motive) cannot be imposed in their model.

to those in the nondurable goods sector, but are also far more volatile. For example, Blinder and Maccini (1991) show that durable goods production is 5 to 6 times more variable than nondurable goods production in US manufacturing. Similarly, Humphreys, Maccini, and Schuh (2001) show that durable goods inventory investment is nearly 5 times more variable than nondurable goods inventory investment in US manufacturing.[3] What can account for such dramatic differences in volatility across the two types of industries?

This paper provides a theoretical model for analyzing durable goods inventories under the stockout-avoidance motive. It shows that the stockout-avoidance theory predicts that the variance of production is negatively related to the degree of durability of consumption goods. In particular, production becomes less variable both absolutely and relative to sales when consumption goods become more durable. In addition, production of durable goods can be less variable than sales even under serially correlated demand shocks. These predictions run counter to the data. Even if we assume that durable-goods consumption and nondurable-goods consumption are driven by entirely separate sources of shocks with a dramatic difference in variance, the phenomenon that production is 5 to 6 times more variable for durable than for nondurable goods remains puzzling.

2 The Model

Assume that the instantaneous utility function, $u(c)$, is strictly concave in the stock of durable goods, c; and that production decision in period t must be made before demand in period t is known. A representative agent (social planner) chooses sequences

[3]The volatility of durable goods manufacturing sector has declined both absolutely and relative to nondurable goods sector since 1983 (see Kahn, McConnell and Perez-Quiros, 2002). Up to the year of 1983, durable goods sector is about 5 times more variable than nondurable goods sector in terms of production and inventory investment in post war US. After 1983, that ratio has declined to about 3.

of production (y), consumption stock (c), and inventory holdings (s) to solve

$$\max_{\{y_t\}} E_{-1} \left\{ \max_{\{c_t, s_t\}} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\theta_t u(c_t) - a y_t \right] \right\} \right\}$$

subject to

$$[c_t - (1-\delta)c_{t-1}] + [s_t - s_{t-1}] = y_t \tag{1}$$

$$s_t \geq 0 \tag{2}$$

where the operator E_t denotes expectation based on information available in period t. The rate of depreciation for durable goods is δ. For simplicity and without loss of generality, the depreciation rate for inventories is assumed to be zero. The cost of production, ay_t, is modeled as a disutility and is assumed to be a linear function of output in order to keep the model simple and tractable.

Denoting λ and π as the Lagrangian multipliers associated with the resource constraint (1) and the nonnegativity constraint on inventory (2) respectively, the first order conditions with respect to $\{y, c, s\}$ are given by:

$$a = E_{t-1}\lambda_t \tag{3}$$

$$\theta_t u'(c_t) = \lambda_t - \beta(1-\delta)E_t\lambda_{t+1} \tag{4}$$

$$\lambda_t = \beta E_t \lambda_{t+1} + \pi_t \tag{5}$$

Utilizing (3), equations (4) and (5) can be simplified respectively to

$$\theta_t u'(c_t) + \beta(1-\delta)a = \lambda_t \tag{6}$$

$$\lambda_t = \beta a + \pi_t. \tag{7}$$

According to (6), the shadow price of one unit of durable goods equals its marginal utility plus the market value of the nondepreciated part, $(1-\delta)$, measured by the production cost the agent gets avoid to pay in the next period, βa. According to (7), the value of one unit of inventory equals the discounted production cost the agent gets avoid to pay next period (βa), plus the shadow value of the slackness constraint (π), which is zero if there is no stockout and is positive if there is. Combining (6) and (7), we have $\theta u'(c) \geq \beta\delta a$, implying that the optimal stock of durable goods measured by its marginal utility is bounded below by the discounted user cost of durable goods, $\beta\delta a$.[4]

In order to solve the model analytically, assume that the utility function is quadratic,

$$\theta u(c) = \theta c - \frac{1}{2}c^2,$$

hence the marginal utility becomes linear,

$$\theta u'(c) = \theta - c.$$

To derive the decision rules of the model, consider two possibilities: demand shock is below "normal" and demand shock is above "normal".

Case A: If demand is below normal, then the nonnegativity constraint on inventories does not bind. Hence $\pi_t = 0$ and $s_t \geq 0$. Equation (7) implies that the shadow price of goods is constant[5],

$$\lambda_t = \beta a.$$

Hence equation (6) implies

$$\theta_t - c_t = \beta\delta a,$$

which gives the optimal consumption policy,

$$c_t = \theta_t - \beta\delta a.$$

[4]Thus, the nonnegativity constraint on inventories acts like a borrowing constraint on durable consumption goods in a competitive rental market.

[5]This implies that goods price is downward sticky in an inventory economy. See Blinder (1982), Amihud and Mendelson (1983) for more discussions on this issue.

The resource constraint (1) then implies

$$s_t = y_t + s_{t-1} + (1-\delta)c_{t-1} - \theta_t + \beta\delta a.$$

The threshold preference shock is then determined by the constraint, $s_t \geq 0$, which implies

$$\theta_t \leq y_t + s_{t-1} + (1-\delta)c_{t-1} + \beta\delta a. \tag{8}$$

Case B: If demand is above normal, then the nonnegativity constraint on inventories binds. Hence $\pi_t > 0$ and $s_t = 0$. The resource constraint (1) implies that optimal consumption policy is given by

$$c_t = y_t + s_{t-1} + (1-\delta)c_{t-1}. \tag{9}$$

To determine the optimal production policy, we can utilize equation (3). Denote by $f()$ the probability density function of innovations in demand (ε) with support $[A, B]$, then

$$\begin{aligned} a &= E_{t-1}\lambda_t & (10) \\ &= \int_A^{z(y_t)} \beta a f(\varepsilon) d\varepsilon + \int_{z(y_t)}^B \left[\theta_t u'(c_t) + \beta(1-\delta)a\right] f(\varepsilon) d\varepsilon \end{aligned}$$

where the cutoff point for demand shock that determines the probability of stocking out, $z(y)$, is implied by (8). Assuming that preference shocks follow a stationary AR(1) process,

$$\theta_t = \gamma + \rho\theta_{t-1} + \varepsilon_t,$$

then (8) can be written as

$$\begin{aligned} \varepsilon_t &\leq y_t + s_{t-1} + (1-\delta)c_{t-1} + \beta\delta a - E_{t-1}\theta_t \\ &\equiv z(y_t). \end{aligned}$$

The interpretation of (10) is straightforward. The expected value of λ is a probability distribution of two terms: $\lambda = \beta a$ if the realized demand shock is small so that there does not stock out ($\pi = 0$); $\lambda = \theta u'(c)$ if the realized demand shock is large so that there is a stockout ($\pi > 0$). In the later case the optimal level of consumption is given by (9). More precisely, the left-hand side of (10) is the cost of producing one extra unit of goods today, a. The marginal benefit of having one extra unit of goods available is given by the right-hand side of (10) with two possibilities. First, in the event of no stockout due to a low demand, the firm gets to save on the marginal cost of production by postponing production for one period. The present value of this term is βa. This event happens with probability $\int_A^{z(y)} f(\varepsilon)d\varepsilon$. Second, in the event of a stockout due to a high demand, the firm gets to sell the product (i.e., consumption takes place). The value of this term is the marginal utility of consumption plus the present market value of the nondepreciated part, $\theta u'(c) + \beta(1-\delta)a$, where c is determined by (9). This event happens with probability $\int_{z(y)}^B f(\varepsilon)d\varepsilon$.

Clearly, the probability of stocking out, $\int_{z(y)} f(\varepsilon)d\varepsilon$, is determined by the level of production (y). If y is larger, then $z(y)$ is larger, hence the probability of stocking out is smaller. Since $\theta u'(c) > \beta\delta a$ in case of stocking out, (10) shows that an optimal cutoff point, $z(y) \in [A, B]$, exists and it is unique given the monotonicity of the marginal utility function, $u'(c)$. This cutoff point $z(y)$ depends on the probability distribution of demand shocks and other structural parameters in general, such as $\{a, \beta, \delta\}$.

Proposition 1 *The optimal cutoff point is a constant k:*

$$z(y_t) = k,$$

where k depends positively on the variance of demand shocks, negatively on the mar-

ginal cost (a), but is independent of the rate of depreciation (δ).

Proof. Rewrite (10) as (utilizing equation 9):

$$\begin{aligned} a &= \int_A^{z(y_t)} \beta a f(\varepsilon) d\varepsilon + \int_{z(y_t)}^B \left[\theta_t - c_t + \beta(1-\delta)a\right] f(\varepsilon) d\varepsilon \\ &= \int_A^{z(y_t)} \beta a f(\varepsilon) d\varepsilon + \int_{z(y_t)}^B \left[\theta_t - (y_t + s_{t-1} + (1-\delta)c_{t-1} + \beta\delta a) + \beta a\right] f(\varepsilon) d\varepsilon \\ &= \beta a + \int_{z(y_t)}^B \left[\varepsilon_t - z(y_t)\right] f(\varepsilon) d\varepsilon, \end{aligned}$$

which implies

$$(1-\beta)a = \int_{z(y_t)}^B \left[\varepsilon - z(y_t)\right] f(\varepsilon) d\varepsilon. \tag{11}$$

Clearly, the right-hand side of (11) is monotonically decreasing in z and it is an implicit function in the form, $g(z) = 0$. Hence, the solution for $z(y)$ is unique and it must be a constant. Furthermore, z negatively depends on a and is independent of δ. Consider an increase in the variance of ε that preserves the mean (i.e., an increase in B). (11) indicates that z must increase in order to maintain the equality.■

Equation (11) has the interpretation that the level of production is chosen such that the expected value of $[\varepsilon - z]$ (marginal utility of excess supply, z, conditioned on $\varepsilon \geq z$) equals the average-period marginal cost of production across time, $\frac{a}{\sum_{j=0}^{\infty} \beta^j}$ (which is $(1-\beta)a$).

Proposition 2 *The optimal decision rules for inventory holdings, durable goods sales, and production are given respectively by*

$$s_t = k - \min\{k, \varepsilon_t\}$$

$$c_t - (1-\delta)c_{t-1} = [1-(1-\delta)L]\left(E_{t-1}\theta_t - \beta\delta a + \min\{k, \varepsilon_t\}\right)$$

$$y_t = [1-(1-\delta)L]\left(E_{t-1}\theta_t - \beta\delta a\right) + \delta \min\{k, \varepsilon_{t-1}\}$$

where L denotes the lag operator.

Proof. Utilizing the identity, $\theta_t = \varepsilon_t + E_{t-1}\theta_t$, and the identity, $k = y_t + s_{t-1} + (1-\delta)c_{t-1} + \beta\delta a - E_{t-1}\theta_t$, case A and case B discussed above indicate that inventory holdings are given by the rule,

$$s_t = \begin{cases} k - \varepsilon_t & \text{if } \varepsilon_t \leq k \\ 0 & \text{if } \varepsilon_t > k \end{cases} = \max\{0, k - \varepsilon_t\} = k - \min\{k, \varepsilon_t\},$$

and that consumption stock is determined by the rule,

$$\begin{aligned} c_t &= \begin{cases} \theta_t - \beta\delta a & \text{if } \varepsilon_t \leq k \\ y_t + s_{t-1} + (1-\delta)c_{t-1} & \text{if } \varepsilon_t > k \end{cases} \\ &= \begin{cases} E_{t-1}\theta_t - \beta\delta a + \varepsilon_t & \text{if } \varepsilon_t \leq k \\ E_{t-1}\theta_t - \beta\delta a + k & \text{if } \varepsilon_t > k \end{cases} \\ &= E_{t-1}\theta_t - \beta\delta a + \min\{k, \varepsilon_t\}. \end{aligned}$$

The sales of durable consumption goods are thus determined by $(1-(1-\delta)L)\, c_t$. Furthermore, we have

$$y_t = k + E_{t-1}\theta_t - \beta\delta a - s_{t-1} - (1-\delta)c_{t-1}.$$

Substituting out $s_{t-1}$and c_{t-1} in y_t following the decision rules for s_t and c_t and simplifying gives the rule of production.■

Notice that when goods are nondurable ($\delta = 1$), the decision rules in proposition (2) become identical to those obtained by Kahn (1987) up to a constant. This shows that although Kahn's (1987) analysis is based on a partial equilibrium model, his result continues to hold in general equilibrium (for the case $\delta = 1$) where demand is endogenous and the equilibrium price (λ) can respond to demand and supply. The reason for this is that the competitive price is downward sticky in general equilibrium because firms opt to hold inventories rather than to decrease price when the marginal utility of consumption is low (i.e., $\lambda_t = \beta a$ when $\pi_t = 0$). Equilibrium price becomes variable (it goes up) only when demand (θ) is high ($\pi_t > 0$ in the event of a stockout). Hence, the simplifying assumption of an exogenously constant price in Kahn's (1987) partial equilibrium model has no fatal consequence on the implications of optimal production and inventory behavior.

Also note that the decision rule for inventory is not affected by durability of consumption goods, suggesting that firms target the inventory stock in the same way regardless of whether goods are durable or not. An implication of this is that the excess demand function, $[c_t - (1-\delta)c_{t-1}] - y_t = \min\{k, \varepsilon_t\} - \min\{k, \varepsilon_{t-1}\}$, does not depend on the rate of depreciation, implying that optimal production reacts to sales so that the excess demand function is the same regardless of durability.

On the other hand, the decision rule for production indicates that durability has a profound effect on production decisions. Proposition (2) shows that production responds to both expected sales (the first term) and innovation in demand (the second term). The rate at which it responds to innovation in demand (ε_{t-1}) is δ : it responds one-for-one only when goods are fully depreciated after one period; it responds less than one-for-one if goods are durable; and it has no response at all if goods are perfectly durable (i.e., if $\delta = 0$). Thus the variance of production positively depends on the rate of depreciation and production is smoothed if goods are durable (even if the marginal cost of production is constant).

Proposition 3 *The relative volatility of production to sales decreases as the durability of consumption goods increases (i.e., as the rate of depreciation δ decreases). Furthermore, it is more likely for production to become less volatile than sales as the* *durability of consumption goods increases.*

Proof. Denote $x_t \equiv E_{t-1}\theta_t - \beta\delta a$ and $v_t \equiv \min\{k, \varepsilon_{t-1}\}$. Denote durable goods sales by

$$\begin{aligned} q_t &\equiv c_t - (1-\delta)c_{t-1} \\ &= y_t + v_{t+1} - v_t. \end{aligned}$$

Since

$$cov(y_t, v_t) = cov(x_t, v_t) + \delta\sigma_v^2 = P\rho\sigma_\varepsilon^2 + \delta\sigma_v^2,$$

$$cov(y_t, v_{t+1}) = cov(y_{t-1}, v_t) = 0,$$

where $P \equiv \Pr[\varepsilon > k]$, the variance of durable goods sales is given by

$$\begin{aligned} \sigma_q^2 &= \sigma_y^2 + 2\sigma_v^2 - 2cov(y_t, v_t) \\ &= \sigma_y^2 + 2(1-\delta)\sigma_v^2 - 2P\rho\sigma_\varepsilon^2. \end{aligned}$$

Since $\sigma_v^2 = P^2\sigma_\varepsilon^2$, we have

$$\sigma_y^2 - \sigma_q^2 = 2P[\rho + (\delta - 1)P]\sigma_\varepsilon^2, \tag{12}$$

which increases with δ, suggesting that the variability of production relative to that of sales decreases as the durability of consumption goods increases. Furthermore, $\sigma_y^2 - \sigma_q^2 < 0$ if $\delta < 1 - \frac{\rho}{P} (\in [0,1)$ if $\rho < P)$.■

Clearly, equation (12) shows that when $\delta = 1, \sigma_y^2 > \sigma_q^2$ as long as $\rho > 0$. This is the result of Kahn (1987). However, as the durability of consumption goods increases (δ decreases), the persistence of preference shocks (ρ) has to increase even further (e.g., $\rho > P$) in order to ensure that production is more variable than sales.

Proposition 4 *The absolute variance of production decreases as the durability of consumption goods increases (i.e., as the rate of depreciation δ decreases).*

Proof. Denote $x_t \equiv E_{t-1}\theta_t - \beta\delta a$ and $v_t \equiv \min\{k, \varepsilon_{t-1}\}$. Note that the covariances, $cov(x_t, v_t) = P \times cov(x_t, \varepsilon_t) = P\rho\sigma_\varepsilon^2$ and $cov(x_{t-1}, v_t) = 0$, where P denotes $\Pr[\varepsilon > k]$. Also note that the variances, $\sigma_x^2, \sigma_v^2, \sigma_\varepsilon^2$ as well as P, do not depend on δ. The decision rule for production can be rewritten as

$$y_t = x_t - (1-\delta)x_{t-1} + \delta v_t,$$

and the variance of production is then

$$\begin{aligned}
\sigma_y^2 &= \sigma_x^2 + (1-\delta)^2\sigma_x^2 - 2(1-\delta)cov(x_t, x_{t-1}) + \delta^2\sigma_v^2 + 2\delta cov(x_t, v_t) \\
&= \left[1 + (1-\delta)^2 - 2(1-\delta)\rho\right]\sigma_x^2 + \delta^2\sigma_v^2 + 2\delta P\rho\sigma_\varepsilon^2 \\
&> \delta^2\sigma_x^2 + \delta^2\sigma_v^2 + 2\delta P\rho\sigma_\varepsilon^2,
\end{aligned}$$

where the inequality comes from $\rho < 1$. Hence, $\frac{\partial\sigma_y^2}{\partial\delta} > 0$.■

Proposition (4) shows that the absolute variance of production decreases as durability increases, suggesting that given the same variance of preference shocks, production should be less volatile in durable goods than in nondurable goods. The reality, however, is that durable goods production is 5 to 6 times more volatile than nondurable goods production in the US. To get a sense of what this implies for preference shocks, compare the variances of production when $\delta = 1$ and $\delta = 0$ ($\delta \approx 0.025$ in the US). Since $\sigma_x^2 = \rho^2\sigma_\theta^2$ and $\sigma_v^2 = P^2\sigma_\varepsilon^2$, we have

$$\sigma_y^2 = \begin{cases} \rho^2\sigma_\theta^2 + (P^2 + 2P\rho)\sigma_\varepsilon^2 & \text{if } \delta = 1 \\ 2(1-\rho)\rho^2\sigma_\theta^2 & \text{if } \delta = 0 \end{cases}$$

Clearly, if $\delta = 1$ the variance of production increases with ρ, and if $\delta = 0$ the variance of production decreases either when $\rho \to 1$ or when $\rho \to 0$. Under these circumstances, the variance ratio of production between nondurable goods and durable goods can be close to infinity if ρ is too large or too small. Since the variance of durable goods production reaches a maximum of $\frac{8}{27}\sigma_\theta^2$ when $\rho = \frac{2}{3}$, the minimum variance ratio between nondurable and durable goods production is (note: $\sigma_\theta^2 = \frac{1}{1-\rho^2}\sigma_\varepsilon^2$)

$$\frac{\rho^2\sigma_\theta^2 + (P^2 + 2P\rho)\sigma_\varepsilon^2}{2(1-\rho)\rho^2\sigma_\theta^2} = \frac{3}{2} + \frac{15}{8}\left(P^2 + \frac{4}{3}P\right).$$

Suppose $\Pr[\varepsilon > k] \approx 0.5$ then this minimum ratio is greater than 3. Hence, unless we are willing to assume that preference shocks to durable goods consumption are separated from shocks to nondurable goods consumption and are at least $3 \times 5 = 15$ times larger than shocks to nondurable goods consumption in terms of variance, the stockout-avoidance theory is hard to reconcile with the stylized fact that durable goods production is 5 to 6 times more volatile than nondurable goods production.[6]

3 Concluding Remarks

The key to the stockout-avoidance theory of Kahn (1987) is its emphasis on demand uncertainty. However, under demand shocks purchases of durable goods are not necessarily more volatile than that of nondurable goods given the variance of shocks. Furthermore, once consumption goods become durable, there is less need for production to respond to innovations in demand under the stockout-avoidance motive for holding inventories, rendering production far less variable in both absolute terms and relative terms. Hence, unless we think that durable goods consumption and nondurable goods consumption are subject to entirely different sources of shocks with dramatically different variances, it is puzzling to observe that production and inven-

[6] In addition, proposition (2) also shows that the volatility of inventory investment is not affected by durability. Hence, even if a 15 times difference in variance between the two different types of shocks were possible, the model would not then be able to explain the volatility ratio of inventory investment between durable and nondurable goods industries. Furthermore, the assumption of independent sources of shocks is not appealing given the fact that durable and nondurable goods demand are highly positively correlated over the business cycle.

tory investment are 5 to 6 times more variable in durable goods than in nondurable goods.

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