Dynamic Pricing and Inventory Management under Fluctuating Procurement Costs

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Motivation

Current global market: Prices of many commodities are now fluctuating as much in a single day as they did in a year in the early 1990s (Wiggins and Blas 2008).

![Crude Oil Prices Since 1986](image-url)
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Goal of our paper: To study the optimal joint pricing and inventory policy of a firm under fluctuating procurement costs.
Introduction

Under procurement cost fluctuation:

1. Inventory Management
   - Uncertainty from both supply and demand sides
   - Inventory becomes a risky asset to invest on.

2. Dynamic Pricing
   - Share the cost risk with customers.
   - Control demand to consume its inventory in a most profitable way.

3. Supply Diversification
   - Procure inventory from a portfolio of complementary sources.
   - Enjoy both the responsiveness and risk reduction.
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Research Questions

In our study, we strive to answer the following questions:

1. What is the structure of the optimal pricing and inventory policy under cost fluctuation?
2. How do the fluctuating costs impact the firm's pricing and inventory decisions? Or how does the firm optimally respond to the cost fluctuation?
3. How does the dual-sourcing policy affect the pricing and inventory decisions?
4. How significant is the value of dynamic pricing and dual-sourcing? Are they strategic complements or substitutes?
5. What is the risk attitude of a firm towards the procurement cost fluctuation?
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Outline

- Contributions and Related Literature
- Model formulation
- Analytical and Numerical results
- Conclusion: Managerial Insights
Contributions

1. We are the first to study joint pricing and inventory management under fluctuating procurement costs. We characterize the optimal inventory replenishment and pricing policy structure in the sole- and dual-sourcing models with and without inventory re-selling.

2. We characterize the impact of fluctuating procurement costs on the firm's procurement and pricing policies.

3. We show that the value of dynamic pricing and dual-sourcing under cost volatility is significant and that they are strategic complements.

4. We find the risk-seeking attitude of a risk-neutral firm under procurement cost fluctuation.
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Literature Review

We are at the cross roads of two streams of literature:

- Our paper: Joint pricing-inventory management under demand uncertainty and cost fluctuation.
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- Inventory management under fluctuating cost:
  - Kalymon (1971)
  - Berlin and Martínez-de-Albéniz (2011)
  - Goel and Gutierrez (2011)
  - Chen et al. (2013).

- Joint price and inventory control:
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Model Formulation: Basics

- A risk-neutral firm procures raw material inventory from a spot market, produces an end-product in an MTO fashion, and prices the product in a final market.

- \( T \) periods in total, labeled backwards, full backorder.

- Sequence of events in period \( t \):
  - Period \( t \) starts
  - Cost realized
  - Decisions made
  - Production happens to satisfy demand
  - Demand Realized
Model Formulation: Demand

\[ D_t = d(p_t) + \epsilon_t. \]

- \( \epsilon_t \): i.i.d. continuous random variables, with \( \mathbb{E}\{\epsilon_t\} = 0. \)

- \( d(\cdot) \): strictly decreasing function of \( p_t \), the sales price of the product, with strictly decreasing inverse \( p(\cdot) \) in the expected demand, \( d_t \).
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**Assumption 1**

\[ R(d_t) := p(d_t)d_t \] is continuously differentiable and strictly concave.

Remark: The concavity of \( R(\cdot) \) implies the decreasing marginal revenue with respect to demand.
Model Formulation: Cost Process

\[ c_{t-1} = s_t(c_t, \xi_t). \]

- \( s_t(\cdot, \cdot) > 0 \text{ a.s., increasing in } c_t \text{ for any given } \xi_t. \)

- \( \xi_t: \) The random perturbation in the cost dynamics.
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- \( \xi_t \): The random perturbation in the cost dynamics.

- \( \mu_t(c_t) := \mathbb{E}\{s_t(c_t, \xi_t)\} < +\infty \) is increasing in \( c_t \).
States, Decisions and Primitives

State variable \( (I_t, c_t) \):
- \( I_t \) = net inventory before replenishment at the beginning of period \( t \).
- \( c_t \) = realized procurement cost in period \( t \).

Decision variable \( (x_t, d_t) \):
- \( x_t \) = net inventory after replenishment in period \( t \).
- \( d_t \) = expected demand in period \( t \).

Model Primitives:
- \( \beta = 1 + \gamma \) = discount factor, where \( \gamma \) is the risk-free interest rate.
- \( b \) = backlogging cost per unit backlogged at the end of a period.
- \( h \) = holding cost per unit stocked at the end of a period.
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Sole-sourcing Model

- The firm procures from a **spot market only** and cannot resell the excess inventory to the spot market.

\[ V_t(l_t|c_t) = \text{the maximal expected discounted profits in periods } t, t - 1, \ldots 1 \text{ with starting inventory } l_t \text{ and cost } c_t \text{ in period } t. \]
The firm procures from a spot market only and cannot resell the excess inventory to the spot market.

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with starting inventory \( I_t \) and cost \( c_t \) in period \( t \).

Terminal condition: \( V_0(I_0|c_0) = 0 \), with \( c_0 = s_1(c_1, \xi_1) \). i.e., excess inventory is discarded without any salvage value in the last period.
Bellman Equation

$V_t(l_t|c_t)$ satisfies the following Bellman equation:

$$V_t(l_t|c_t) = c_t l_t + \max_{x_t \geq l_t, d_t \in [d, d]} J_t(x_t, d_t|c_t),$$

where

$$J_t(x_t, d_t|c_t) = -c_t l_t + \mathbb{E}\{p(d_t)D_t - c_t(x_t - l_t) - h(x_t - D_t)^+ - b(x_t - D_t)^-$$

$$+ \alpha V_{t-1}(x_t - D_t|s_t(c_t, \xi_t))\}$$

$$= R(d_t|c_t) + (b - c_t + \alpha \mu_t(c_t)) x_t + G_t(x_t - d_t|c_t),$$

with $R(d_t|c_t) := (p(d_t) - b - \alpha \mu_t(c_t)) d_t$ and

$$G_t(y|c_t) := \mathbb{E}\{-(h+b)(y-\epsilon_t)^+ + \alpha [V_{t-1}(y-\epsilon_t|s_t(c_t, \xi_t)) - s_t(c_t, \xi_t)(y-\epsilon_t)]\}.$$
Dual-sourcing Model

- The firm procures from the spot market or signs a forward-buying contract, without inventory reselling. The expiration time of the forward-buying contract is 1 period. i.e., the inventory ordered in period $t$ is received at the beginning of period $t - 1$. 

Forward-buying contract: $(f_t, q_t)$, where $f_t = \frac{\gamma c_t}{\alpha}$, with $0 < \gamma < 1$ as the pre-order discount and/or convenience yield. In period $t$, the firm receives $q_t$ unit of inventory and pays $f_t q_t$. 

Terminal condition: $V_d(0, c_0) = 0$, with $c_0 = s_1(c_1, \xi_1)$. 

$I_t$ = the sum of the on-hand and pipeline inventories. 

$V_d(t, c_t)$ = the maximal expected discounted profit in periods $t$, $t-1$, $t-2$, ...
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- $l_t = \text{the sum of the on-hand and pipeline inventories.}$

- Terminal condition: $V_0^d(l_0|c_0) = 0$, with $c_0 = s_1(c_1, \xi_1)$.
Bellman Equation

\[ V_t^d(l_t | c_t) \] satisfies the following Bellman equation:

\[ V_t^d(l_t | c_t) = c_t l_t + \max_{x_t \geq l_t, q_t \geq 0, d_t \in [d, \bar{d}]} J_t^d(x_t, q_t, d_t | c_t), \]

where

\[ J_t^d(x_t, q_t, d_t | c_t) = -c_t l_t + \mathbb{E}\{p(d_t)D_t - c_t(x_t - l_t) - \gamma c_t q_t - h(x_t - D_t)^+ \]
\[ - b(x_t - D_t)^- + \alpha V_{t-1}^d(x_t + q_t - D_t | s_t(c_t, \xi_t))\}
\[ = R(d_t | c_t) + (b - c_t + \alpha \mu_t(c_t))x_t + (\alpha \mu_t(c_t) - \gamma c_t)q_t \]
\[ + L(x_t - d_t) + H_t^d(x_t + q_t - d_t | c_t), \]

with \( L(y) := \mathbb{E}[-(b + h)(y - \epsilon_t)^+] \) and

\[ H_t^d(y | c_t) := \alpha \mathbb{E}[V_{t-1}^d(y - \epsilon_t | s_t(c_t, \xi_t)) - s_t(c_t, \xi_t)(y - \epsilon_t)]. \]
Optimal Policy Structure

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2. **Cost-dependent order-up-to/pre-order-up-to list-price policy.** (Dual-sourcing, without inventory reselling)

\[ \text{Via both sources } x_t^d(c_t) \quad \text{Forward-buying only } x_t^d(c_t) + q_t^d(c_t) \quad \text{Not order anything} \]
Optimal Policy Structure with Inventory Reselling

With inventory reselling:

1. Starting inventory does not influence the optimal policy.

2. Dual-sourcing model is reduced to the sole-sourcing model for a risk-neutral firm.
Impact of Procurement Cost Fluctuation

1. The optimal sales price is increasing in the current procurement cost, i.e., the firm would like to pass its cost risk to customers.

2. The firm may respond to a higher spot market price by increasing or decreasing its safety-stock, order-up-to level and pre-order quantity (it's a tradeoff between current cost saving and future speculation opportunity).
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Impact of Procurement Cost Trend

1. The optimal sales price is increasing in the potential procurement cost trend, i.e., the firm should control its demand so as to consume its inventory in a most profitable fashion.

2. The firm should increase its safety-stock, order-up-to level and pre-order quantity with a higher future cost trend, i.e., the firm bets more on potentially higher future costs.
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Value of Dynamic Pricing and Dual-sourcing

1. Very significant value of dynamic pricing and dual-sourcing, at least 20% for the former and on average 7.9% for the latter.

2. Dual-sourcing motivates the firm to decrease its order-up-to level and sales price.

3. Dynamic pricing and dual-sourcing are strategic complements, i.e., the application of one strategy increases the value of the other.
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Risk-seeking Attitude of the Risk-neutral Firm

If the future procurement cost is concavely increasing in the current cost (e.g., Geometric Brownian Motion and mean-reverting process), the firm will earn more profit under a more volatile procurement cost process, i.e., the risk-neutral firm will exhibit a risk-seeking attitude towards the cost fluctuation risk.
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Conclusion: Managerial Insights

1. The impact of procurement cost fluctuation is significant and should not be ignored. Effective approaches:
   - Pass the cost risk to customers.
   - Carefully forecast future cost trends.

2. Dual-sourcing opportunity decreases the supply risk so that the firm keeps less inventory and less intensively passes risks to customers.

3. Dual-sourcing commits to the less responsive forward-buying channel, which increases the value of the flexibility to control demand via pricing.

4. Procurement cost fluctuation creates more opportunities than risks for a risk-neutral profit-maximizing firm.

5. The feedback mechanism partially contributes to the wild fluctuation of commodity prices in recent years.
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Q&A

Thank you!

Questions?