Dynamic Pricing and Inventory Management under Fluctuating Procurement Costs

Philip (Renyu) Zhang

(Joint work with Guang Xiao and Nan Yang)

Olin Business School
Washington University in St. Louis

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Motivation

Inventory management: To mitigate the demand uncertainty risk.
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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).
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- **Dynamic Pricing**: Dynamically adjust the sales price in each period.
  1. Demand control effect.
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  2. Portfolio effect among different sourcing channels.

Goal of our paper: To understand how to coordinate the dynamic pricing and dual-sourcing strategies to hedge against demand uncertainty and procurement cost fluctuation risks.
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Research Questions

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2. How to optimally respond to the cost fluctuation?

3. How does the dual-sourcing flexibility affect the optimal policy?

4. What is the relationship between dynamic pricing and dual-sourcing?
Outline

- Related Literature
- Model
- Impact of Cost Volatility
- Impact of Dual-Sourcing
- Conclusion: Takeaway Insights
Literature Review

Inventory management under fluctuating costs:
- Kalymon (1971),
- Berling and Martínez-de-Albéniz (2011),
- Chen et al. (2013).

Joint price & inventory control:
- Federgruen and Heching (1999),
- Zhou and Chao (2014).

Our paper: Joint pricing & inventory management under demand uncertainty, cost fluctuation, and dual-sourcing.
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Model Formulation: Basics

- A risk-neutral firm modeled as a $T$—period stochastic inventory system, labeled backwards, with discount factor $\alpha \in (0, 1)$.

- Maximize the total expected profit over the planning horizon.
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- Dual-sourcing:
  - Spot market: immediate delivery, fluctuating cost $c_t$.
  - Forward-buying contract: postponed delivery, with unit cost $F_t(c_t)$. 
Sequence of Events

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  - $x_t - I_t \geq 0$: spot-purchasing, delivered immediately;
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- Net inventory fully carried over to the next period:
  - Excess inventory fully carried over with unit cost $h$;
  - Unsatisfied demand fully backlogged with unit cost $b$. 
Demand Model

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

- \( \epsilon_t \): independent continuous random variables, with \( \mathbb{E}\{\epsilon_t\} = 0 \).
- \( d(\cdot) \): strictly decreasing function of \( p_t \), with a 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.
Spot-Market Price Fluctuation

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

- \( \xi_t \): The random perturbation in the cost dynamics.
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- \( s_t(\cdot, \cdot) > 0 \text{ a.s., and } s_t(\hat{c}_t, \xi_t) \geq_{s.d.} s_t(c_t, \xi_t) \text{ for any } \hat{c}_t > c_t. \)
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- \( \mu_t(c_t) := \mathbb{E}\{s_t(c_t, \xi_t)\} < +\infty \) is increasing in \( c_t \).
  - Perfect market: \( \mu_t(c_t) = c_t/\alpha. \)
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- Examples: GBMs, mean-reverting processes.
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- Inventory resale is not allowed: no room for arbitrage.
Forward-Buying Contract

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- Forward-buying contract: \((f_t, q_t)\):
  - The firm pays \(f_t q_t\) to the supplier in period \(t^e\);
  - The supplier delivers \(q_t\) to the firm in period \(t^e\);
  - For technical tractability, \(t^e = t - 1\).
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- \(f_t = \gamma c_t / \alpha\).
  - Effective unit cost: \(\gamma c_t\).
  - Perfect market: \(\gamma = 1\).
  - In general, \(f_t\) is determined through bilateral negotiations.
  - Most results hold for general \(f_t = F_t(c_t)\).
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- Focus on the operational effect of forward-buying.
  - The contract cannot be traded in the derivatives market.
Bellman Equation

\[ V_t(I_t|c_t) = \text{the maximal expected discounted profit in periods } t, t - 1, \ldots, 1 \]

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

Terminal condition: \( V_0(I_0|c_0) = 0 \).
Bellman Equation

\[ V_t(l_t|c_t) = \text{the maximal expected discounted profit in periods } t, t-1, \cdots, 1 \]

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

Terminal condition: \( V_0(l_0|c_0) = 0 \).

Bellman equation:

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

\[ J_t(x_t, q_t, d_t|c_t) = -c_l l_t + \mathbb{E}\{p(d_t)D_t - c_t(x_t - l_t) - \gamma c_t q_t - h(x_t - D_t)^+ \}
\]

\[ - b(x_t - D_t)^- + \alpha V_{t-1}(x_t + q_t - D_t|s_t(c_t, \xi_t)) \}
\]

\[ = R(d_t) - c_l x_t - \gamma c_t q_t + \Lambda(x_t - d_t) + \psi_t(x_t + q_t - d_t|c_t) \]

with \( \Lambda(y) = \mathbb{E}\{-h(y - \epsilon_t)^+ - b(y - \epsilon_t)^-\} \),

and \( \psi_t(y|c_t) = \mathbb{E}\{V_{t-1}(y - \epsilon_t|s_t(c_t, \xi_t))|c_t\} \).
Optimal Policy

- $(x_t^*(l_t, c_t), q_t^*(l_t, c_t), d_t^*(l_t, c_t))$: the optimal decisions in period $t$.
- $\Delta_t^*(l_t, c_t) := x_t^*(l_t, c_t) - d_t^*(l_t, c_t)$: the optimal safety stock.
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- The cost-dependent order-up-to/pre-order-up-to list-price policy.

- If \(l_t \leq x_t(c_t)\), order from both channels and charge a list price.

- If \(l_t \in [x_t(c_t), l_t^*(c_t)]\), order via the forward-buying contract only and charge a discounted price.

- If \(l_t \geq l_t^*(c_t)\), order nothing and charge a discounted price.
Impact of Cost Volatility

- Higher demand variability $\rightarrow$ lower profit.
Impact of Cost Volatility

- Higher demand variability → lower profit.

- Surprisingly, the prediction is reversed for cost volatility.

**Theorem 1**

For two procurement cost processes \( \{c_t\}_{t=1}^{T} \) and \( \{\hat{c}_t\}_{t=1}^{T} \), assume that for every \( t = T, T - 1, \ldots, 1 \), \( s_t(c_t, \xi_t) \) and \( \hat{s}_t(c_t, \xi_t) \) are concavely increasing in \( c_t \) for any realization of \( \xi_t \). The following statements hold:

(a) \( V_t(I_t|c_t) \) is convexly decreasing in \( c_t \), for any \( I_t \).

(b) If \( \{c_t\}_{t=1}^{T} \) and \( \{\hat{c}_t\}_{t=1}^{T} \) are identical except that \( \hat{s}_\tau(c_\tau, \xi_\tau) \geq_{cx} s_\tau(c_\tau, \xi_\tau) \) for some \( c_\tau \) and \( \tau \), \( \hat{V}_t(I_t|c_t) \geq V_t(I_t|c_t) \) for each \( (I_t, c_t) \) and \( t \), where \( \geq_{cx} \) refers to larger in convex order, and \( \{\hat{V}_t(I_t|c_t)\}_{t=1}^{T} \) are the value functions associated with \( \{\hat{c}_t\}_{t=1}^{T} \).
Impact of Cost Volatility (Cont’d)

- Higher cost volatility $\rightarrow$ higher profit.

The fundamental difference between demand and cost risks:

- Demand risk: decisions made prior to demand realization.
- Cost risk: decisions made posterior to cost realization.

The impact of decision timing with respect to uncertainty realization in capacity management and newsvendor network models with responsive/postponed pricing: Van Mieghem and Dada (1999), Chod and Rudi (2005) and Bish et al. (2012).
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- Responding to cost volatility.

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Impact of Cost Volatility: Assumptions

- Risk neutrality is necessary for Theorem 1 to hold.

- The concavity of $s_t(c_t, \xi_t)$ generally can be satisfied (e.g., GBMs, mean-reverting processes).

- When $s_t(c_t, \xi_t)$ is not concave in $c_t$, the result holds for the majority of numerical cases (except when the initial cost is low), in particular when the initial cost follows the stationary distribution.
Optimal Response to Cost Volatility

- Optimal sales price: $d_t^*(l_t, c_t) \downarrow c_t$, i.e., $p_t^*(l_t, c_t) \uparrow c_t$. The firm passes (part of) the cost risk to customers.
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$$J_t(x_t, q_t, d_t | c_t) = [R(d_t) - c_t d_t] + [\Lambda(\Delta_t) - (1 - \gamma)c_t \Delta_t]$$
$$+ [\Psi_t(\Delta_t + q_t | c_t) - \gamma c_t (\Delta_t + q_t)].$$

- Three objectives: (a) generating revenue, (b) hedging against demand uncertainty, and (c) speculating on future costs.
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- Three objectives: (a) generating revenue, (b) hedging against demand uncertainty, and (c) speculating on future costs.

- Optimal safety-stock and spot-purchasing: \( \Delta_t(c_t), x_t(c_t) \downarrow c_t \), if \( \gamma \leq 1 \); \( \Delta_t(c_t) \uparrow c_t \), if \( \gamma > 1 \).
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- Optimal forward-buying quantity: generally not monotone in $c_t$.

- Higher future cost trend $\rightarrow d_t^*(l_t, c_t) \downarrow, x_t^*(l_t, c_t) \uparrow, \Delta_t^*(l_t, c_t) \uparrow$, and $q_t^*(l_t, c_t) \uparrow$. 
Impact of Dual-Sourcing Flexibility

- \( \gamma \): the cost ratio between forward-buying and spot-purchasing. Lower \( \gamma \) implies higher dual-sourcing flexibility.
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  - $\gamma \downarrow \rightarrow d^*_t(l_t, c_t) \uparrow, x^*_t(l_t, c_t) \downarrow, \Delta^*_t(l_t, c_t) \downarrow$.

- $q^*_t(l_t, c_t)$ may not be monotone in $\gamma$, because lower $\gamma$ also decreases the marginal value of inventory in future periods.
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- $q_t^*(l_t, c_t)$ may not be monotone in $\gamma$, because lower $\gamma$ also decreases the marginal value of inventory in future periods.

- When $\gamma$ is big enough ($\gamma \geq \sup\{\frac{\alpha_{\mu_t}(c_t)}{c_t}\}$), the model is reduced to one with sole-sourcing from spot market alone.
  - Dual-sourcing $\rightarrow d_t^*(l_t, c_t) \uparrow, x_t^*(l_t, c_t) \downarrow, \Delta_t^*(l_t, c_t) \downarrow$ (Zhou and Chao, 2014).
Value of Dynamic Pricing and Dual-sourcing

- 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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- Compared with Zhou and Chao (2014), cost volatility renders the value of dynamic pricing and dual-sourcing significantly higher.
Conclusion: Takeaway Insights

- A risk-neutral firm benefits from the procurement cost volatility.
- Timing of decision making and uncertainty realization.
- Dynamic pricing and dual-sourcing are strategic complements.
- Dynamic pricing dampens both demand and cost risks, while dual-sourcing mitigates the cost risk but intensifies the demand risk.
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Thank you!

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