Stockups, Stockouts, and the Role for Strategic Reserves

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Motivation

- Numerous supply disruptions have occurred in the U.S. in recent years:
  1. Gasoline shortage caused by Colonial Pipeline ransomware attack in May 2021
  2. Semiconductor chip shortage caused by the pandemic
  3. Baby formula shortage caused by the shutdown of Abbott Nutrition's plant
- Obvious response: stockpiling
  - Firms: Sanz (2024), Alicke et al (2022)
  - Consumers: Amaral et al (2022), Kilander (2021)

This paper: Consumer stockpiling + dynamic pricing/inventory when facing supply disruptions

- How does consumers' ability to stockpile affect firm inventory and pricing?
- Identify two economic distortions
- Explore potential remedies: rationing, price controls, and strategic reserves.

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Preview

1. Equilibrium Dynamics
   - Normal phase -> no stockpiling -> mixing period -> price hike
   - Firm mixes over when to hike the price
   - Fraction of consumers with stockpile increases over time

2. Economic Implications of Consumer Stockpiling
   - Decreases firm profits
     - Rationing is good for the firm!
   - Benefits consumers

3. Strategic Reserves
   - Resolves underprovision of buffer stock (through quantity) and allocative distortion (through influence on firm pricing)
   - Can achieve the social optimum

Related Literature

Self-Fulfilling Shortages

- Niedermayer (2021), Awaya and Krishna (2021), Klumpp (2021)

Consumer Stockpiling

- Guo and Villas-Boas (2007), Anton and Varma (2005), Hong et al (2002), Gangwar et al (2014), Antoniou and Fiocco (2023)

Strategic Reserves

- Nichols and Zeckhauser (1977)

Dynamic Pricing

- Benabou (1989), Garrett (2016), Dilme and Li (2019)

Model

- Monopolist firm
  - Converts an input good into output good
  - Sells output good to consumers
- Mass of consumers
  - Unit flow demand for the good
  - Heterogeneous values: $v_H > v_L$
  - Measure ϕ have high value, $1 - \phi$ have low value
- All players: risk-neutral, infinitely lived, discount rate $r = 0$

Supply Disruptions

- There are two phases: normal and disruption
  - Normal phase: Firm can purchase input good at unit cost normalized to zero
  - Disruption phase: Firm cannot purchase input good. Must rely on inventory.

- The game begins in the normal phase
  - Disruption arrives at rate λ
  - Disruption is an absorbing state
    - Extension to transitory disruptions

Storage Technology

Firm

- Flow inventory carrying cost $\rho > 0$ per unit
- Unlimited capacity

Consumers

- Purchase flow demand from firm if their value exceeds the price
- Can also *stock up*
  - Purchase a fixed atom of γ units
  - Flow inventory carrying cost of $\bar{\rho} \geq \rho$ per unit

Strategies

Firm

- Inventory level to hold in normal times
- When to raise the price (from v_L to v_H) after a disruption

Consumers

- When to stock up (if ever)

Parametric Assumptions

Assumption 1

$$v_L > \phi v_H$$

- Firm sells to all consumers in normal times

Assumption 2

$$v_L - \rho/\lambda > 0$$

- It is optimal for the firm to hold a buffer stock

Benchmark

- k_0: buffer stock of inventory firm holds in normal state
- k_1: inventory level at which firm raises price during disruption

Firm expected profit is

$$\Pi(k_0, k_1) = \underbrace{\frac{1}{\lambda}(v_L - \rho k_0)}_{\text{Normal state}} + \underbrace{v_L(k_0 - k_1) + v_H k_1 - \frac{\rho}{2}(k_0^2 - k_1^2) - \frac{\rho}{2\phi}k_1^2}_{\text{Disruption state}}$$

First-order conditions give:

$$k_0^* = \frac{v_L - \rho/\lambda}{\rho} \qquad k_1^* = \frac{\phi(v_H - v_L)}{\rho(1-\phi)}$$

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Benchmark

Proposition 1

In the no-storage benchmark:

(i) *If* $k_0^* > k_1^*$*, then the firm carries buffer* k_0^* *in the normal phase and raises the price when inventory reaches* k_1^* *during the disruption.*

(ii) *Otherwise, the firm holds buffer* $k_0^\dagger = \frac{\phi}{\rho}\left(v_H - \frac{\rho}{\lambda}\right)$ *in the normal phase and raises the price immediately when the disruption hits.*

Illustration

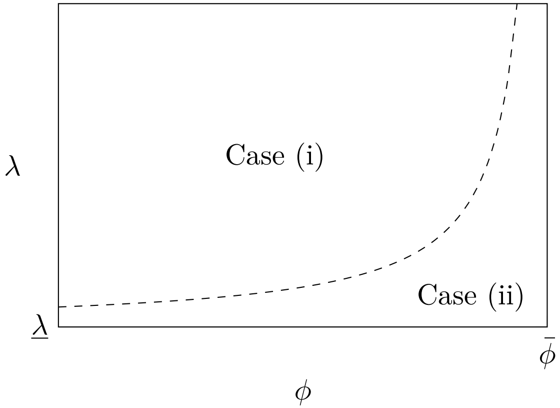

Figure: In the NW region, $k_0^* > k_1^*$, and the price remains at v_L when the disruption hits. In the SE region, the firm increases the price to v_H when the disruption hits.

Planner's solution

Planner's problem is to maximize total surplus:

$$\Pi(k_0, k_1) + \phi(v_H - v_L)(k_0 - k_1)$$

First-order conditions yield:

$$\begin{aligned} k_0^{\mathrm{SP}} &:= k_0^* + \tfrac{\phi(v_H - v_L)}{\rho} \\ k_1^{\mathrm{SP}} &:= (1-\phi)k_1^* \quad (< k_0^{\mathrm{SP}}) \end{aligned}$$

Two Distortions

1. Firm holds too little buffer: $k_0^* < k_0^{\mathrm{SP}}$
   - since it does not capture all the surplus from its inventory
2. Firm raises the price too soon: $k_1^* > k_1^{\mathrm{SP}}$
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Model with Consumer Storage

Henceforth "consumer" means high-value consumer:

- A consumer who stocks up buys a fixed stockpile of γ units.
- A consumer is *full* if she has stocked up and *empty* if not.
- Full consumers do not eat stockpiles until price hike.
- Firm and consumers have perfect information
  - Observe the disruption occurrence, and history of firm/consumer inventory

Model with Consumer Storage

Assumption 3

(i) Consumer storage cost is weakly higher than firm's: $\bar{\rho} \geq \rho$.

(ii) Consumer stockpile size is bounded: $\gamma \leq \frac{v_H - v_L}{\bar{\rho}}$

- For talk will focus on $\bar{\rho} = \rho$.
- Stockpile size, γ, is not a choice.
- If γ small, consumers will optimally hold until price hike.

Model with Storage

- Equilibrium concept: Markov Perfect Equilibrium (MPE)
  - State variable is firm inventory (k) and mass of full consumers (z)

- The firm's strategy in the case (i) benchmark is **not** an equilibrium with stockpiling
  - All H consumers would stock up right before price hike
  - Firm should hike price right before stock up

- Ties broken in consumers favor (Consumer Priority Rule)
  - Only required at disruption onset
  - Akin to DT game where: 1) firm sets price, 2) disruption realized (or not), 3) consumers choose quantity

Disruption Subgame

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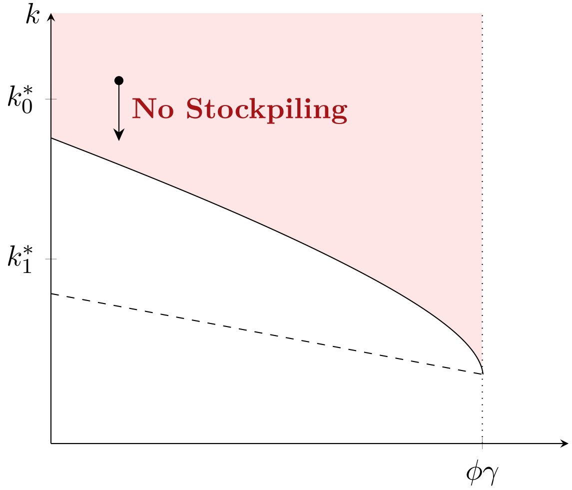


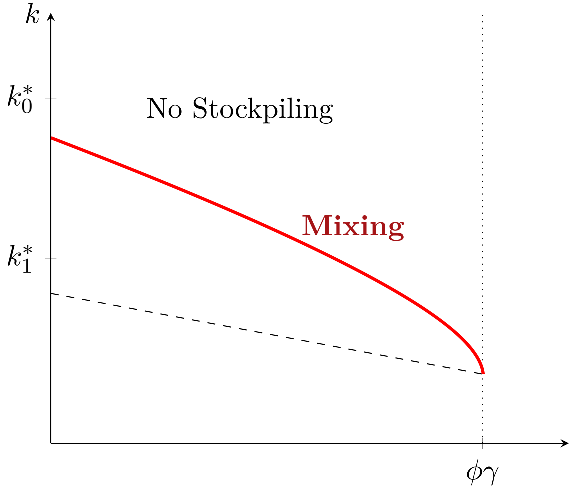
Consumers

- No one stocks up

Firm

- Keeps the price low

Disruption Subgame



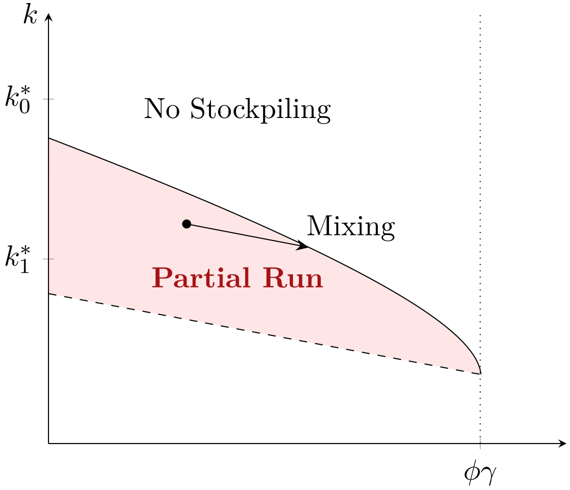
Consumers

- Consumers stockpile at rate μdt

Firm

- Hikes price with probability σdt

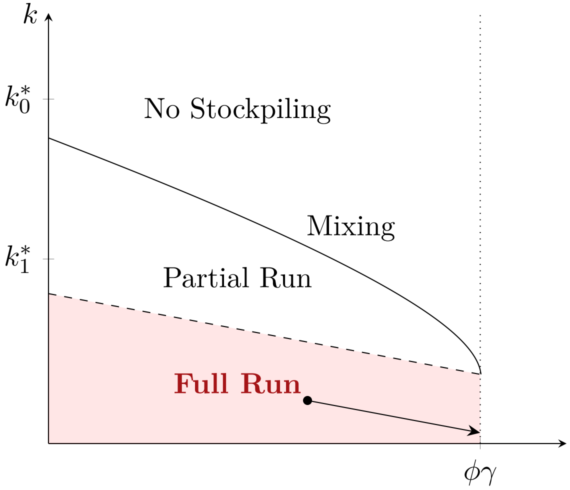
Disruption Subgame



<u>Consumers</u>

- Mass of empty consumers stock up
- Triggers mixing

Disruption Subgame



Consumers

- Empty consumers run to stock up

Firm

- Hikes the price immediately

Equilibrium Construction

Steps

1. Find σ that makes empty consumers indifferent
2. Characterize candidate $\dot{z}(\mu)$ for firm indifference
   - Yields a vector field
3. Argue that the terminal point of the mixing path is unique
   - Pins down a unique candidate mixing path
4. Verification (above and below the mixing path)

Firm mixing

After a price hike

- Empty consumer's get zero
- Full consumers get

$$V_F \equiv v_H\gamma - \bar{\rho}\int_0^{\gamma}(\gamma - t)dt = v_H\gamma - \frac{\bar{\rho}}{2}\gamma^2$$

Before a price hike

- Let σ denote the rate of the firm's hike
- Let f denote the value function of a full consumer prior to a hike

$$f(z,k) = (v_H - v_L - \bar{\rho}\gamma)dt + \sigma dt V_F + (1-\sigma dt)f(z+\dot{z}dt, k+\dot{k}dt) \tag{1}$$

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Firm mixing

The indifference condition for empty consumers is

$$\underbrace{f(z,k) - v_L\gamma}_{\text{Stockpiling today}} = \underbrace{(v_H - v_L)dt + (1-\sigma dt)(f(z+\dot{z}dt, k+\dot{k}dt) - v_L\gamma)}_{\text{Stockpiling tomorrow}} \tag{2}$$

Substituting (1) into (2) and canceling like terms, we are left with

$$\underbrace{\sigma(V_F - v_L\gamma)}_{\text{Benefit}} = \underbrace{\bar{p}\gamma}_{\text{Cost}}$$

So, the equilibrium rate of a price hike is $\sigma^* = \frac{\bar{p}\gamma}{V_F - v_L\gamma}$

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Consumer stockpiling

Suppose the firm raises price at (z, k), then full consumers deplete their stockpiles, and the firm's continuation profit is

$$F(z,k) = \underbrace{v_H k}_{\text{(i)}} - \overbrace{\rho\gamma\left(k - \frac{1}{2}(\phi\gamma - z)\right)}^{\text{(ii)}} - \underbrace{\frac{\rho}{2\phi}(k - (\phi\gamma - z))^2}_{\text{(iii)}} \tag{3}$$

(i) Revenue from selling k at price v_H.

(ii) Carrying cost from selling only to empties while fulls deplete.

(iii) Carrying cost from selling to all consumers after stockpiles are depleted.

Consumer stockpiling

If empties stockpile at rate μ, then z changes at rate

$$\dot{z} = \mu\gamma \underbrace{\left(\phi - \frac{z}{\gamma}\right)}_{\text{mass of empties}}$$

Firm must be indifferent about hiking immediately or waiting:

$$\underbrace{F(z,k)}_{\text{hike today}} = \underbrace{(v_L(1+\dot{z}) - \rho k)dt + F(z+\dot{z}dt, k+\dot{k}dt)}_{\text{hike tomorrow}}$$

Using a Taylor expansion and $\dot{k} = -(1+\dot{z})$, the indifference condition becomes:

$$0 = v_L(1+\dot{z}) - \rho k + F_z\dot{z} - F_k(1+\dot{z}). \tag{4}$$

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Making Sense of the Indifference Condition

Using (3) to evaluate F_z and F_k

$$F_z = -\rho\left(\frac{k+z}{\phi} - \frac{\gamma}{2}\right), \quad F_k = v_H - \rho\left(\frac{k+z}{\phi}\right)$$

So the indifference condition becomes

$$\underbrace{(v_H - v_L)(1+\dot{z})}_{\text{benefit of hike today}} = \underbrace{\rho\left(\frac{k+z}{\phi} - k + \frac{\gamma}{2}\dot{z}\right)}_{\text{cost of hike today}}$$

- Benefit: more units sold at v_H
- Cost: higher inventory cost
  - Full and L consumers don't buy today
  - Empties don't stockpile

Consumer stockpiling

Solving (4) for $\dot{z}$ yields:

$$\dot{z} = \frac{k - \left(k_1^* - \frac{z}{1-\phi}\right)}{k_1^* - \frac{\phi\gamma}{2(1-\phi)}}$$

- Note that $\dot{z} = 0$ when $k = k_1(z) \equiv k_1^* - \frac{z}{1-\phi}$.
  - For $k < k_1(z)$, firm prefers to hike even without more stockpiling.
  - Ergo, mixing must end weakly before $k = k_1(z)$.

Equilibrium Mixing Path

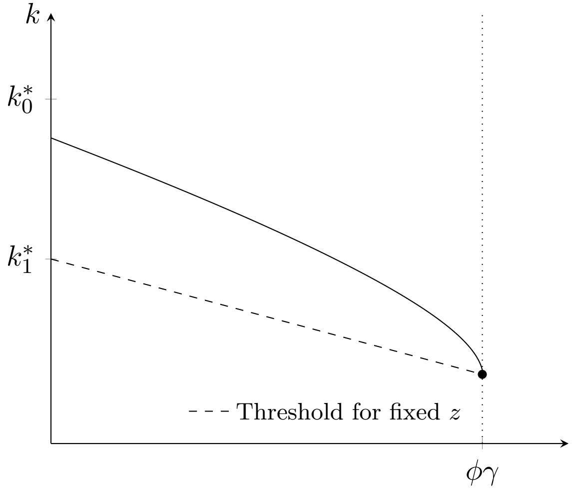
Lemma 1

The mixing period terminates when all consumers are full (i.e., $z = \phi\gamma$) and $k = k_1(\phi\gamma)$, at which point the firm raises the price with probability one.

- This pins down the terminal point of the mixing path
- The (unique) path can then be constructed from the ODE

$$\frac{dk}{dz} = -\frac{1+\dot{z}}{\dot{z}}$$

Illustrative Proof of Lemma 1



- Why is the path unique?

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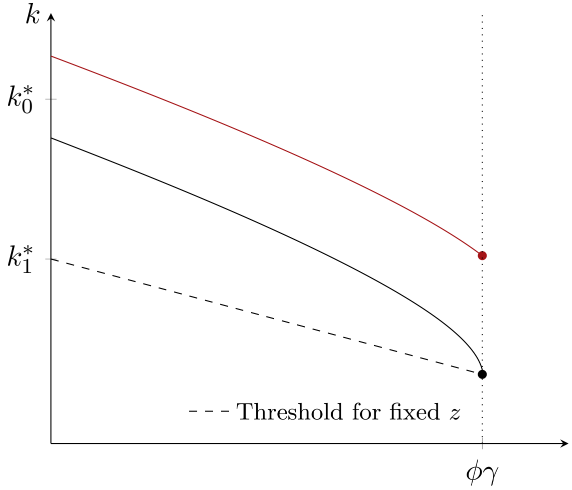

Above the equilibrium path?

- Eventually $z = \phi$
  - $\dot{z} = 0$ thereafter
- But then the firm wants to keep the price low
- Recent stock ups not optimal

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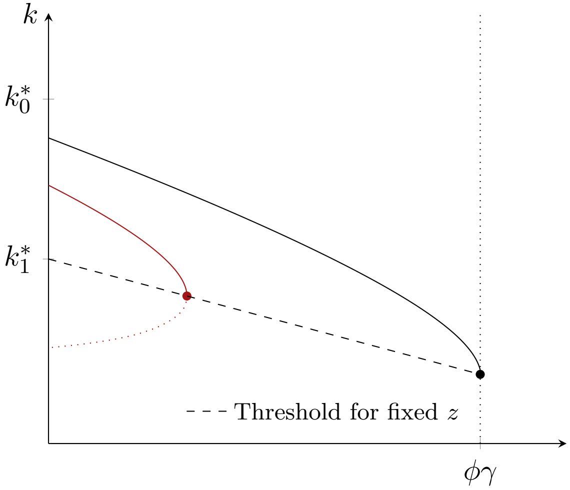


Below the equilibrium path?

- Firm hikes price when path hits threshold
- Empty consumers should stock up beforehand

The Equilibrium Mixing Path

Solving the mixing path ODE with the terminal condition in Lemma 1 yields the following.

Lemma 2

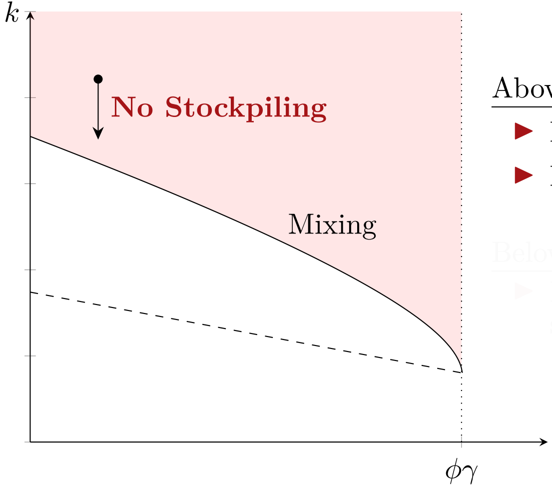
The unique equilibrium mixing path in the disruption phase, $\hat{k}(z)$, is given by

$$\hat{k}(z) = k_1(z) + \frac{1}{\underline{\sigma}}\left(1 + W\left(-e^{-1-\alpha\underline{\sigma}(\phi x - z)}\right)\right) \tag{5}$$

where W is the principal branch of the Lambert (aka product log) function.

For convenience define $\overline{k} \equiv \hat{k}(0)$ and $\underline{k} \equiv \hat{k}(\phi\gamma)$.

Off the Mixing Path



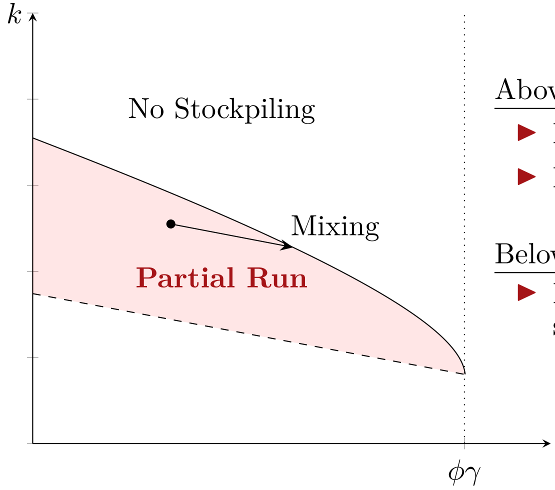
Above the Mixing Path

- No price hikes
- No consumer stockpiling

Below the Mixing Path

- Mass Δ of empty consumers “run” to stockpile
  1. Partial Run: State jumps to mixing path
  2. Full Run: All empty consumers stockpile

Off the Mixing Path



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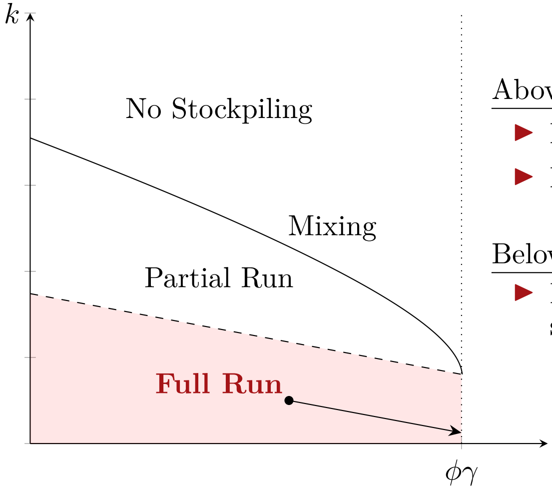

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Firm Buffer Stock Decision

The firm's buffer stock choice determines the initial state at the disruption onset.

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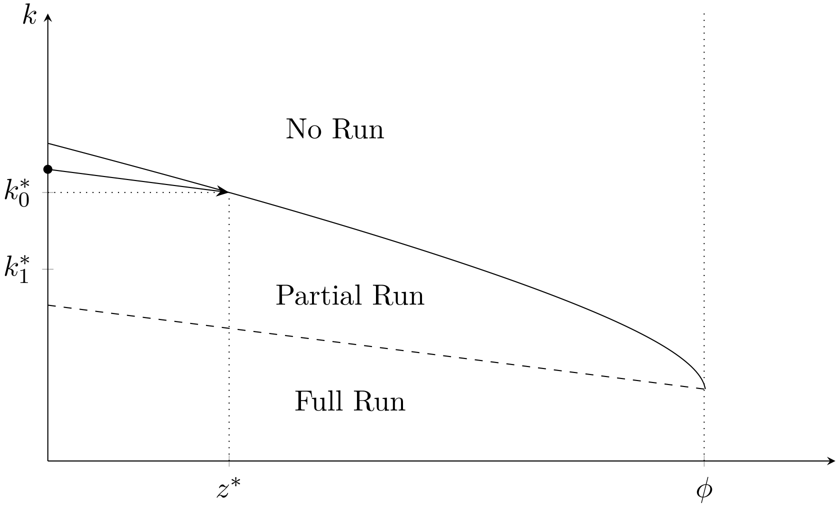
Proposition 2

The firm's buffer stock and equilibrium behavior at the disruption onset are as follows:

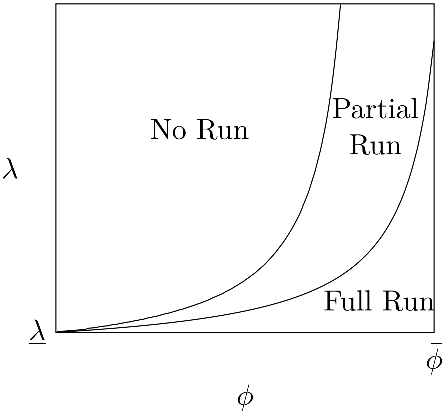
1. *If $k_0^* \geq \overline{k}$, the firm carries inventory k_0^* in the normal phase, and there is no run when the disruption hits. (The no-run regime.)*
2. *If $k_0^* \in (\underline{k} + \phi * \gamma, \overline{k})$, the firm carries inventory $k_0^* + \hat{k}^{-1}(k_0^*)$ in the normal phase, and there is a partial run when the disruption hits. (The partial-run regime.)*
3. *If $k_0^* \leq \underline{k} + \phi * \gamma$, the firm carries inventory $k_0^\dagger$ in the normal phase, and there is a full run when the disruption hits. (The full-run regime.)*

Partial Run Case: $k_0^* < \hat{k}(0)$



Regime Comparative Statics

- Higher $\lambda \Rightarrow$ higher k_0^*, but no effect on $\hat{k}$. So, no run when λ is high.
- Lower $\phi \Rightarrow \hat{k}$ shifts down, but no effect on k_0^*. So, no run when ϕ is low



Welfare Implications of Consumer Storage

Proposition 3

If $\bar{\rho} = \rho$, then, compared to the benchmark, consumer storage leads to:

(i) *A decrease in firm profit.*

(ii) *An increase in consumer surplus.*

(iii) *Total surplus that is lower in the no-run regime, unchanged in the full-run regime, and that can be higher (or lower) in the partial-run regime.*

Intuition for Welfare in the No-Run Regime

Price remains v_L after disruption onset and inventory is k_0^* in both cases.

- Why firm profit falls
  - Benchmark: price hiked at profit-maximizing k_1^*
  - Storage: profit is the same *as if* price hiked at $k = \bar{k} > k_1^*$

- Why consumer surplus rises
  - Benchmark CS: $(v_H - v_L)(k_0^* - k_1^*)$
  - Storage CS: $(v_H - v_L)\mathbb{E}[\tau] + (V_F - v_L\gamma)\Pr(\tau = \bar{\tau})$
  - When $\bar{\rho} = \rho$, $\mathbb{E}[\tau] = (k_0^* - k_1^*)$

- Why total surplus falls
  - Expected time of price hike is the same $\mathbb{E}[\tau] = k_0^* - k_1^*$.
  - But surplus is concave (due to quadratic storage costs). So, mixing destroys surplus by Jensen's inequality.

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  - Storage CS: $(v_H - v_L)\mathbb{E}[\tau] + (V_F - v_L\gamma)\Pr(\tau = \bar{\tau})$
  - When $\bar{\rho} = \rho$, $\mathbb{E}[\tau] = (k_0^* - k_1^*)$
- Why total surplus falls
  - Expected time of price hike is the same $\mathbb{E}[\tau] = k_0^* - k_1^*$.
  - But surplus is concave (due to quadratic storage costs). So, mixing destroys surplus by Jensen's inequality.

Welfare in the Full-Run and Partial-Run Regimes

- Full-Run: Why no change?
  - Inventory $k_0^\dagger$ and price hiked immediately in both cases.
  - With storage, all consumers run and appropriate surplus from firm.
  - Because $\bar{\rho} = \rho$ this is a pure transfer.
- Partial Run: Why welfare can be higher?
  - With storage, firm buffer is higher.
  - If mixing period is short (γ is low), then higher welfare with storage than without.

Policy Implications

- Rationing
  - If rationing prevents stockpiling, then benchmark obtains
    - Firm profits are higher, consumer surplus is lower
    - Total surplus higher in no-run regime, may be lower in partial-run regime
  - Rationing does not resolve benchmark distortions
- Price Controls
  - Prevents efficient allocation
  - Produces a run when $k = \phi\gamma$
  - Does not solve underprovision of inventory
- Strategic Reserves
  - Our focus

Strategic Reserves

- The US government maintains stockpiles of various goods that can be drawn upon during supply disruptions
  - Examples: medical equipment, petroleum, rare earth metals, helium, cheese
- Stated intention is for national security
  - Also subsidizes farmers
- Question: is there an economic role for strategic reserves (even absent national security considerations)?

Strategic Reserves

- We introduce a third player (the government, G)
  - Objective is to maximize total welfare
  - Can hold/release strategic reserves (of the output good)
  - Same inventory costs as the firm, ρ

Definition

A ***simple policy*** *is one where the government holds some amount Q of strategic reserves in the normal state and commits to sell them for a price of v_L during a disruption.*

Strategic Reserves

Proposition 4

When $\bar{\rho} = \rho$, the government can achieve the social optimum with a simple reserve policy.

Equilibrium Induced by a Simple Policy

The equilibrium of the disruption subgame has the following timing:

1. Firm sells $k_0 - k_1$ units, then raises the price to v_H and *waits*.
2. Government services flow demand until it has $\phi\gamma$ units remaining.
3. Consumers run to buy up the remaining government reserves.
4. Consumers deplete their stockpiles.
5. After waiting time $Q - \phi\gamma + \gamma$, firm (finally) sells k_1 units at price v_H.

Firm's Response

- $k_1(Q)$, $\downarrow$ in Q

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Intuition?

Recall the two distortions in the no stockpiling benchmark:

- Firm holds too little inventory
- Firm increases the price too soon

A simple policy helps alleviate both:

- Total buffer increases with Q
- Firm delays price hike in response to higher Q

Two distortions, one degree of freedom. Coincidence?

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Extensions

1. WHEN CONSUMER HAVE STRICTLY HIGHER STORAGE COSTS
   - Consumer surplus decreases with storage when $\bar{\rho}$ is high enough
   - A simple reserve policy and the associated "run on reserves" does not achieve the social optimum.

2. TRANSITORY DISRUPTION SHOCKS
   - Introduce transitory disruptions shocks (ξ) and discounting (δ)
   - Consumers can refund excess inventory (for tractability)
   - Equilibrium has the same structure, converges to baseline as $\xi, \delta \to 0$

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Strategic Reserves with $\bar{\rho} > \rho$

Result

With consumer storage and $\bar{\rho} > \rho$, the government can achieve the social optimum by holding Q^* in reserves and charging a price that increases as reserves are depleted.

- Holding Q^* in reserves, only to be sold to high types, is sufficient to prevent firm from a price hike
- Once firm inventory is exhausted, release reserves at a price (starting from v_L) that **gradually** increases as reserves are depleted
- Gradual price increase makes consumer indifferent to stockpiling because they will continue to service flow from reserves for some time so inventory costs are high

Conclusion

- Investigate price dynamics, inventory choice, and consumer stockpiling in the face of a supply disruption.
- Two economic distortions
  - Under-provision of good in disruption
  - Inefficient allocation of inventory
- Consumer stockpiling hurts the firm and benefits consumers
- Strategic reserves can restore the social optimum