Sharif University of Technology,
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# Examining the Implications of the Bullwhip Effect in Perishable Product Supply Chain and Its Mitigation through Buy-Back Contract Coordination

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## Presentation Outline

- Introduction and Research Motivation
- Problem Statement and Research Objectives
- Literature Review
- Methodology (Mathematical Modeling)
- Simulation Results and Comparative Analysis
- Managerial Implications and Recommendations
- Conclusions and Future Research Directions

# Introduction and Research Motivation

- Growing instability in global supply chains
- Severe challenges in managing perishable products
- Bullwhip effect worsens waste and inefficiency
- Lack of coordination → higher costs, lower service levels
- Strong need for integrated and incentive-aligned solutions

# Problem Statement & Research Objectives

**Problem Statement:**

- Perishable supply chains face amplified demand fluctuations due to the bullwhip effect.
- Decentralized systems worsen this issue through poor coordination and misaligned incentives.
- Spoilage and service failures increase overall inefficiency.
- Buy-back contracts may offer a solution to reduce volatility and improve alignment.

**Research Objectives:**

- Investigate the bullwhip effect in perishable product supply chains.
- Develop and compare models for centralized, decentralized, and coordinated (buy-back) systems.
- Represent perishability via fixed deterioration and price-sensitive demand.
- Assess how buy-back contracts improve efficiency and reduce waste.
- Provide insights for better supply chain strategies and policy-making.

# Literature Review

**Perishable Products in Supply Chains: Importance, Challenges, and Modeling Approaches**

- **High Vulnerability**: Short shelf-life, rapid quality decay → complex inventory & logistics.
- **Economic Losses**: $400B+ in global food waste; 20% of Canada's food production lost.
- **Environmental Impact**: Perishable waste → 8–10% of global GHG emissions.
- **Social Consequences**: Unequal food access, vaccine spoilage in cold-chain failures.
- **Bullwhip Effect Amplified**: Forecast errors → accelerated waste & overstocking.
- **Cold-Chain Complexity**: Requires strict temperature control, especially in vast geographies.
- **Behavioral Biases**: Over-ordering, misalignment in decentralized systems.
- **Need for Modeling**: Mathematical tools essential to optimize pricing, inventory & coordination.

# Modeling Approaches for Perishable Supply Chains

**Purpose:**
Enhance decision-making under perishability through analytical tools.

**Inventory Models:**
Modified EOQ & Newsvendor models to incorporate spoilage and dynamic pricing

## Deterioration functions:

| Decay Function Type | Mathematical Formulation | Application Context |
|---|---|---|
| Exponential | $I(t) = I_0 e^{-\theta t}$ | Dairy, pharmaceuticals, fresh produce |
| Linear | $I(t) = I_0 - \alpha t$ | Bakery, fresh vegetables |
| Stepwise | $I(t) = I_0 - \delta_n$(interval-based) | Vaccines, packaged perishables |
| Weibull Distribution | $I(t) = I_0 e^{-(t/\beta)^{\gamma}}$ | Seafood, meat products |

## Freshness-Sensitive Demand

| Demand Model Type | Mathematical Formulation | Key Parameters |
|---|---|---|
| Exponential Freshness-Sensitive | $D(t) = D_0 e^{-\alpha(T-t)}$ | α: Freshness sensitivity |
| Linear Freshness-Dependent | $D(t) = D_0 - \beta(T - t)$ | β: Linear freshness reduction rate |
| Stochastic Freshness-Sensitive | $D(t, \theta) = (D_0 + \varepsilon_t) e^{-\gamma(1-\theta)}$ | γ: Freshness sensitivity, $\varepsilon_t$: Demand shock |

## Role of Contractual Mechanisms:

- Align decentralized decisions across the supply chain
- Reduce inefficiencies from double marginalization and spoilage
- Promote risk-sharing and freshness-sensitive collaboration

| Contract Type | Key Mathematical Components | Main Benefits | Primary Limitations |
|---|---|---|---|
| **Revenue-Sharing** | Revenue distribution ($\phi$), pricing decisions | Reduced double marginalization | Implementation complexity |
| **Buy-Back** | Buy-back price (b), leftover stock quantity | Risk mitigation, inventory alignment | Potential moral hazard |
| **Quantity Flexibility** | Flexibility parameter ($\delta$), order deviations | Demand responsiveness, reduced uncertainty | Complexity in flexibility management |
| **Freshness-Dependent Incentive** | Freshness incentive rate ($\psi$), target freshness level ($F^*$) | Direct freshness incentives, waste reduction | Freshness measurement complexity |

# Model Development – Problem Description

**Supply Chain Structure:**

- Two-tier: 1 Manufacturer + 1 Retailer
- Product: Perishable (deteriorates at constant rate $\delta$)
- Time horizon: Single selling season, no restocking
- Demand: Linearly price-sensitive → $D(p) = \alpha - \beta p$

**Objectives:**

- Optimize **retail price (p)** and **order quantity (Q)**
- Analyze impact of **wholesale price (w)** and **buy-back incentive (b)**
- Compare **Decentralized**, **Centralized**, and **Coordinated** setups in terms of:

→ Profitability
→ Efficiency
→ Incentive alignment

# Supply Chain Modelling: Decentralized Structures (Stackelberg Game)

- Two-stage decision process:
  - **Manufacturer (Leader)** sets wholesale price *w*.
  - **Retailer (Follower)** selects retail price *p* and order quantity *Q*.

**Retailer's Profit Function:**

$$\pi_R = p\left[min\left(Q(1-\delta), D(p)\right)\right] - wQ - (h-s)max[0, Q(1-\delta) - D(p)] - kQ\delta$$

assuming available inventory after deterioration meets demand:

$$\pi_R = p(\alpha - \beta p) - wQ - kQ\delta$$

**Retailer's Optimization Problem**

- Maximize with respect to *p:* $\frac{d\pi_R}{dp} = 0$
- Optimal order quantity: $Q^*(w) = \frac{D(p^*(w))}{1-\delta}$

# Supply Chain Modelling: Decentralized Structure (Stackelberg Game)

**Manufacturer's Profit Function by** anticipating retailer's optimal response:

$$\pi_M = (w - c)Q^*(w)$$

**Manufacturer's Optimization Problem**

- Maximize with respect to *w:* $\frac{d\pi_M}{dw} = 0 \;\Rightarrow\; w^*$
- Obtain optimal wholesale price w*

**Total Supply Chain Profit:** $\pi_{Total} = \pi_R(p^*(w^*), Q^*(w^*); w^*) + \pi_M(w^*)$

# Supply Chain Modelling: Centralized Structure (Unified Optimization)

A single decision-maker optimizes both retail price $p$ and order quantity $Q$ to **maximize total supply chain profit**.
•Eliminates **double marginalization** and aligns incentives across the chain.

**Profit Function**
(Assuming supply meets demand Q(1−δ) =D(p) ) : $\pi_{SC} = p(\alpha - \beta p) - cQ - kQ\delta$
**Optimization Strategy**
•Maximize with respect to $p$: $\frac{d\pi_{SC}}{dp} = 0$
Compute optimal order quantity: $Q^*_{SC} = \frac{D(p^*_{SC})}{1-\delta}$
**Total Supply Chain Profit:** $\pi^*_{SC} = \pi_{SC}(p^*_{SC})$

# Supply Chain Modelling: Coordinated Structure (Buy-Back Contract)

**Contract Description**

**Retailer's Profit Function:**

$$\pi_R^{BB} = (p - w)(1 - \delta)D(p) + (b - h)(1 - \delta)(Q - D(p)) - k\delta Q$$

**Manufacturer's Profit Function:**

$$\pi_M^{BB} = (w - c)Q - b(1 - \delta)(Q - D(p))$$

**Total Supply Chain Profit:**

$$\pi_{SC}^{BB} = \pi_M^{BB} + \pi_R^{BB}$$

**Constraints for Optimization:**

- $Q > D(p)$
- $Q > 0, p > 0$
- $p > w$ , $b \leq p$, $h \leq b$

•**Optimization Strategy:**

Numerical maximization using **NMaximize** in Mathematica to jointly determine:

(b, p*, Q*)

# Comparative Analysis: Centralized, Decentralized and Coordinated

In decentralized supply chains, double marginalization leads to **higher retail prices** and **lower order quantities** compared to centralized systems. Centralized coordination improves system-wide efficiency by jointly optimizing pricing and inventory decisions.

| Decision Variable | Decentralized (Stackelberg) | Centralized |
|---|---|---|
| Retail Price p* | $\frac{3\alpha}{4\beta}+\frac{c+k\delta}{4(1-\delta)}$ | $\frac{\alpha}{2\beta}+\frac{c+k\delta}{2(1-\delta)})$ |
| Order Quantity Q* | $\frac{\alpha-\alpha\delta-\beta(c+k\delta)}{4(-1+\delta)^2}$ | $\frac{\alpha-\alpha\delta-\beta(c+k\delta)}{2(-1+\delta)^2}$ |
| Wholesale Price w* | $\frac{\alpha+c\beta-\alpha\delta-k\beta\delta}{2\beta}$ | – |

# Simulation Setup and Base Parameter Configuration

| Parameter | Symbol | Base Value | Description |
|---|---|---|---|
| **Demand Intercept** | α | 200 | Maximum market potential at zero price |
| **Price Sensitivity** | β | 1.5 | Rate at which demand decreases with price |
| **Unit Production Cost** | c | 20 | Manufacturer's cost per unit |
| **Spoilage Cost** | k | 5 | Cost incurred for each unsold, deteriorated unit |
| **Deterioration Rate** | δ | 0.3 | Fraction of stock lost to spoilage before sale |
| **Salvage Value** | s | 2 | Revenue recovered per unit of unsold but salvaged product |
| **Holding Cost** | h | 1 | Inventory holding cost per unsold unit (excluding spoilage) |
| **Buy-Back Price** | b | Variable | Price paid by manufacturer to buy back unsold, non-deteriorated units from the retailer |

## Simulation Focus:

- Optimize decisions: **p, Q, w, b**
- Compare supply chain efficiency under each structure
- Analyze impact of parameter changes (in sensitivity section)

# Optimal Outcomes across Supply Chain Structures

| Structure | Optimal Retail Price (p*) | Optimal Order Quantity (Q*) | Buy-Back Price (b*) | Total Profit ($\pi$) |
|---|---|---|---|---|
| **Centralized** | 82.02 | 109.95 | N/A | 3949.00 |
| **Decentralized (Stackelberg)** | 107.68 | 54.97 | N/A | 2961.75 |
| **Coordinated (Buy-Back)** | 74.25 | 106.35 | 40.00 | 3665.09 |

**Key Insights:**

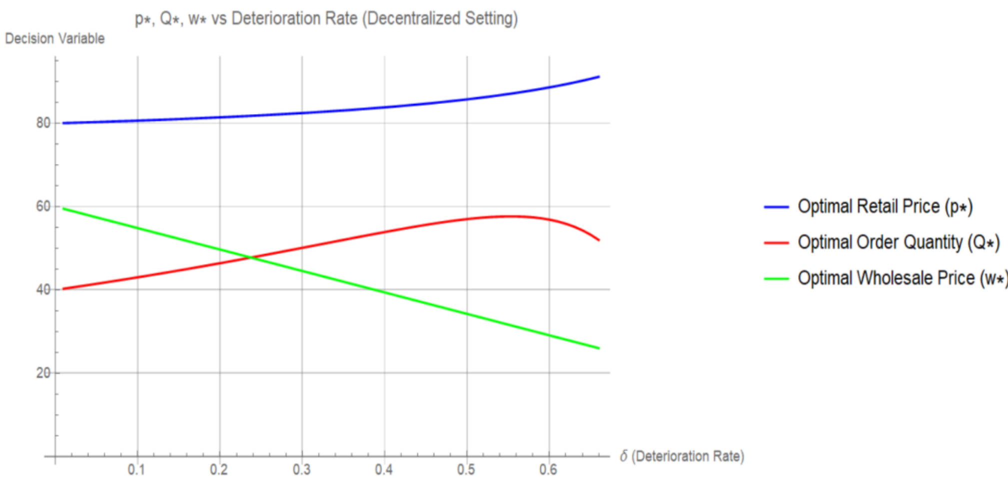
Centralized model gives highest profit and largest order quantity.

Decentralization causes double marginalization → higher p*, lower profit.

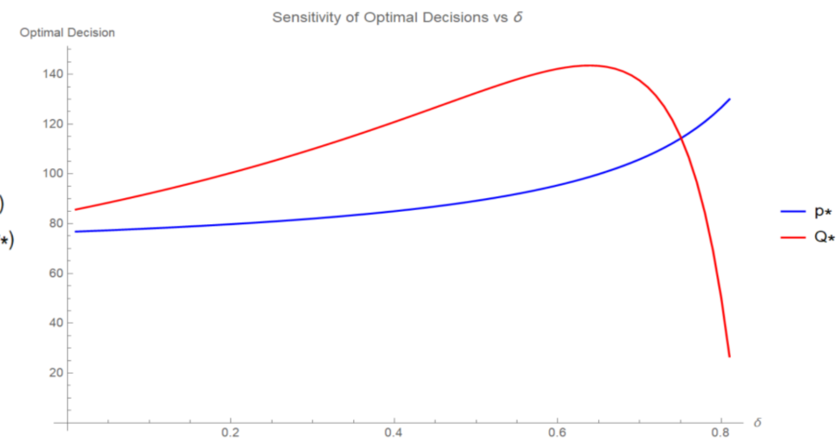
Coordinated model (Buy-Back) closes the gap with centralized.

Contract-based coordination improves efficiency in perishable supply chains.

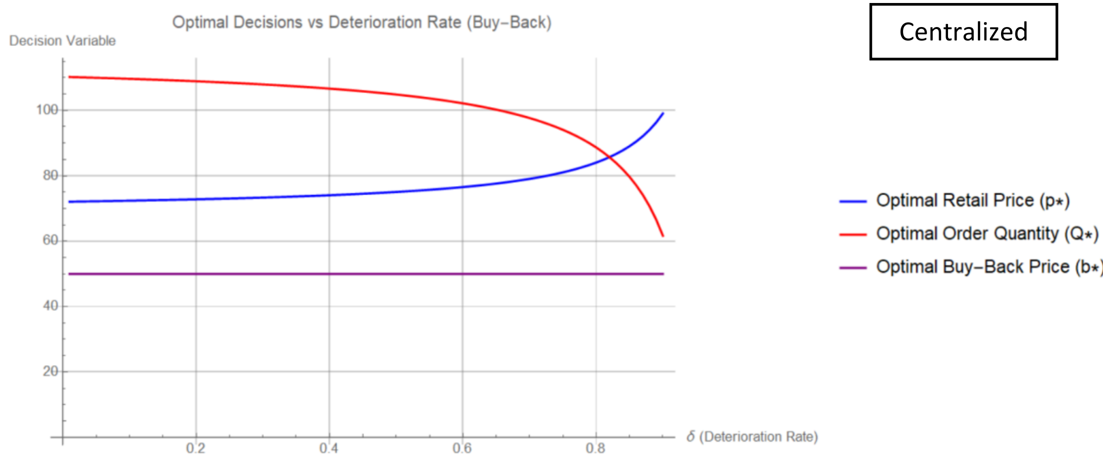
# Sensitivity of Optimal Decisions to Deterioration Rate (δ)




Decentralized

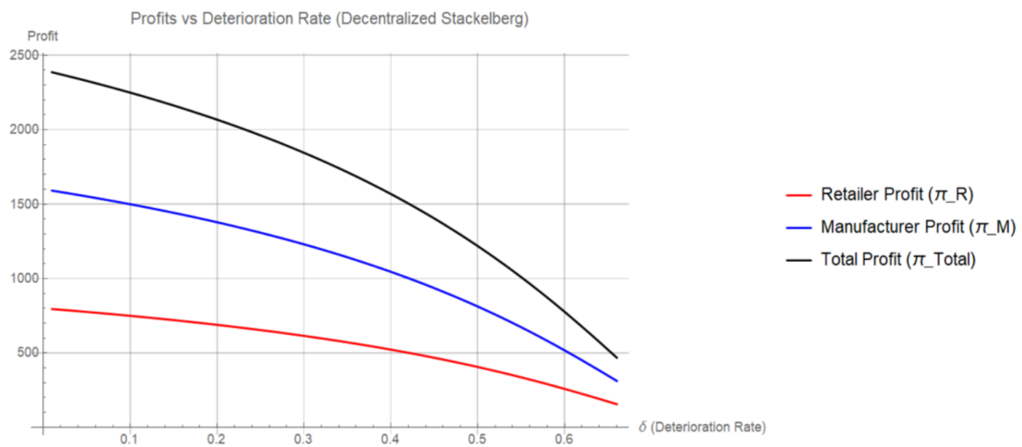



Centralized

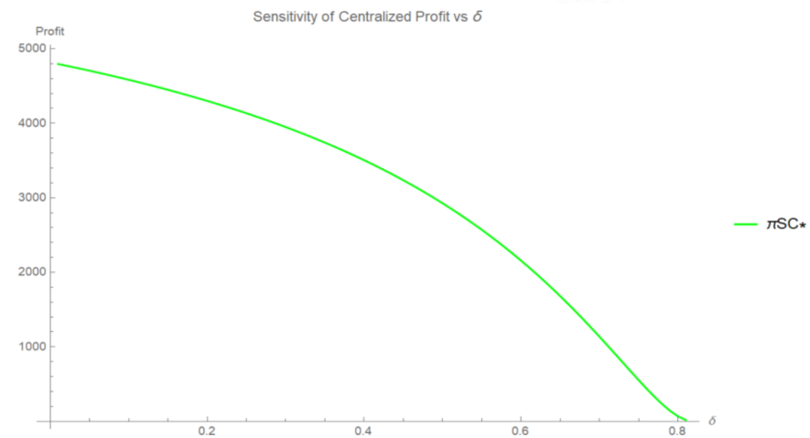



Coordinated

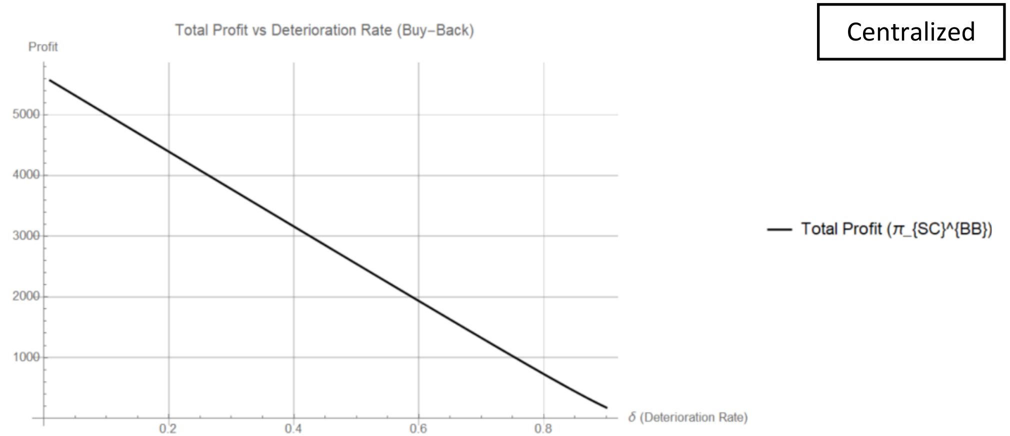
# Profitability vs. Deterioration Rate (δ)




Decentralized

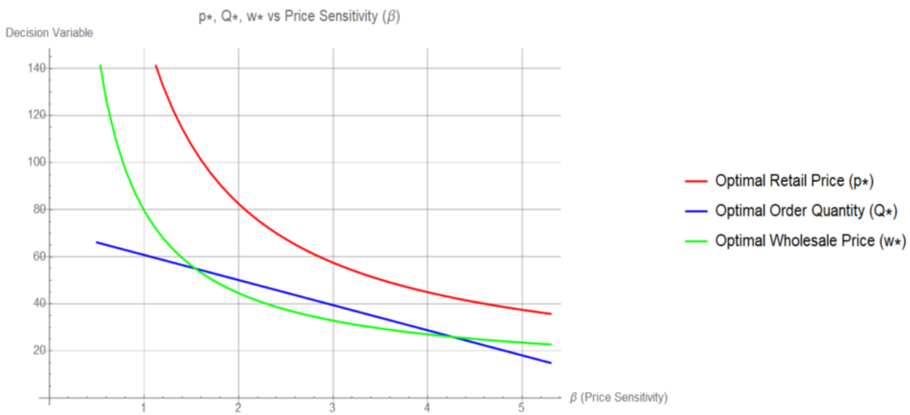



Centralized

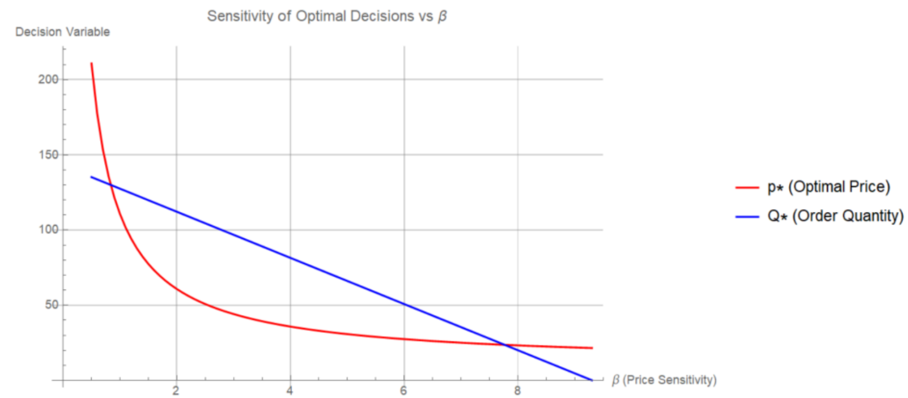



Coordinated

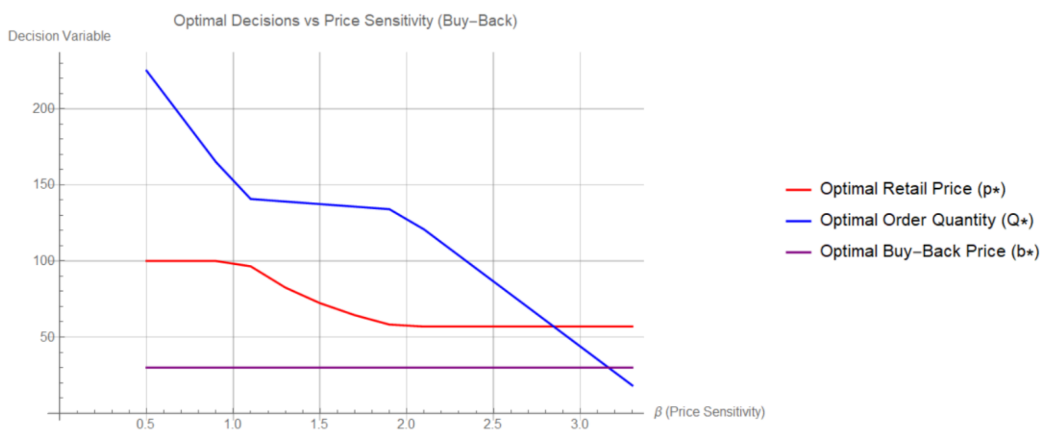
# Sensitivity of Optimal Decisions to Price Sensitivity (β)




Decentralized



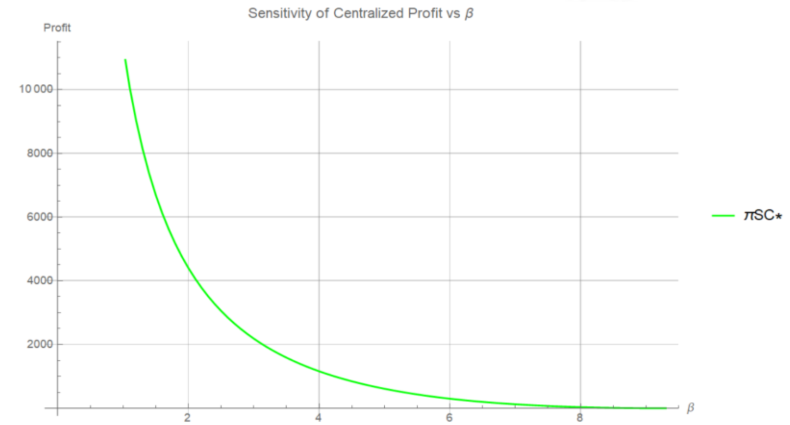

Centralized



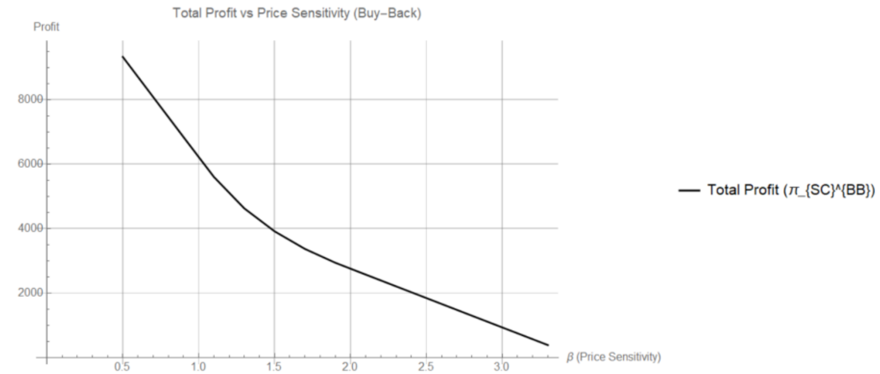

Coordinated

# Profitability vs. Price Sensitivity (β)


Decentralized

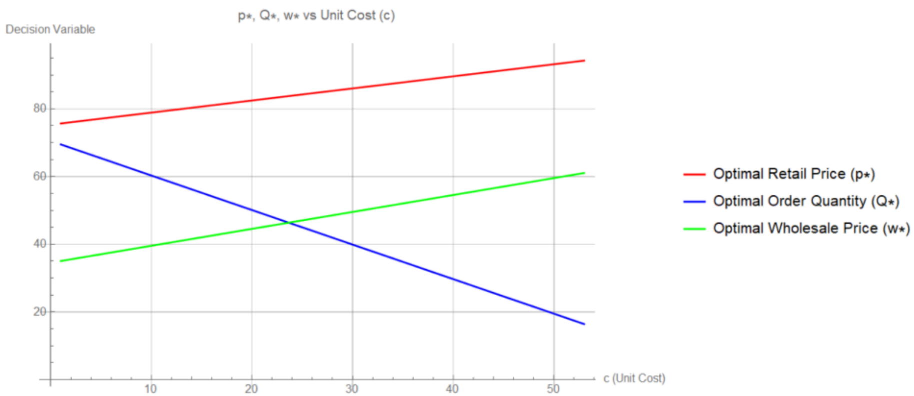



Centralized

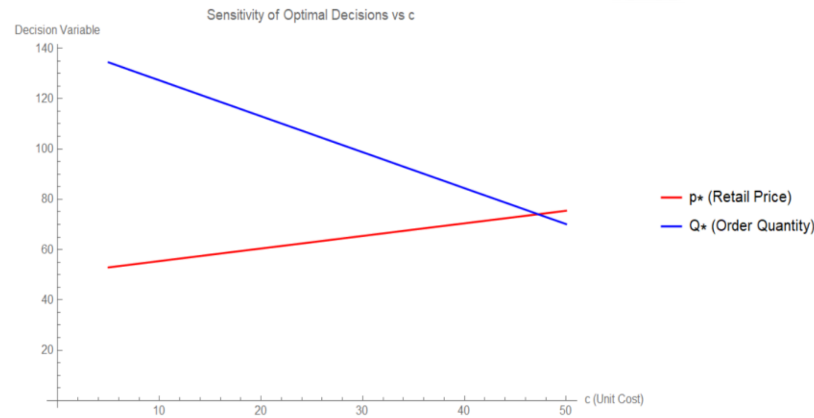



Coordinated

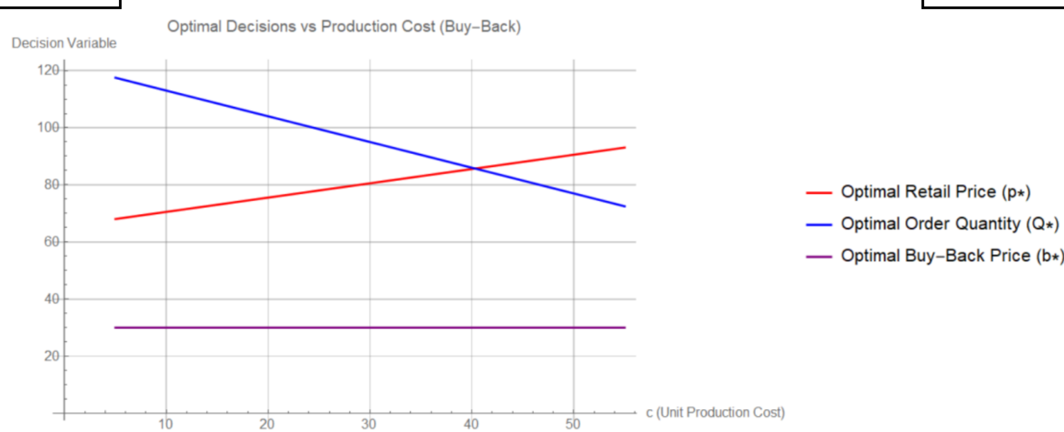
# Sensitivity of Optimal Decisions to Unit Cost (c)




Decentralized



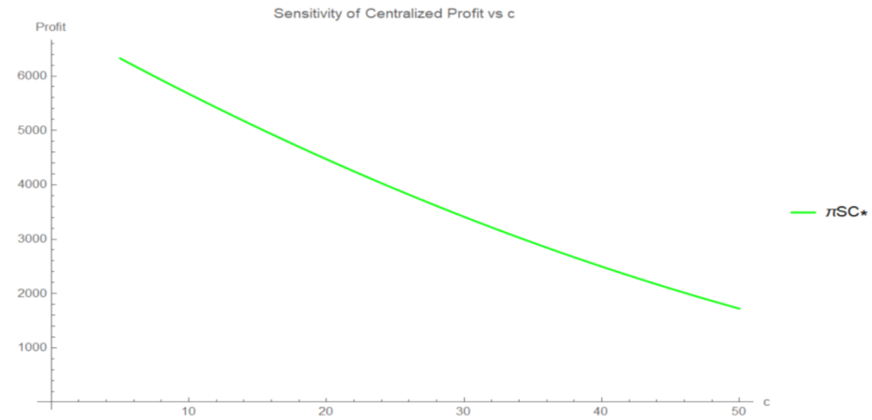

Centralized



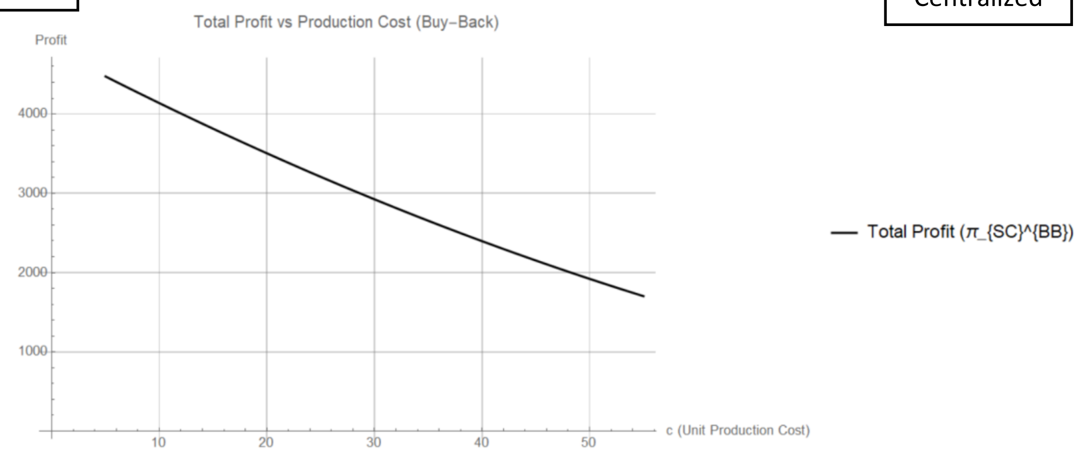

Coordinated

# Profitability vs. Unit Cost Sensitivity


Decentralized

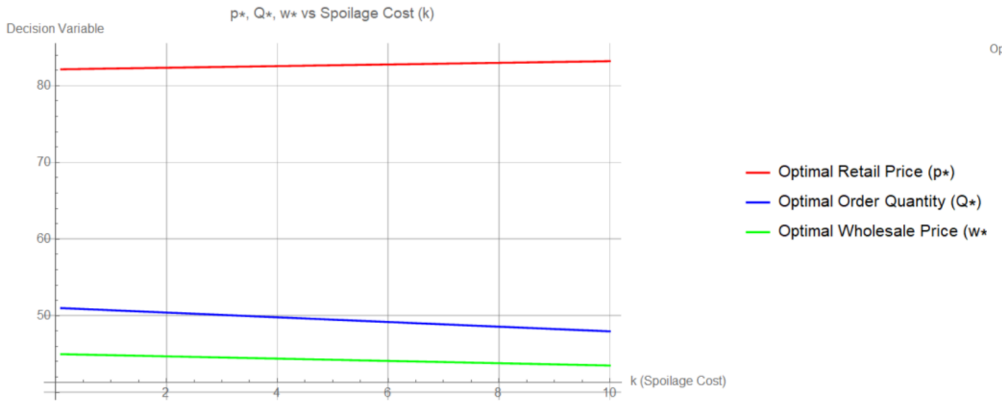



Centralized

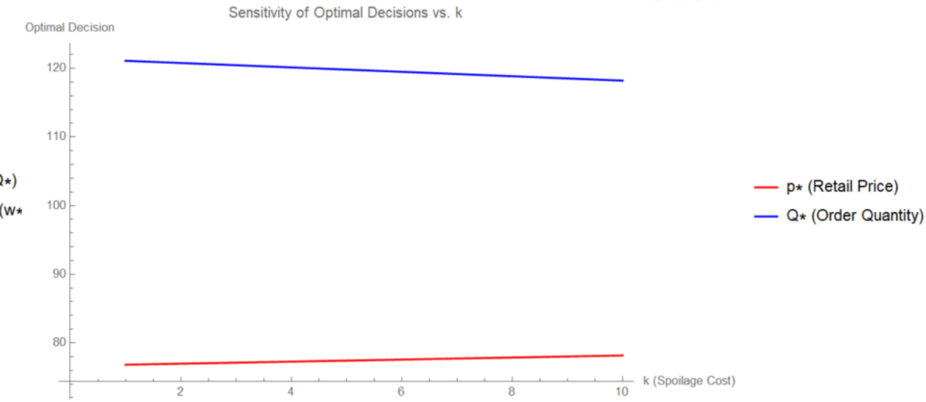



Coordinated

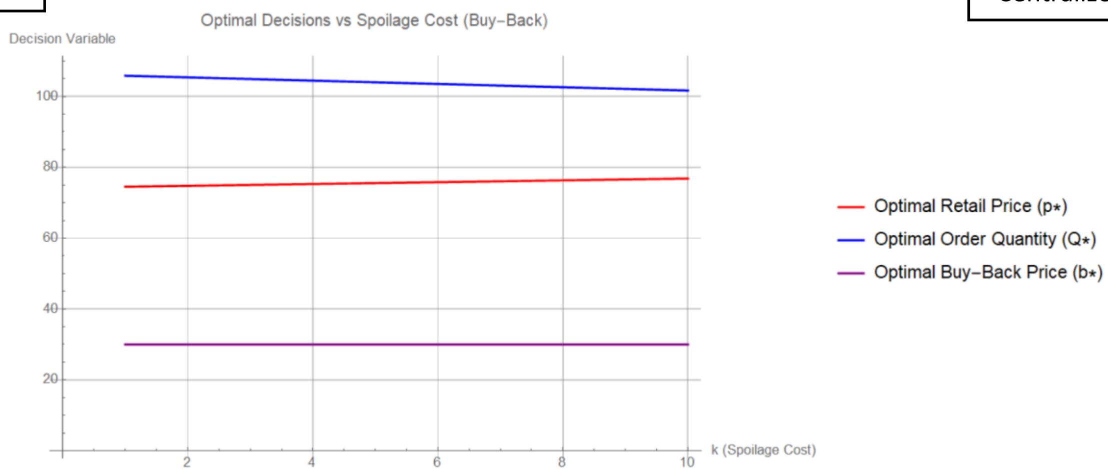
# Sensitivity of Optimal Decisions to Spoilage Cost (k)




Decentralized

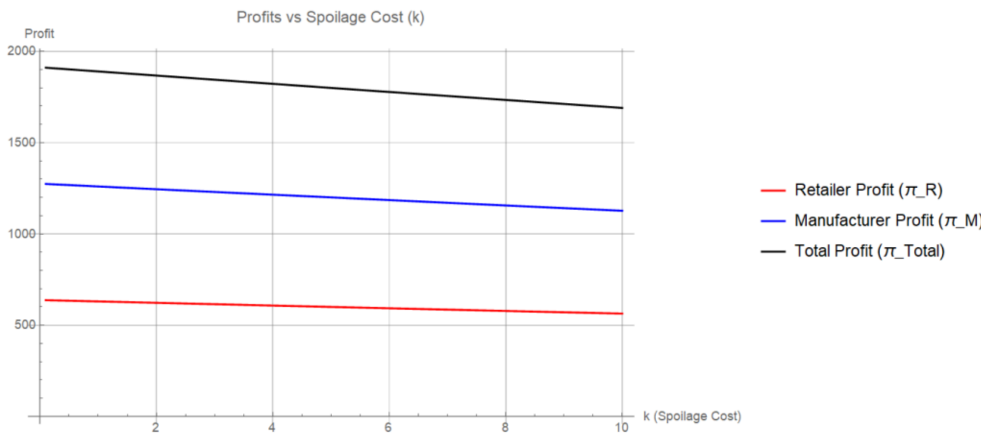



Centralized

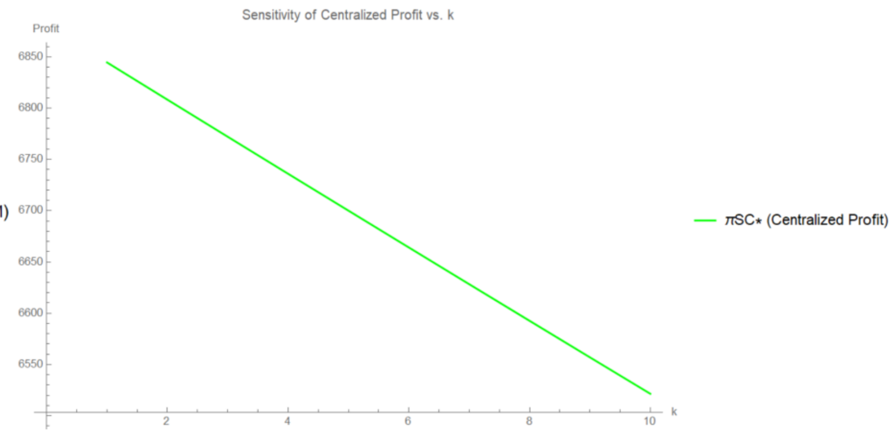



Coordinated

# Profitability vs. Spoilage Cost Sensitivity




Decentralized




Centralized


Coordinated

# Sensitivity to Buy-Back Price (b)


# Managerial Insights and Comparative Evaluation

**Structural Efficiency:**

- Centralized model consistently yields the highest profit due to unified pricing and ordering decisions.
- Decentralized model suffers from **double marginalization**, causing inflated prices and low order volumes.
- Coordinated model (buy-back) **bridges the gap**, enabling shared risk and improved decisions.

**Profit Comparison:**

- Centralized > Coordinated > Decentralized
- Coordination recovers much of the efficiency lost in decentralization.

**Decision Quality:**

- Centralized: Most aligned and responsive to parameters ($\delta$, $\beta$, c, k).
- Decentralized: Unstable, conservative ordering; inflated prices.
- Coordinated: Near-centralized performance with smoother decisions.

**Managerial Implications:**

- **Centralization or incentive-aligned contracts** (e.g., buy-back) are essential in perishable supply chains.
- Contractual coordination enhances **resilience**, **profitability**, and **risk-sharing**.

# Future Directions

# Future Research Opportunities

- Incorporating stochastic demand instead of deterministic demand functions.
- Extending the model to allow both demand regimes ($Q \leq D(p)$ and $Q > D(p)$) without pre-assumption, enabling the model to select the optimal regime endogenously.
- Designing adaptive, piecewise-based decision frameworks for hybrid regimes.
- Developing smart mechanisms for contract selection (e.g., buy-back, revenue-sharing) based on product characteristics.
- Expanding the model to multi-echelon or multi-retailer supply chains.
- Adding realistic constraints such as warehouse capacity and lead time.
- Employing machine learning or reinforcement learning for optimal decision policy in uncertain environments.
- Formal modeling of the **Bullwhip Effect** is proposed as future work, since this study addressed it conceptually through coordination (e.g., Buy-Back) as a step toward centralized decision-making which inherently mitigates such distortions.

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Thanks for your attention