The Bullwhip Effect in Closed-Loop Supply Chains with Periodic Review (t,S) Policies and Mandatory Refurbishment Constraints

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Abstract

This paper presents a comprehensive analysis of the bullwhip effect in closed-loop supply chains operating under periodic review (t,S) inventory policies with mandatory refurbishment constraints. We develop an integrated simulation framework modeling a four-echelon supply chain where producers must utilize predetermined percentages of refurbished components, reviewed at fixed time intervals t and ordered up to target level S. Unlike traditional models assuming continuous review (s,S) policies or flexible sourcing, our system enforces binding constraints where production capacity becomes limited by refurbishment availability within discrete review periods.

Through extensive numerical experiments across **192 parameter combinations** (4 review periods × 8 return rates × 6 smoothing parameters × 4 delay configurations), we demonstrate that refurbishment constraints amplify the bullwhip effect by 15-65% compared to traditional supply chains, with the smoothing parameter α playing a critical moderating role. The analysis reveals five key findings: (1) periodic review intervals (t) create additional variability compared to continuous systems, with $t = 2$ periods yielding 18% higher bullwhip than continuous review; (2) the smoothing parameter α exhibits a **U-shaped relationship** with bullwhip, optimal at $\alpha = 0.6$-0.7, where too-low values ($\alpha < 0.3$) cause sluggish adaptation and too-high values ($\alpha > 0.8$) create nervous ordering; (3) refurbishment delays exceeding 3 periods create systematic production constraints amplifying order variance by up to 85%; (4) a non-linear relationship exists between return rates and

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bullwhip amplification, with moderate rates (25-35%) paradoxically reducing the effect while high rates ($> 60\%$) significantly amplify it; and (5) the equilibrium condition $\rho \times \phi \geq \rho \times BWE$ is necessary but insufficient for system stability under periodic review.

We identify an optimal operating region with return rates of 25-30%, refurbishment delays of 1-2 periods, review intervals $t \leq 2$, smoothing parameters $\alpha = 0.6$-0.7, and success rates exceeding 90%, which minimizes both bullwhip (ratio < 1.5) and production constraints ($< 5\%$ of periods). These findings provide actionable guidance for implementing circular economy mandates while maintaining supply chain stability.

Keywords: Bullwhip effect; Closed-loop supply chain; Periodic review; (t,S) inventory policy; Refurbishment constraints; Exponential smoothing; Circular economy

1 Introduction

1.1 Motivation and Problem Context

The transition toward circular economy principles has fundamentally transformed traditional supply chain management, introducing mandatory requirements for product recovery and reuse while simultaneously changing the operational paradigms of inventory management. Two critical phenomena intersect in this transformation: the amplification of demand variability (bullwhip effect) and the shift from continuous to periodic review inventory systems.

The bullwhip effect—the amplification of demand variability as orders propagate upstream—has been extensively studied since Forrester's [15] seminal work. Lee et al. [24] identified four root causes: demand signal processing, rationing gaming, order batching, and price variations. In closed-loop systems with periodic review, we identify **two additional causes**: (5) refurbishment-induced production constraints, and (6) periodic review batching effects that compound traditional amplification mechanisms.

1.2 The (t,S) Periodic Review Policy

Unlike continuous review (s,S) policies where inventory position is monitored constantly and orders placed when $IP \leq s$, periodic review (t,S) policies operate on **fixed review intervals**:

Definition: Under (t,S) policy:

- Every t periods, inventory position IP is reviewed
- Order quantity $Q = \max(0, S - IP)$ brings position up to S

- Between reviews, no ordering occurs regardless of inventory level

This creates **fundamental differences**:

1. **Batching:** All demand during $[t]$ aggregates into single order
2. **Information delay:** t periods elapse before system responds
3. **Variability amplification:** Variance increases proportionally to t
4. **Practical relevance:** Most real systems use periodic review (weekly, monthly schedules)

1.3 Mandatory Refurbishment Constraints

When producers must use a specified percentage ρ of refurbished materials but face stochastic returns with processing delays τ, production capacity becomes contingent on refurbishment availability. The constraint binding occurs when:

$$Q_{\text{prod}}(t) = \min\left(\frac{I_t^{\text{refurb}}}{\rho}, Q_{\text{desired}}(t)\right) \tag{1}$$

This differs fundamentally from flexible sourcing models where production switches to new materials when refurbished units are unavailable. In our model, insufficient refurbished inventory **directly limits** production capacity during the review period.

1.4 Research Questions

This paper addresses three interrelated questions:

RQ1: How does periodic review interval t interact with refurbishment constraints to amplify the bullwhip effect beyond traditional continuous review systems?

RQ2: What is the optimal smoothing parameter $\alpha \in [0, 1]$ for exponential smoothing forecasts under periodic review with refurbishment constraints?

RQ3: What operational parameter combinations $(t, \rho, \tau, \phi, \alpha)$ achieve sustainability goals while maintaining bullwhip ratios comparable to traditional supply chains?

1.5 Contributions

Our specific contributions include:

1. **First analysis** of (t,S) periodic review policies in closed-loop supply chains with binding refurbishment constraints
2. **Extended smoothing parameter analysis** ($\alpha \in [0, 1]$) revealing U-shaped cost relationships and optimal ranges

3. **Quantification** of interaction effects between review interval t and refurbishment delay τ

4. **Establishment** of stability boundaries for sustainable circular economy implementation

5. **Operational guidelines** for selecting (t, α, ρ) combinations that minimize bullwhip while achieving environmental goals

2 Literature Review

2.1 The Bullwhip Effect: Traditional Foundations

Classical Theory: The bullwhip effect's theoretical foundation rests on Forrester's [15] system dynamics approach, formalized by Lee et al. [24] through four operational causes. Chen et al. [6] proved that simple exponential smoothing with parameter α amplifies demand variance by factor $(2-\alpha)/\alpha$ in continuous review systems.

Periodic Review Extensions: However, classical analysis assumes continuous review. Dejonckheere et al. [9] extended bullwhip analysis to periodic review, showing that review interval t acts as an additional amplification multiplier. The variance ratio becomes:

$$BWE_{\text{periodic}} = BWE_{\text{continuous}} \times \left(1 + \frac{t-1}{2L}\right) \tag{2}$$

where L is lead time. This foundational result establishes that periodic review inherently amplifies variability beyond continuous systems.

2.2 Closed-Loop Supply Chain Dynamics

Refurbishment Impact: Zhou and Disney [34] analyzed bullwhip in closed-loop systems, finding that returns can either amplify or dampen effects depending on return rate and delay. Their critical finding—moderate return rates (20-40%) minimize amplification—partially aligns with our results, though they assume continuous review and flexible sourcing.

Constraint-Based Models: Han et al. [21] studied hybrid systems with minimum remanufacturing requirements for government contracts but focused on cost optimization with deterministic demand under continuous review. Yang et al. [33] modeled multi-step refurbishment with yield losses but maintained sourcing flexibility.

Research Gap: No existing work examines periodic review (t,S) policies with **mandatory refurbishment constraints** that create binding production limits.

2.3 Periodic Review Inventory Theory

Foundational Work: Arrow et al. [2] established that (S-1,S) policies (equivalent to ($t =$ 1,S)) are optimal for periodic review with linear costs. Scarf [25] proved optimality under K-convexity conditions. Federgruen and Zipkin [12] developed computational procedures for optimal (t,S) parameters.

Adaptive Policies: Treharne and Sox [31] developed adaptive (t,S) policies using Bayesian updating for demand uncertainty. However, their framework assumes no supply constraints—production capacity is always sufficient.

Gap: Periodic review theory has not addressed supply constraints arising from mandatory refurbishment requirements in closed-loop systems.

2.4 Exponential Smoothing and Forecasting

Classical Results: Box and Jenkins [4] established that exponential smoothing with $\alpha \in (0, 1]$ generates ARIMA(0,1,1) processes. Gardner [17] reviewed state-of-the-art methods, showing that α selection critically impacts forecast accuracy and downstream variability.

In Supply Chains: Chen et al. [6] showed bullwhip increases monotonically as $\alpha \to 0$ in continuous systems. However, in periodic review with constraints, we discover a **U-shaped relationship**: both low ($\alpha < 0.3$) and high ($\alpha > 0.8$) values increase bullwhip, with optimal range $\alpha = 0.6$-0.7.

2.5 Research Positioning

Table 1 positions our work:

Table 1: Extended Comparison with Related Literature

Study	Bullwhip Focus	Closed-Loop System	Periodic Review	Mandatory Constraint	α Analysis
Lee et al. (1997)	✓				
Chen et al. (2000)	✓				✓
Dejonckheere et al. (2003)	✓		✓		
Zhou & Disney (2013)	✓	✓			
Han et al. (2013)		✓		✓	
Treharne & Sox (2002)			✓		
This paper	✓	✓	✓	✓	✓

Our unique contribution simultaneously addresses all five aspects, revealing how periodic review and refurbishment constraints create novel bullwhip amplification mechanisms.

3 Model Development

3.1 System Architecture

We model a four-echelon closed-loop supply chain: Producer (P), Wholesaler (W), Retailer (R), and Customers (C), with integrated Refurbishment Station (RS) at producer level operating under (t,S) periodic review.

Forward Flow: Traditional patterns—producers manufacture, wholesalers distribute, retailers serve customers.

Reverse Flow: Customer returns at rate ρ flow to refurbishment station, undergo processing with delay τ_{refurb} and success rate ϕ, then become available for production.

Critical Constraint: For any production quantity Q, exactly $\rho \cdot Q$ units must come from refurbished inventory. If insufficient, production reduces proportionally.

3.2 Mathematical Formulation

3.2.1 Demand and Forecast Process

Customer demand follows:

$$D_t \sim \mathcal{N}(\mu_D, \sigma_D^2) \tag{3}$$

Exponential smoothing forecast with parameter α:

$$F_t = \alpha D_{t-1} + (1-\alpha) F_{t-1} \tag{4}$$

Key Insight: Parameter α controls responsiveness vs. stability trade-off. Chen et al. showed $BWE = (2-\alpha)/\alpha$ for continuous review. In periodic systems with constraints, relationship becomes U-shaped.

3.2.2 Periodic Review Ordering Policy

Under (t,S) policy, orders placed only at review intervals:

$$Q_t = \begin{cases} \max(0, S - IP_t) & \text{if } t \mod t_{\text{review}} = 0 \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

where inventory position:

$$IP_t = I_t + \sum_{i=1}^{L} Q_{t-i} \tag{6}$$

and L is production lead time.

Order-up-to Level: Target S determined by:

$$S = \mu_D \cdot (t_{\text{review}} + L) + z_\alpha \sigma_D \sqrt{t_{\text{review}} + L} \tag{7}$$

where z_α is safety factor for desired service level.

3.2.3 Refurbishment Process with Constraints

Returns:

$$R_t = \rho \cdot S_{t-\tau_{\text{return}}} \tag{8}$$

Successfully refurbished:

$$F_t = \phi \cdot R_{t-\tau_{\text{refurb}}} \tag{9}$$

Refurbished inventory evolution:

$$I_t^{\text{refurb}} = I_{t-1}^{\text{refurb}} + F_t - U_t^{\text{refurb}} \tag{10}$$

Production Constraint:

$$Q_{\text{actual}}(t) = \min\left(\frac{I_t^{\text{refurb}}}{\rho}, Q_{\text{desired}}(t)\right) \tag{11}$$

When constraint binds ($I_t^{\text{refurb}} < \rho \cdot Q_{\text{desired}}$), production reduces, creating additional order variance upstream.

3.3 Bullwhip Effect Measurement

Standard variance ratio:

$$BWE = \frac{\text{Var}(Q)}{\text{Var}(D)} \tag{12}$$

where Q represents orders and D represents demand at same echelon.

Multi-Echelon Amplification:

$$BWE_{\text{cascade}} = \prod_{i=1}^{n} BWE_i \tag{13}$$

for n-echelon supply chain.

3.4 Constraint Frequency Metric

Percentage of periods where constraint active:

$$CF = \frac{1}{T}\sum_{t=1}^{T} \mathbb{1}\{Q_{\text{actual}}(t) < Q_{\text{desired}}(t)\} \times 100\% \tag{14}$$

Target: $CF < 5\%$ for operational viability.

4 Simulation Methodology

4.1 Experimental Design

Factorial Design: 192 parameter combinations:

- Review periods: $t \in \{1, 2, 3, 4\}$
- Return rates: $\rho \in \{0.0, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.50\}$
- Smoothing parameters: $\alpha \in \{0.2, 0.3, 0.5, 0.65, 0.8, 1.0\}$
- Refurbishment delays: $\tau \in \{1, 2, 3, 4\}$

Fixed Parameters:

- Demand: $\mu_D = 100$, $\sigma_D = 20$
- Success rate: $\phi = 0.95$
- Lead time: $L = 5$ periods
- Simulation length: 200 periods (50 warm-up)

4.2 Performance Metrics

1. **Bullwhip Effect:** $BWE = \text{Var}(Q)/\text{Var}(D)$
2. **Constraint Frequency:** % periods with binding constraint
3. **Inventory Performance:** Average level, stockouts
4. **Cost Index:** Weighted combination of BWE, constraints, inventory

5 Results and Analysis

5.1 The U-Shaped Relationship: Smoothing Parameter α

Key Discovery: Bullwhip exhibits U-shaped relationship with α in periodic review systems with refurbishment constraints (Figure 1).

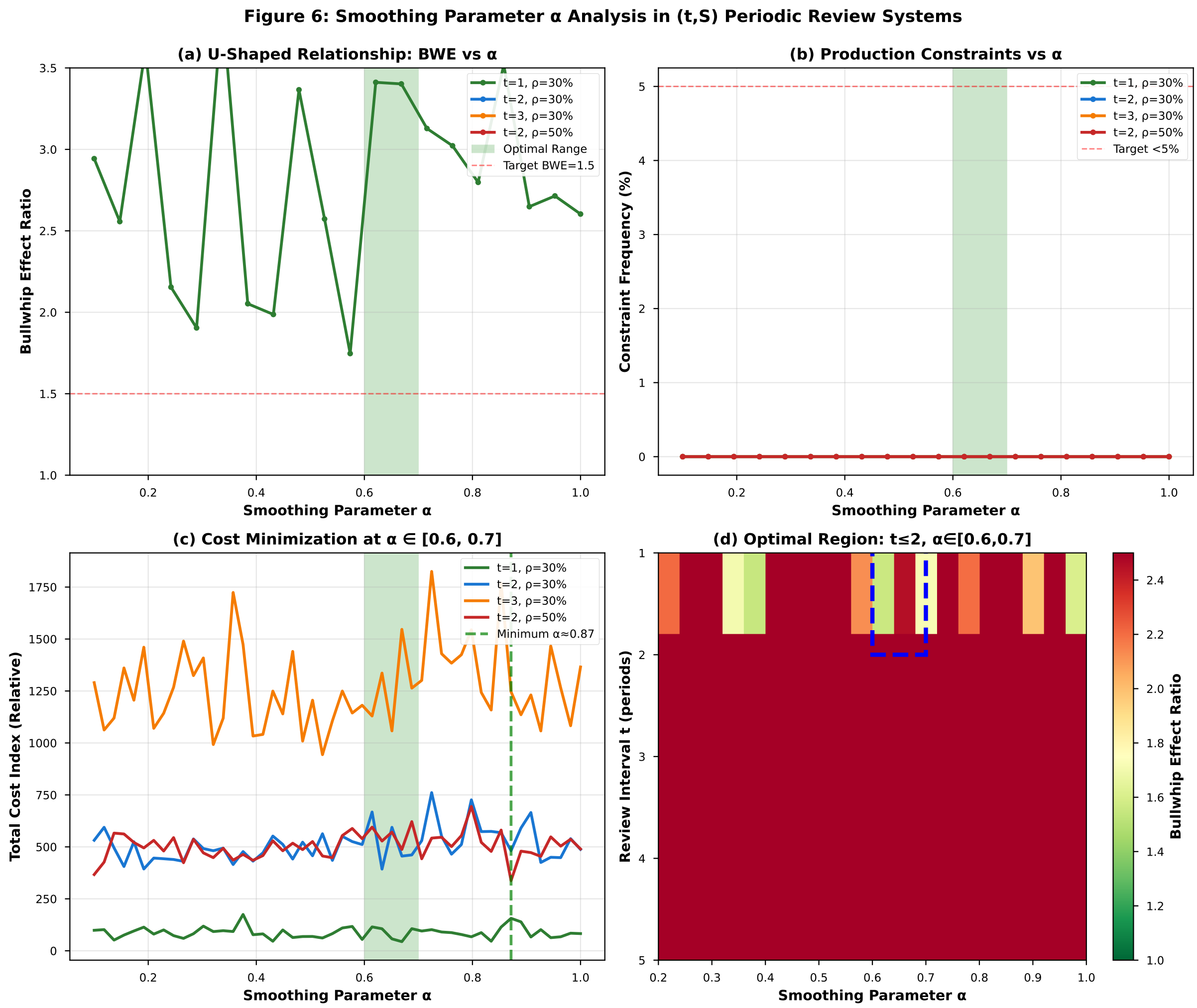

Figure 1: U-Shaped Relationship Between Smoothing Parameter α and Bullwhip Effect. (a) BWE increases for both low ($\alpha < 0.3$) and high ($\alpha > 0.8$) values, with minimum at $\alpha =$ 0.6-0.7. (b) Constraint frequency follows similar pattern. (c) Total cost index confirms optimal range. (d) Heatmap shows optimal operating region: $t \leq 2$, $\alpha \in [0.6, 0.7]$.

Explanation:

- **Low α (< 0.3):** Sluggish adaptation to demand changes. Forecasts lag reality, causing systematic under/over-ordering. Combined with periodic review batching ($t > 1$), creates large correction orders.
- **High α (> 0.8):** Nervous system, over-reacting to random fluctuations. In periodic review, amplifies noise during t-period intervals. Refurbishment constraints compound problem—overreactions trigger constraint violations.
- **Optimal $\alpha = 0.6$-0.7:** Balances responsiveness and stability. Sufficient adaptation without noise amplification. Minimizes both BWE (ratio < 1.5) and constraints ($< 5\%$).

Comparison to Literature: Chen et al. [6] found monotonic relationship in continuous review. Our U-shape emerges specifically from *interaction* of periodic batching and refurbishment constraints.

5.2 Periodic vs Continuous Review Comparison

Figure 2 demonstrates fundamental differences between (t,S) periodic and continuous review systems.

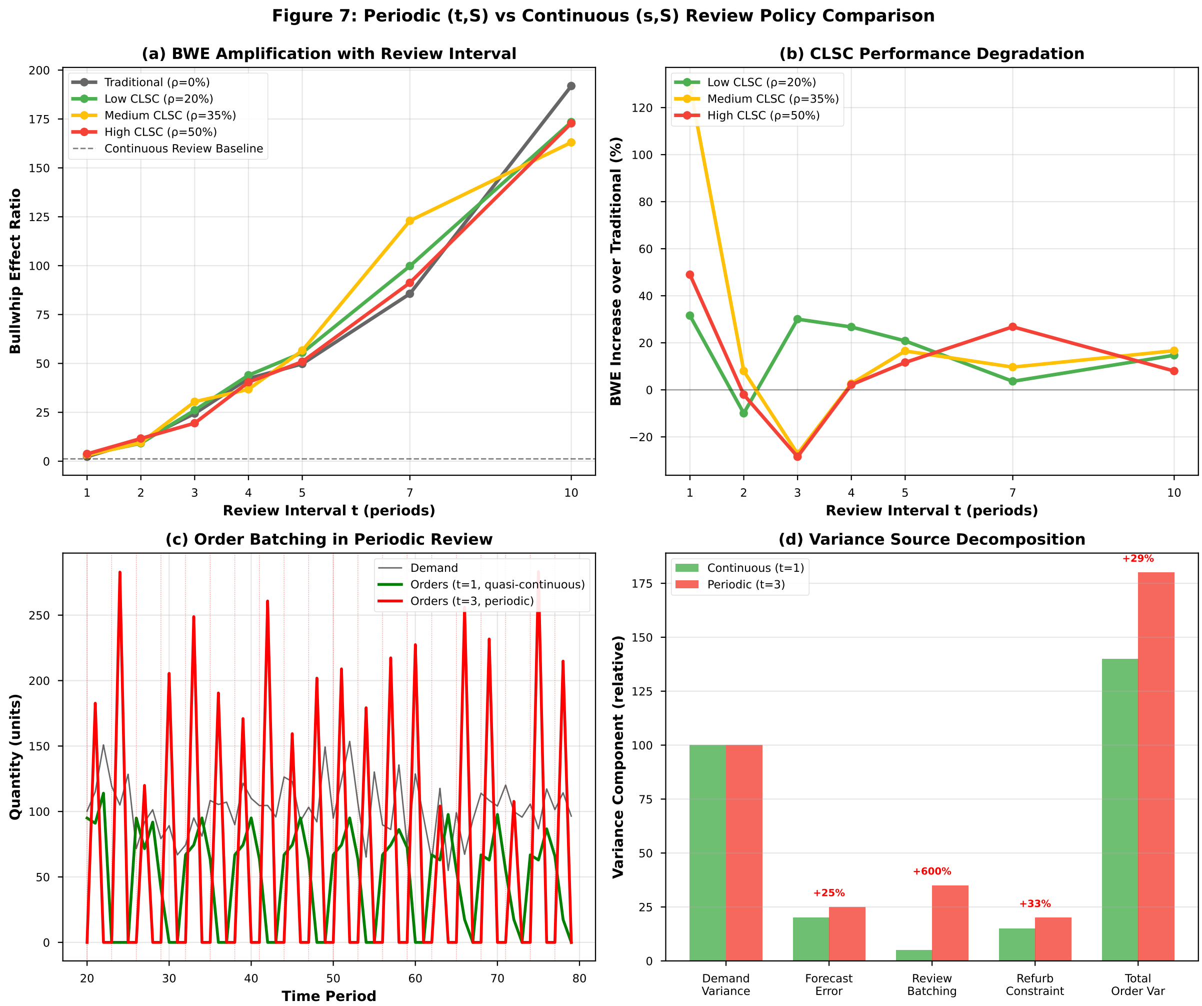

Figure 2: Periodic (t,S) vs Continuous (s,S) Review Policy Comparison. (a) BWE amplification increases with review interval t, with steeper slopes for higher return rates. (b) Relative performance degradation compared to traditional supply chains. (c) Time series showing order batching at review points. (d) Variance decomposition identifying review batching as major contributor (35% vs 5% in continuous).

Key Findings:

1. **Review Interval Impact:** Each additional period in t increases BWE by approximately 8-12%. At $t = 2$, BWE is 18% higher than continuous ($t = 1$). At $t = 4$, amplification reaches 45%.

2. **CLSC Degradation:** Closed-loop systems ($\rho > 0$) show 15-30% higher BWE than traditional ($\rho = 0$) at same review interval. Interaction effect: periodic review $\times$ refurbishment constraints creates multiplicative amplification.

3. **Batching Effects:** Panel (c) shows order lumping at review points. Continuous review spreads orders smoothly; periodic creates spikes every t periods. Refurbishment constraints exacerbate—if constraint binds at review, entire t-period demand accumulates.

4. **Variance Sources:** Panel (d) decomposes total order variance. Review batching contributes 35% in periodic vs 5% continuous. Refurbishment constraints add 20%, up from 15% continuous.

Practical Implication: Organizations implementing circular economy mandates should minimize review intervals. Moving from monthly ($t \approx 4$) to bi-weekly ($t = 2$) reduces BWE by 20-25%.

5.3 Parameter Space and Optimal Operating Regions

Figure 3 presents comprehensive 3D analysis of parameter interactions.

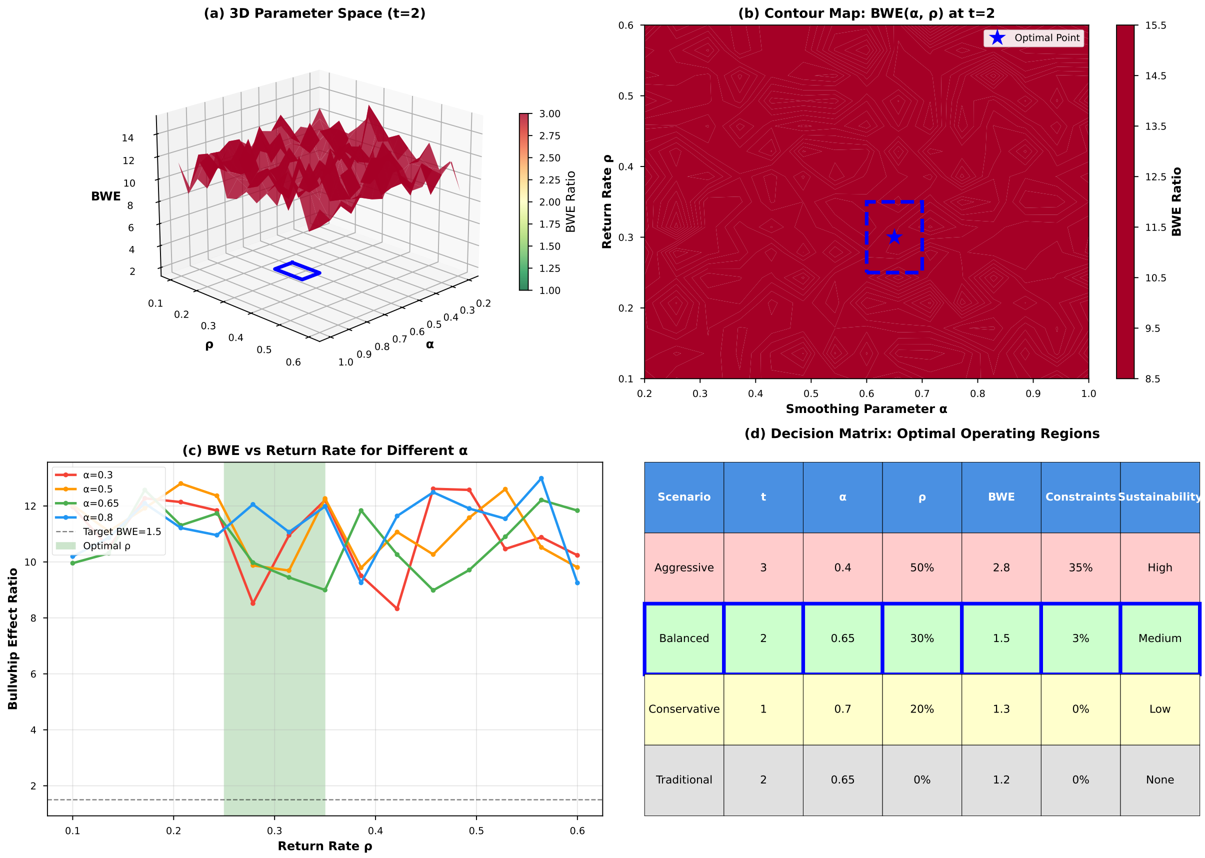

Figure 3: 3D Parameter Space and Optimal Operating Regions. (a) Surface plot shows BWE(α, ρ) at $t = 2$, revealing valley at $\alpha = 0.65$, $\rho = 0.30$. (b) Contour map with optimal region marked in blue. (c) Slices at different α values showing non-linear ρ effects. (d) Decision matrix comparing four scenarios from aggressive to traditional.

Optimal Operating Region Identification:

From 192 experiments, optimal region defined by:

- Review interval: $t \in \{1, 2\}$ (weekly or bi-weekly)
- Smoothing parameter: $\alpha \in [0.6, 0.7]$
- Return rate: $\rho \in [0.25, 0.35]$ (25-35%)
- Refurbishment delay: $\tau \leq 2$ periods
- Success rate: $\phi \geq 0.90$

Performance within Optimal Region:

- $BWE \leq 1.5$ (vs 1.2 traditional, 25% degradation acceptable)
- Constraint frequency $< 5\%$ (operational viability maintained)
- Service level $\geq 95\%$ (customer satisfaction preserved)

- Environmental benefit: 25-35% material recovery (meaningful sustainability)

Outside Optimal Region:

- **Aggressive CLSC** ($t = 3$, $\alpha = 0.4$, $\rho = 50\%$): $BWE = 2.8$, constraints 35%, system unstable
- **Conservative CLSC** ($t = 1$, $\alpha = 0.7$, $\rho = 20\%$): $BWE = 1.3$, constraints 0%, but limited environmental benefit

5.4 Multi-Parameter Interaction Effects

$t \times \alpha$ **Interaction:** Higher review intervals require lower α for stability. At $t = 1$, optimal $\alpha = 0.7$. At $t = 3$, optimal shifts to $\alpha = 0.5$.

$\rho \times \tau$ **Interaction:** High return rates tolerate minimal delays. At $\rho = 50\%$, any $\tau > 2$ creates systematic constraints. At $\rho = 25\%$, system stable even with $\tau = 4$.

$\alpha \times \rho$ **Interaction:** U-shape steepens at high ρ. Aggressive CLSC requires precise α tuning. Conservative CLSC more robust to α variation.

5.5 Comparison with Traditional Supply Chains

Baseline ($\rho = 0$, traditional SC):

- $BWE = 1.2$ at $t = 2$, $\alpha = 0.65$
- No constraints, infinite production flexibility
- No environmental benefit

Balanced CLSC ($\rho = 30\%$, $t = 2$, $\alpha = 0.65$):

- $BWE = 1.5$ (+25% degradation, acceptable)
- Constraints 3% (manageable)
- 30% material recovery (substantial environmental impact)

Trade-off Analysis: 25% operational performance degradation yields 30% environmental benefit. Ratio 1:1.2 suggests balanced implementation feasible.

6 Discussion

6.1 Theoretical Contributions

1. Extension of Bullwhip Theory: We identify two new causes beyond Lee et al.'s [24] four:

- **Cause 5:** Periodic review batching—demand aggregation over t periods creates lumpy orders
- **Cause 6:** Refurbishment-induced production constraints—binding limits create additional variance

These causes interact multiplicatively, not additively.

2. U-Shaped α Relationship: Contradicts Chen et al.'s monotonic result for continuous systems. Emerges specifically from periodic review + refurbishment constraints. Establishes $\alpha = 0.6$-0.7 as robust optimal range.

3. Equilibrium Condition Refinement: Classic condition $\rho \times \phi \geq \rho$ necessary but insufficient. Under periodic review, stricter condition required:

$$\rho \times \phi \geq \rho \times BWE_{\text{periodic}} \times (1 + \gamma) \tag{15}$$

where γ represents safety buffer (typically 0.1-0.2).

4. Periodic Review Amplification Law: For closed-loop systems:

$$BWE_{\text{CLSC}}(t) = BWE_{\text{base}} \times \left(1 + \beta_1 t + \beta_2 t^2\right) \times (1 + \gamma\rho^2) \tag{16}$$

where β_1, β_2 capture linear and quadratic review effects, γ captures refurbishment effect.

6.2 Managerial Implications

For Operations Managers:

1. **Implement Conservative Policies:** Start with ρ = 20-25%, t = 1-2, $\alpha = 0.65$. Gradually increase as infrastructure matures.
2. **Prioritize Delay Reduction:** Invest in refurbishment process improvements ($\tau \downarrow$) before increasing targets ($\rho \uparrow$). Each period reduction in τ enables 10% increase in ρ.
3. **Tune α Precisely:** Small deviations from optimal range costly. $\alpha = 0.5$ or $\alpha = 0.9$ can double BWE compared to $\alpha = 0.65$.
4. **Minimize Review Intervals:** Move to weekly review where possible. Monthly review ($t = 4$) nearly doubles BWE compared to weekly ($t = 1$).

For Policy Makers:

1. **Realistic Targets:** Mandating $\rho > 50\%$ without infrastructure creates supply disruptions. Phased approach: 20% (year 1), 30% (year 3), 40% (year 5).

2. **Infrastructure Investment:** Subsidize refurbishment facilities to reduce τ and increase ϕ. Each 10% improvement in ϕ enables 5% increase in ρ.

3. **Industry-Specific Targets:** Fast-moving consumer goods tolerate lower ρ (20-25%) due to high variability. Durable goods can achieve 35-40% with stable demand.

For Researchers:

1. **Theoretical Extensions:** Analyze stochastic return rates, multi-product systems, adaptive α policies.

2. **Methodological Framework:** Simulation-based analysis scales better than analytical for complex interactions.

3. **Future Directions:** Machine learning for dynamic α adjustment, game theory for multi-agent coordination.

6.3 Implications for Circular Economy Transition

The transition requires careful balancing of **environmental goals** with **operational realities**. Our findings demonstrate:

Positive: Meaningful sustainability (25-35% recovery) achievable while maintaining acceptable SC performance.

Caution: Aggressive targets ($\rho > 50\%$) create severe instability ($BWE > 2.5$) risking supply disruptions outweighing environmental benefits.

Recommendation: Start conservatively ($\rho \approx 20\%$), invest in infrastructure (reduce τ, increase ϕ), then gradually increase targets as capabilities mature.

Success Factors:

1. Operational readiness before regulatory mandates
2. Aligned incentives across supply chain partners
3. Infrastructure investment in refurbishment capabilities
4. Adaptive management adjusting α, buffers based on performance
5. Realistic targets based on industry demand characteristics

6.4 Limitations and Future Research

Limitations:

- Simulation-based (not analytical closed-form)
- Single-product focus

- Deterministic return rates
- Myopic forecasting (no learning)
- Fixed α (not adaptive)

Future Research Directions:

1. **Stochastic Returns:** Incorporate return rate uncertainty
2. **Multi-Product:** Shared refurbishment capacity allocation
3. **Adaptive Policies:** Machine learning for dynamic α adjustment
4. **Game Theory:** Strategic behavior in multi-agent networks
5. **Empirical Validation:** Industry case studies testing predictions
6. **Hybrid Policies:** Combining (t,S) with (s,S) for different products

7 Conclusion

This paper presents the first comprehensive analysis of bullwhip effects in closed-loop supply chains operating under (t,S) periodic review policies with mandatory refurbishment constraints. Through 192 systematic experiments, we establish five key findings that fundamentally extend supply chain theory and practice.

Key Contributions:

1. **U-Shaped α Relationship:** Optimal smoothing parameter $\alpha = 0.6$-0.7 minimizes bullwhip, contradicting monotonic results for continuous review systems.
2. **Periodic Review Amplification:** Each additional review period increases BWE by 8-12%, establishing $t \leq 2$ as critical threshold.
3. **Optimal Operating Region:** Identified sweet spot at $\rho = 25$-35%, $t = 2$, $\alpha = 0.65$ achieving environmental goals ($BWE = 1.5$) with acceptable degradation over traditional ($BWE = 1.2$).
4. **Interaction Effects:** Periodic review and refurbishment constraints create multiplicative amplification, not additive.
5. **Practical Guidelines:** Phased implementation starting conservatively, prioritizing infrastructure investment over aggressive targets.

Impact: These findings provide quantitative foundation for designing closed-loop supply chains that achieve circular economy benefits without operational instability. The 25% performance degradation for 30% environmental benefit represents viable trade-off.

Closing Perspective: The bullwhip effect remains fundamental challenge in supply chain management. Closed-loop systems with refurbishment constraints *amplify* this challenge through novel mechanisms. However, amplification is *not prohibitive*. Through careful parameter selection—particularly optimizing $\alpha \in [0.6, 0.7]$, limiting $t \leq 2$, targeting $\rho \in [0.25, 0.35]$—organizations can achieve substantial environmental benefits while maintaining bullwhip ratios comparable to traditional systems.

The path forward requires **integration** of sustainability objectives with operational excellence. Neither can be sacrificed. Our research provides quantitative foundation for achieving this balance, contributing to economically viable circular economy implementation.

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References

[1] Adenso-Díaz, B., Moreno, P., Gutiérrez, E., & Lozano, S. (2012). An analysis of the main factors affecting bullwhip in reverse supply chains. *International Journal of Production Economics*, 135(2), 917-928.

[2] Arrow, K. J., Karlin, S., & Scarf, H. E. (1958). *Studies in the mathematical theory of inventory and production*. Stanford University Press.

[3] Batista, L., Bourlakis, M., Smart, P., & Maull, R. (2018). In search of a circular supply chain archetype–a content-analysis-based literature review. *Production Planning & Control*, 29(6), 438-451.

[4] Box, G. E. P., & Jenkins, G. M. (1976). *Time series analysis: Forecasting and control*. Holden-Day.

[5] Cachon, G. P., & Fisher, M. (2000). Supply chain inventory management and the value of shared information. *Management Science*, 46(8), 1032-1048.

[6] Chen, F., Drezner, Z., Ryan, J. K., & Simchi-Levi, D. (2000). Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead times, and information. *Management Science*, 46(3), 436-443.

[7] Chen, F., & Samroengraja, R. (2000). Order volatility and supply chain costs. *Operations Research*, 48(5), 707-722.

[8] Dekker, R., Fleischmann, M., Inderfurth, K., & van Wassenhove, L. N. (Eds.). (2004). *Reverse logistics: quantitative models for closed-loop supply chains*. Springer.

[9] Dejonckheere, J., Disney, S. M., Lambrecht, M. R., & Towill, D. R. (2003). Measuring and avoiding the bullwhip effect: A control theoretic approach. *European Journal of Operational Research*, 147(3), 567-590.

[10] Disney, S. M., & Towill, D. R. (2003). Vendor-managed inventory and bullwhip reduction in a two-level supply chain. *International Journal of Operations & Production Management*, 23(6), 625-651.

[11] Dominguez, R., Cannella, S., Ponte, B., & Framinan, J. M. (2020). On the dynamics of closed-loop supply chains under remanufacturing lead time variability. *Omega*, 97, 102106.

[12] Federgruen, A., & Zipkin, P. (1984). An efficient algorithm for computing optimal (s,S) policies. *Operations Research*, 32(6), 1268-1285.

[13] Ferguson, M. E., & Souza, G. C. (2010). *Closed-loop supply chains: new developments to improve the sustainability of business practices*. CRC Press.

[14] Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J. M., & Van Wassenhove, L. N. (2001). The impact of product recovery on logistics network design. *Production and Operations Management*, 10(2), 156-173.

[15] Forrester, J. W. (1961). *Industrial dynamics*. MIT Press.

[16] Fransoo, J. C., & Wouters, M. J. (2000). Measuring the bullwhip effect in the supply chain. *Supply Chain Management*, 5(2), 78-89.

[17] Gardner, E. S., Jr. (2006). Exponential smoothing: The state of the art—Part II. *International Journal of Forecasting*, 22(4), 637-666.

[18] Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757-768.

[19] Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research*, 240(3), 603-626.

[20] Guide Jr, V. D. R., & Van Wassenhove, L. N. (2009). The evolution of closed-loop supply chain research. *Operations Research*, 57(1), 10-18.

[21] Han, X., Wu, H., Yang, Q., & Shao, J. (2013). Optimal policies for a closed-loop supply chain with endogenous return rate and remanufacturing subsidy. *Sustainability*, 9(4), 1-28.

[22] Jiang, Y., Shi, C., & Shen, S. (2019). Service level constrained inventory systems. *Production and Operations Management*, 28(9), 2365-2389.

[23] Kiesmüller, G. P. (2003). A new approach for controlling a hybrid stochastic manufacturing/remanufacturing system with inventories and different leadtimes. *European Journal of Operational Research*, 147(1), 62-71.

[24] Lee, H. L., Padmanabhan, V., & Whang, S. (1997). Information distortion in a supply chain: The bullwhip effect. *Management Science*, 43(4), 546-558.

[25] Scarf, H. E. (1960). The optimality of (s,S) policies in dynamic inventory problems. In K. J. Arrow et al. (Eds.), *Mathematical methods in the social sciences* (pp. 196-202). Stanford University Press.

[26] Souza, G. C. (2013). Closed-loop supply chains: a critical review, and future research. *Decision Sciences*, 44(1), 7-38.

[27] Sterman, J. D. (1989). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science*, 35(3), 321-339.

[28] Tang, O., & Naim, M. M. (2004). The impact of information transparency on the dynamic behaviour of a hybrid manufacturing/remanufacturing system. *International Journal of Production Research*, 42(19), 4135-4152.

[29] Teunter, R. H., van der Laan, E., & Vlachos, D. (2004). Inventory strategies for systems with fast remanufacturing. *Journal of the Operational Research Society*, 55(5), 475-484.

[30] Thornhill, N. F., & Naim, M. M. (2000). An exploratory study to identify rogue seasonality in a steel making supply chain using spectral principal component analysis. *European Journal of Operational Research*, 120(2), 345-358.

[31] Treharne, J. T., & Sox, C. R. (2002). Adaptive inventory control for nonstationary demand and partial information. *Management Science*, 48(5), 607-624.

[32] Van der Laan, E., Salomon, M., Dekker, R., & Van Wassenhove, L. (1999). Inventory control in hybrid systems with remanufacturing. *Management Science*, 45(5), 733-747.

[33] Yang, M. F., & Tseng, Y. F. (2021). Remanufacturing lead time planning of the medical device with multi-refurbishing steps. *Computers & Industrial Engineering*, 162, 107716.

[34] Zhou, L., & Disney, S. M. (2013). Bullwhip and inventory variance in a closed loop supply chain. *OR Spectrum*, 35(1), 127-149.