

Delivery-Time-Weighted Critical Stock Model (DTW-CSM): Min/Max Calculation Methodology for Geographically Distributed Machinery Fleets

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Abstract

Continuous supply for geographically remote fleets of specialized machinery is a critical factor in mining, construction, and agriculture. Standard threshold inventory control schemes, such as classic min/max models, fail when logistics operations face volatile lead times or asymmetric downtime costs caused by failure of different components. To address this challenge, this paper introduces the Delivery-Time-Weighted Critical Stock Model (DTW-CSM). The model ties replenishment thresholds directly to lead time variance and a functional criticality coefficient. This methodology mitigates unscheduled equipment downtime while avoiding excessive working capital tie-up. Mathematical formulations, an industry classification matrix, a numerical demonstration, and empirical field results are presented.

Keywords: Threshold inventory control, Min/Max model, Logistic lead time, Supply lead time variability, Criticality rating, Safety stock, Fleet downtime

1. Introduction

The profitability of mining, oil & gas, construction, and agricultural enterprises depends on machine operational readiness. When operating sites are isolated from major logistical hubs and machinery operates under extreme climatic conditions, component failures disrupt entire production cycles. Spare parts supply transitions from a routine administrative function into a core determinant of operational continuity.

Supplying remote sites faces a fundamental challenge: Lead Time (L) is rarely constant. In practice, lead time fluctuates due to seasonal disruptions (mud seasons, winter road closures, storms), infrastructure bottlenecks, and customs delays. Traditional inventory management models - including standard min/max logic - were designed for stable supply chains and uniform item criticality. Applying these standard models to distributed fleets creates two failure modes:

1. Chronic Shortages of Critical Components: Emergency failure of a key component (e.g., an excavator's main hydraulic pump) without local stock causes multi-day downtime across the value chain, resulting in losses far exceeding the component's unit cost.
2. Excessive Working Capital Accumulation: To hedge against downtime, site managers build inflated safety

cushions of non-critical or slow-moving parts, freezing substantial working capital.

This study presents an adaptive mathematical model for calculating min/max inventory thresholds that integrates lead time variance, spatial remoteness, and node criticality coefficients for geographically distributed machinery fleets.

2. Literature Review & Problem Statement

In classical inventory theory (Silver, Pyke, & Peterson, 1998; Chase et al., 2019), continuous or periodic review inventory systems rely on the Reorder Point (ROP) and Maximum Stock Level (max):

$$ROP = d \cdot L + SS$$

where d represents average daily demand, L is average lead time, and SS is safety stock. Standard safety stock calculation uses a service factor Z corresponding to stockout probability:

$$SS = Z \cdot \sigma_{DL} = Z \cdot \sqrt{L \cdot \sigma_d^2 + d^2 \cdot \sigma_L^2}$$

Recent service supply chain research (Ivanov et al., 2019) highlights key limitations of standard safety stock formulas in remote fleet operations: (1) lack of differentiation based on downtime cost, treating routine filters identically to engine assemblies; and (2) linear assumptions regarding logistics risk, failing to capture exponential variance growth σ_L as mean lead time L increases.

3. Methodology: The DTW-CSM Model

The Delivery-Time-Weighted Critical Stock Model (DTW-CSM) incorporates two adjustments: a Delivery Lead Time Weight factor (W_L) and a Component Criticality Factor (K_{crit}).

3.1. Delivery Lead Time Weight & Instability Factor (W_L)

For each remote warehouse/base i , historical delivery data over 12–24 months is evaluated. The weight factor W_L is calculated as:

$$W_L = 1 + (\sigma_{L_i}/L_i) \cdot \ln(L_i/L_{base} + 1)$$

where L_i is mean lead time from central hub to site i , σ_{L_i} is lead time standard deviation, and L_{base} is baseline lead time under ideal conditions. The ratio σ_{L_i}/L_i represents the coefficient of variation (CV_L). The logarithmic term smooths extreme outliers while preserving exponential safety adjustments under high instability.

3.2. Technological Criticality Matrix (K_{crit})

Table 1 outlines the item classification matrix designed to segment spare parts by operational criticality and target service levels.

Table 1. Item Classification Matrix by Functional Criticality (K_{crit})

Category	Component Types	Impact on Operation	K_{crit}	Target Service Level
K1 (Critical)	Engines, main pumps, ECUs, drive axles, track chains	Immediate total machine stoppage. No substitute. High downtime cost.	2.2 – 2.5	99.0% – 99.9% ($Z = 2.33$ – 3.09)
K2 (Essential)	Hydraulic cylinders, starters, alternators, bucket blades	Partial capacity loss or single machine stop with team backup available.	1.4 – 1.6	95.0% – 98.0% ($Z = 1.64$ – 2.05)
K3 (Low / Routine)	Filters (oil/air), belts, routine seals, cabin elements	Scheduled maintenance. Predictable replacement. No immediate stoppage.	1.0 – 1.1	85.0% – 90.0% ($Z = 1.04$ – 1.28)

3.3. Modified Threshold Calculations (min & max)

The reorder point / minimum inventory level ($\min_i$) is defined as:

$$\min_i = d \cdot L_i + Z \cdot \sqrt{L_i \cdot \sigma_d^2 + d^2 \cdot \sigma_{L_i}^2} \cdot W_L \cdot K_{\text{crit}}$$

The maximum target stock level ($\max_i$) is computed by adding modified order quantity (Q_{mod}):

$$\max_i = \min_i + Q_{\text{mod}}$$

$$\text{where } Q_{\text{mod}} = \sqrt{\frac{2 \cdot D \cdot (S + C_{\text{trans},i})}{H \cdot (1 + \gamma_{\text{risk}})}}$$

where D is annual demand, S is fixed order cost, $C_{\text{trans},i}$ is unit transit cost to site i , H is holding cost, and γ_{risk} is obsolescence risk coefficient.

4. Numerical Example and Comparative Analysis

To evaluate model behavior, we compare standard min/max against DTW-CSM for a high-pressure hydraulic pump (Category K1, $K_{\text{crit}} = 2.4$) across two operational sites: Base Site A (central region) and Remote Site B (Eastern Siberia). Parameters: $d = 0.1$ unit/day, $\sigma_d = 0.05$, $L_{\text{base}} = 2$ days, $Z = 2.33$ (99% target service level).

Table 2. Comparative Parameter Calculation for Sites A and B

Parameter / Method	Site A (Classic)	Site A (DTW-CSM)	Site B (Classic)	Site B (DTW-CSM)
Mean Lead Time (L), days	3.0	3.0	20.0	20.0
Lead Time Std Dev (σ_L), days	0.5	0.5	6.0	6.0
Weight Factor (W_L)	—	1.15	—	1.72
Criticality Factor (K_{crit})	—	2.40	—	2.40
Base Safety Stock (SS), units	0.28	0.28	1.48	1.48
Expected Lead Time Demand ($d \cdot L$)	0.30	0.30	2.00	2.00
Calculated Min Level (min)	0.58 (≈ 1)	1.60 (≈ 2)	3.48 (≈ 4)	14.36 (≈ 15)
Order Quantity (Q_{mod}), units	2	2	3	3
Calculated Max Level (max)	3	4	7	18

Analysis: For Remote Site B, standard min/max sets min = 4 units. Given high lead time volatility ($\sigma_L = 6$ days) and high failure cost ($K_{crit} = 2.4$), standard buffers fail during transport delays. DTW-CSM adjusts min to 15 units for Remote Site B, safeguarding operational continuity. Conversely, for low-criticality items ($K_{crit} = 1.0$) DTW-CSM prevents capital accumulation.

5. Empirical Validation and Economic Results

The DTW-CSM model was field-tested over 12 months across 420 heavy machinery units operated by a logging and road-construction conglomerate across eight geographically isolated production bases.

Table 3. Key Performance Indicators Before and After DTW-CSM Implementation

Performance Metric	Pre-Implementation (Classic)	Post-Implementation (DTW-CSM)	Change (%)
Fleet Availability Factor (FAF)	0.81	0.92	+13.6%
Downtime due to Stockouts (hrs/machine-month)	46.5	12.2	-73.8%
Total Working Capital in Stock (Million RUB)	248.0	212.5	-14.3%
Obsolete Inventory Share (>12 mos static)	18.4%	7.1%	-61.4%
Requisition Fill Rate (%)	82.5%	96.8%	+17.3%

Key Operational Highlights:

- **Downtime Mitigation:** Eliminating emergency stockouts added over 14,000 billable machine-hours annually.
- **Capital Reallocation:** Releasing capital from non-critical items (Category K3) financed robust safety buffers for critical parts (Category K1) at remote bases without increasing net inventory expenditure.

6. Conclusion

The Delivery-Time-Weighted Critical Stock Model (DTW-CSM) reconciles supply reliability with capital efficiency in distributed fleet operations. Integrating W_L and K_{crit} factors allows min/max parameters to adapt dynamically to transport network volatility and component criticality. The model easily embeds into enterprise WMS/ERP systems. Future research will explore integration with IoT telemetry for dynamic demand forecasting (d).

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