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Empirical Evaluation of Continuous Review Inventory Policies for Spare Parts in the Wire and Cable Manufacturing Industry: A Multi-Scenario Cost Analysis with Multi-Criteria Classification and Demand Behavior Integration

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Abstract: This study aims to enhance spare parts inventory management efficiency in the wire and cable manufacturing industry through a systematic analysis and data-driven approach. The analysis combines multi-criteria inventory classification methods: ABC analysis (based on annual consumption value), VED analysis (assessing vital, essential, and desirable criticality), and SDE analysis (evaluating scarce, difficult, and easy procurement levels) to efficiently group inventory based on annual consumption value, operational criticality, and procurement difficulty. Subsequently, demand pattern analysis is performed to evaluate each spare part's demand characteristics. From an empirical dataset of 377 spare part items, fifteen items were selected from four high-priority classification groups ESA, VEA, VDA, and VSA for a detailed evaluation of suitable inventory control policies. Analysis of the selected items showed smooth demand behavior, whereas only two items in the ESA group exhibited intermittent demand. Two continuous review inventory control models, (s, S) and (s, Q), were assessed across four service levels 80, 90, 95, and 99 percent to evaluate their effectiveness in minimizing shortages and overall inventory costs. Accurately estimating shortage and opportunity-loss costs remains a significant challenge. To analyze the cost-performance trade-offs among ordering, holding, and shortage costs, three scenarios were considered: (1) total inventory cost (TIC) without shortage cost, (2) TIC including expedited shortage cost, and (3) TIC including opportunity-loss shortage. Results revealed that the (s, S) policy not only eliminated spare part shortages but also yielded significant reductions in total inventory costs by approximately 46 percent for TIC with expedited shortage costs and 97 percent for TIC with opportunity loss shortages relative to the manufacturer's existing operational practices. Optimal service levels were determined by balancing TIC and shortage risk based on each item's demand variability and criticality. The findings indicate that aligning inventory control policies with demand behavior and part criticality enhances cost efficiency, reliability, and production continuity.

Keywords: Spare parts inventory, Multi-criteria inventory classification, Continuous review inventory policies, Opportunity loss shortages, Expedited shortage costs

Introduction

Efficient spare parts inventory management is a critical factor in maintaining operational reliability and minimizing production downtime, particularly in industries with continuous manufacturing processes such as wire and cable production. In such environments, the unavailability of even a single spare part can halt production and lead to significant financial losses. Therefore, establishing a systematic, data-driven approach to spare parts management is critical to ensure both cost efficiency and production continuity.

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Traditional inventory management practices often rely on intuition or historical experience rather than analytical evaluation. These methods may be sufficient for regular materials but are inadequate for spare parts, whose demand is irregular, infrequent, and difficult to forecast. To address this constraint, recent studies have proposed multi-criteria approaches that integrate both quantitative and qualitative dimensions in inventory classification. Frameworks such as ABC–VED–SDE enable decision-makers to consider annual consumption value, operational criticality, and procurement difficulty simultaneously, leading to a more balanced inventory-control strategy (Amer & Jawad, 2023; Hatefi et al., 2014; Nirmala et al., 2021).

However, classification alone does not account for the stochastic nature of spare parts demand. Understanding demand variability and identifying demand patterns are equally important in determining suitable inventory control policies. Boylan et al. (2008) and Kim et al. (2019) highlighted that the combination of the average demand interval (ADI) and the coefficient of variation (CV^2) can effectively distinguish demand behaviors into smooth, intermittent, lumpy, and erratic types, providing a basis for policy selection.

Numerous researchers have examined continuous-review inventory models, such as (s, S) and (s, Q), for managing uncertain demand conditions. Durán et al. (2004) introduced expediting mechanisms to minimize shortage impacts, while Kocer and Yalçın (2020) and Bazizi et al. (2021) analyzed stochastic variations in lead times and demand. These studies have shown that continuous-review systems are flexible and effective in balancing service-level and cost trade-offs.

Despite these advances, limited research has integrated multi-criteria classification with demand pattern analysis for spare parts management in the wire and cable manufacturing industry, a sector characterized by high operational dependency on machine availability. This study aims to bridge this gap by developing a data-driven framework that combines the ABC–VED–SDE classification with demand pattern analysis to evaluate and compare two continuous-review policies, (s, S) and (s, Q), under different service levels. The objective is to identify the appropriate policy that minimizes total inventory cost while trying to ensure zero shortages, thus enhancing cost efficiency, reliability, and sustainable decision-making in industrial operations.

Method

Multi-Criteria Inventory Classification

This stage aimed to classify spare parts into strategic inventory groups by applying a multi-criteria inventory-classification framework, which integrates three analytical dimensions: ABC, VED, and SDE. The framework was designed to reflect the economic significance, operational criticality, and procurement difficulty of each item, thereby establishing a comprehensive foundation for determining appropriate inventory-control policies (Ramanathan, 2006; Lolli et al., 2010; Hatefi et al., 2014; Sarkar & Mukherjee, 2020; Amer & Jawad, 2023; Nirmala et al., 2021).

The VED analysis assessed the operational criticality of each item in relation to production continuity. Vital items are those whose absence causes immediate production stoppage. Essential items affect efficiency or product quality but do not halt production entirely, while desirable items are useful for maintenance or improvement but have minimal operational impact (Amer & Jawad, 2023; Hatefi et al., 2014). The SDE analysis evaluated the procurement difficulty of spare parts, considering supplier lead time, sourcing complexity, and market availability. Scarce items have limited suppliers or long procurement times, difficult items have moderate sourcing constraints, and easy items are readily available or locally sourced (Sarkar & Mukherjee, 2020).

The ABC analysis categorized items according to their annual consumption value, calculated by multiplying the unit cost by the annual usage quantity. Items were arranged in descending order of annual consumption value, and cumulative percentages were applied to classify them into three groups: Class A includes items that contribute the highest share of total annual consumption value, accounting for approximately 70 percent of the overall value; Class B comprises items with a moderate share, representing the next 20 percent; and Class C covers items with the lowest share, accounting for the remaining 10 percent.

The results from these three analytical criteria were integrated to form combined strategic groups such as VEA, ESA, VDA, and VSA. Each group reflects a distinct balance between operational importance and procurement complexity, enabling a clearer understanding of the strategic role of each spare part (Lolli et al., 2010; Ramanathan, 2006). Overall, this multi-criteria classification approach provides a systematic and data driven foundation for linking each inventory category to its suitable control policy. The outcomes serve as a crucial basis for further quantitative analysis (Boylan et al., 2008; Kim et al., 2019).

Demand Pattern Analysis

A total of fifteen representative spare parts were selected from the company's inventory database. These items were chosen based on the completeness of available data, operational importance, and diversity of usage characteristics. Their demand behavior was analyzed to identify their usage characteristics and classify demand variability. Two statistical indicators were applied: the average demand interval (ADI) and the squared coefficient of variation (CV^2). These indicators were calculated from historical weekly usage data collected over a three-year period to measure the regularity and fluctuation of demand for each spare part (Syntetos et al., 2005; Boylan et al., 2008; Kim et al., 2019).

$$\text{ADI} = \left(\frac{N}{n}\right) \tag{1}$$

The ADI represents the average time interval between two consecutive demands and is expressed as follows:

where N is the total number of periods observed, and n is the number of periods with nonzero demand.

The coefficient of variation (CV) measures the relative variability of demand, and its squared value (CV^2) is used to increase sensitivity to fluctuations in demand. It is calculated as follows:

$$\text{CV}^2 = \left(\frac{\sigma}{\mu}\right)^2 \tag{2}$$

where σ is the standard deviation of demand, and μ is the mean demand. Items with lower ADI and CV^2 values indicate consistent, predictable usage, while higher values reflect sporadic or uncertain demand behavior (Willemain et al., 2004; Syntetos et al., 2005). Based on these parameters, demand patterns were classified according to the criteria proposed by Boylan et al. (2008), as summarized below.

- Smooth ADI $\leq$ 1.32 and $CV^2 \leq 0.49$ Continuous and stable demand with low variability
- Intermittent ADI > 1.32 and $CV^2 \leq 0.49$ Irregular demand with long intervals but low volume fluctuation
- Erratic ADI $\leq$ 1.32 and $CV^2 > 0.49$ Frequent demand but high variability
- Lumpy ADI > 1.32 and $CV^2 > 0.49$ Irregular and highly variable demand

Inventory Control Model Formulation

The objective is to develop and evaluate optimal inventory control policies for spare parts by comparing two continuous review models: the (s, S) and (s, Q) systems. The analysis aims to identify the policy that balances total inventory cost with the required service levels, ensuring minimal stockouts. This evaluation considers historical demand, lead time, ordering cost, holding cost, and shortage related cost. It is conducted under four service level scenarios (80 percent, 90 percent, 95 percent, and 99 percent) to examine the trade-off between cost and service reliability. The results provide practical insights for selecting the most cost-effective and reliable inventory control policy for each spare part category, supporting sustainable and data-driven decision-making in industrial operations.

(s, S) Inventory Policy

The continuous review (s, S) inventory model initiates a replenishment order when inventory position reaches or falls below the reorder point s. This reorder point is calculated based on the expected demand during lead time together with the safety stock required to buffer against uncertainty in both demand and lead time variability, as shown in Equation (3) (Axsäter, 2015; Silver et al., 2017). Once an order is triggered, the system replenishes inventory up to the order-up-to level S, which is obtained by adding the economic order quantity (Q_{EOQ}) to the reorder point, as shown in Equation (4).

$$s = \mu_D L + z\sqrt{L\sigma_D^2 + \mu_D^2\sigma_L^2} \quad (3)$$

$$S = s + Q_{EOQ} \quad (4)$$

μ_D = average demand per unit time
σ_D= standard deviation of demand per unit time
L = average lead time (in the same time units as demand)
σ_L = standard deviation of lead time
z = inverse standard normal value corresponding to the target service level
s = reorder point under continuous review
S = order-up-to level
Q_{EOQ} = economic order quantity

(s, Q) Inventory Policy

The continuous review (*s, Q*) model uses a fixed replenishment quantity (*Q*), which is placed whenever the inventory position drops below the reorder point (s). The reorder point considers both expected demand and uncertainty during lead time, as expressed in Equation (3) (Axsäter, 2015; Silver et al., 2017). The order quantity (*Q*) is constant and is typically determined by the economic order quantity (EOQ) formula:

$$Q = \sqrt{\frac{2DC_o}{C_h}} \quad (5)$$

With
D = annual demand
C_o = ordering cost per order
C_h = annual holding cost per unit
s = reorder point under the
Q = fixed order quantity

The (s, Q) model maintains a constant order quantity while adjusting the reorder point according to demand variability and service level.

Shortage Performance Analysis

This stage focused on evaluating the effectiveness of inventory control policies in minimizing spare part shortages, which is consistent with previous studies emphasizing the role of analytical inventory models in reducing service disruptions (Silver et al., 1998; Zipkin, 2000). The objective was to compare the performance of the current inventory control policy (as-is) with the proposed analytical policies (to be) in reducing both the frequency and quantity of shortages. Shortage related information was extracted from the company's warehouse transaction database, following typical approaches used in empirical inventory control research (Boylan et al., 2008).

The evaluation was conducted in two scenarios. The first scenario analyzed actual operational data under the existing policy, while the second scenario simulated two continuous review policies: (s, S) and (s, Q), which have been widely applied for managing variable spare part demand in manufacturing industries (Duran et al., 2004; Hadley & Whitin, 1963; Kocer & Yalçın, 2020).

Service levels (Z) were assigned differently across classification groups such as ESA, VDA, VEA, and VSA to reflect differences in operational criticality, in line with the role of service level differentiation in optimizing inventory performance (Gupta & Maranas, 2003). The (s, S) and (s, Q) models were then used to derive s, S, and Q values under these service levels.

After establishing both policies, a comparative analysis using shortage occurrences and shortage quantities was conducted. Measuring shortage reduction is a standard method for assessing policy improvement in spare part inventory contexts (Driessen et al., 2014). The results form the foundation for understanding the relationship between service level and shortage reduction effectiveness and also provide key inputs for subsequent total inventory cost analysis.

Total Inventory Cost Performance

This section aimed to evaluate the cost performance of the proposed continuous review inventory policy by comparing the annual total inventory cost (TIC) under the current policy (as-is) and the improved policies (to-be). The analysis was based on the classical economic order quantity (EOQ) model and extended to include shortage related cost components under various operating conditions (Durán et al., 2004; Kocer & Yalçın, 2020; Amer & Jawad, 2023). This approach aligns with previous studies on spare parts inventory cost modeling (Bazizi et al., 2021; Boylan et al., 2008; Hatefi et al., 2014). To capture the trade-offs among ordering, holding, and shortage costs, three cost scenarios were examined:

(1) annual TIC without shortage cost,
(2) annual TIC with expedited shortage cost, and
(3) annual TIC with opportunity-loss shortage cost.

(1) Annual TIC without Shortage Cost

In this baseline scenario, it is assumed that no shortage occurs during the year. The total annual inventory cost consists of two components: annual ordering cost and annual holding cost (Durán et al., 2004; Ramanathan, 2006), calculated as follows:

$$\text{TIC} = \left(\frac{D}{Q} \times S\right) + \left(\frac{Q}{2} \times H\right) \tag{6}$$

With
D = annual demand (units/year)
Q = order quantity (units/order)
S = ordering cost per order (THB/order)
H = holding cost per unit per year (THB/unit/year)

This formula provides a reference point for subsequent comparisons with scenarios involving shortages.

(2) Annual TIC with Expedited Shortage Cost

This scenario considers the case where shortages are resolved through urgent or expedited procurement, resulting in additional per-unit cost (Durán et al., 2004; Bazizi et al., 2021). The total annual cost is expressed as follows:

$$\text{TIC}_{\text{expedited}} = \left(\frac{D}{Q} \times S\right) + \left(\frac{Q}{2} \times H\right) + \left(Q \text{ x } C_{exp}\right) \tag{7}$$

With
C_{exp}= expedited cost per unit (THB/unit)

(3) Annual TIC with Opportunity Loss Shortage Cost

This scenario considers the case where shortages are resolved through urgent or expedited procurement and opportunity-loss cost, resulting in additional per-unit cost (Bazizi et al., 2021; Durán et al., 2004). The total annual cost is expressed as:

$$\text{TIC}_{\text{opportunity}} = \left(\frac{D}{Q} \times s\right) + \left(\frac{Q}{2} \times H\right) + \left(B \text{ x } C_{opp}\right) \tag{8}$$

With
C_{opp} = combined shortage penalty cost per unit (THB/unit), consisting of:

- expedited procurement cost, and
- opportunity-loss cost

D = annual demand (units/year)
Q= order quantity for each replenishment cycle (units)
S= ordering cost per order (THB/order)
H= holding cost per unit per year (THB/unit/year)
B= total annual shortage quantity under the policy (units/year)

Results and Discussion

This section presents the results of the multi-criteria inventory classification and demand pattern analysis, followed by a discussion that links these findings to the determination of appropriate inventory control policies. The results aim to explain relationship among spare parts characteristics, demand behavior, and service level. These factors all influence total inventory cost decisions and are key to effective spare parts management strategies.

Multi-criteria Inventory Classification

The analysis employed a multi-criteria inventory classification framework for fifteen representative spare parts, integrating three analytical approaches: VED, SDE, and ABC. The classification results are summarized in Table 1.

Table 1. Multi-criteria inventory classification

SKU Code	VED	SDE	ABC	GROUP
A010	V	E	A	VEA
A003	E	S	A	ESA
A015	V	D	A	VDA
A013	E	S	A	ESA
A011	V	S	A	VSA
A008	E	S	A	ESA
A001	E	S	A	ESA
A009	V	D	A	VDA
A014	V	S	A	VSA
A006	V	D	A	VDA
A004	E	S	A	ESA
A012	V	S	A	VSA
A005	E	S	A	ESA
A007	V	E	A	VEA
A002	E	S	A	ESA

The analysis revealed that the ESA group accounted for the largest proportion, representing seven items, or 46.7 percent of the total sample (A003, A013, A008, A001, A004, A005, A002). These items are moderately important and easy to procure. The VDA and VSA groups each contained three items (20 percent); VDA included codes A015, A009, and A006, and VSA included A011, A014, and A012. VDA items are vital but difficult to source. VSA items are also vital but easier to procure, this group comprised two items (13.3 percent): A010 and A007. These are strategically important parts with high annual consumption and ease of procurement. Overall, the classification provides a clear understanding of each group's strategic role and procurement difficulty, forming the basis for determining appropriate inventory control policies in subsequent stages of analysis.

Demand Pattern Analysis

The fifteen representative spare parts was analyzed using two indicators: *ADI* and CV^2. Based on these parameters, their demand patterns were classified into two categories smooth and intermittent as shown in Table 2. The analysis revealed that most spare parts, totaling thirteen items or 86.67percent, exhibited smooth demand patterns, indicating continuous usage with low variability ($ADI \leq 1.32$ and $CV^2 \leq 0.49$). For example, parts with codes A010, A003, and A015 showed stable and predictable usage behavior. In contrast, only two items, or 13.33 percent of the total (A001 and A002), were classified as intermittent, reflecting irregular demand with longer intervals between usages. Overall, majority of spare parts in the company demonstrated stable and predictable demand.

Table 2. Demand Pattern Classification Based on ADI and CV^2

Code	GROUP	ADI	CV^2	Pattern Type
A010	VEA	1.13	0.26	Smooth
A003	ESA	1.19	0.31	Smooth
A015	VDA	1.25	0.25	Smooth
A013	ESA	1.20	0.30	Smooth
A011	VSA	1.11	0.31	Smooth
A008	ESA	1.31	0.31	Smooth
A001	ESA	1.42	0.31	Intermittent
A009	VDA	1.30	0.30	Smooth
A014	VSA	1.20	0.35	Smooth
A006	VDA	1.18	0.29	Smooth
A004	ESA	1.16	0.26	Smooth
A012	VSA	1.16	0.30	Smooth
A005	ESA	1.26	0.37	Smooth
A007	VEA	1.15	0.32	Smooth
A002	ESA	1.39	0.27	Intermittent

Inventory Control Model Formulation

Shown in Table 3, the numerical calculation using (s, S) policy is conducted under four service-level scenarios (80, 90, 95, and 99 percent, respectively) to examine the trade-off between cost and service reliability. The results demonstrate that both s and S increase consistently as the target service level rises. This behavior aligns with the theoretical expectations of continuous review models, where higher service levels require additional safety stock to mitigate demand and lead-time uncertainty (Durán et al., 2004; Kocer & Yalçın, 2020).

For instance, item A001 shows an increase in the reorder point from *s* equals to 4 at the 80 percent service level to *s* equals to 6 at 99 percent, while the corresponding order-up-to level increases from *S* equals to 6 to *S* equals to 9. This trend is consistent across most items, indicating a direct relationship between service level and inventory buffer. Items with relatively stable demand patterns, such as A005, A006, and A015, exhibit small differences between *s* and *S*, suggesting low variability and predictable consumption behavior.

Table 3. Reorder points (s) and order up to levels (s) under different service levels

Code	80% Service Level		90% Service Level		95% Service Level		99% Service Level	
	s	S	s	S	s	S	s	S
A001	4	6	4	7	5	8	6	9
A002	8	11	9	12	10	12	11	14
A003	29	31	31	33	33	35	36	39
A004	12	15	13	16	14	17	15	19
A005	4	6	4	7	5	8	6	9
A006	4	6	4	7	5	8	6	9
A007	5	8	5	9	6	10	7	11
A008	8	11	9	12	10	12	11	14
A009	3	6	4	7	5	8	6	9
A010	5	8	5	9	6	10	7	11
A011	12	15	13	16	14	17	15	19
A012	8	11	9	12	10	12	11	14
A013	8	11	9	12	10	12	11	14
A014	8	11	9	12	10	12	11	14
A015	4	6	4	7	5	8	6	9

In contrast, item A003 shows the highest inventory control parameters among all examined items. The reorder point increases from 29 units at the 80 percent service level to 36 units at the 99 percent level. Similarly, the order-up-to level increases from 31 to 39 units across the same service levels. These increases are solely the result of higher target service levels, which require greater inventory coverage. The consistently higher values of both parameters indicate that A003 requires more substantial protection against uncertainty compared with the other parts. This behavior suggests that maintaining stricter service level targets for this item leads to a larger safety stock requirement. Consequently, A003 becomes one of the most inventory intensive items under the evaluated policies.

The overall results indicate that increasing the service level from 80 percent to 99 percent substantially raises both the reorder point and order-up-to level. While this leads to higher holding costs, it also enhances service reliability and reduces the likelihood of stockouts. Therefore, the selection of the appropriate service level should be based on the operational importance of each spare part and the acceptable trade-off between cost and service reliability.

Table 4 presents the calculated reorder points (*s*) and fixed order quantities (*Q*) for fifteen representative spare parts under four target service levels. The results show a clear and consistent pattern in which the value of *s* increases as the service level becomes higher, while *Q* remains constant for each item. For example, item A001 shows an increase in the reorder point from 3 to 5 units as the service level rises from 80 percent to 99 percent, while the fixed order quantity remains unchanged at six units. Similar trends can be observed for stable demand items such as A005, A006, and A015, where the reorder point changes only slightly across service levels and *Q* remains fixed. This indicates relatively predictable demand patterns typical of frequently used maintenance parts. In contrast, items A003 and A004 exhibit consistently higher reorder points across all service levels, indicating greater demand rates or higher demand variability. For instance, item A003 shows the highest reorder point among all fifteen items (*s* ranging from 28 to 36) while maintaining a constant *Q* of three units.

Overall, the findings demonstrate that increasing the service level primarily affects the safety stock component, thereby raising the reorder point (*s*), while *Q* remains stable because it is determined by economic order quantity parameters rather than service level. This makes the (*s*, *Q*) model operationally simpler than the (*s*, *S*) model, as the replenishment quantity does not change from order to order. However, achieving higher service levels requires larger safety stock and therefore incurs higher holding costs. The results suggest that the (*s*, *Q*) model is particularly suitable for items with stable demand and moderate criticality, where maintaining fixed order quantities improves procurement efficiency and inventory stability.

Table 4. Reorder points (s) and fixed order quantities (q) under different service levels

Code	80% Service Level		90% Service Level		95% Service Level		99% Service Level	
	s	Q	s	Q	s	Q	s	Q
A001	3	6	4	6	4	6	5	6
A002	8	8	9	8	10	8	11	8
A003	28	3	31	3	32	3	36	3
A004	11	9	12	9	13	9	15	9
A005	3	9	4	9	4	9	5	9
A006	3	7	4	7	4	7	5	7
A007	4	10	5	10	5	10	6	10
A008	8	6	9	6	9	6	11	6
A009	3	6	4	6	4	6	5	6
A010	4	4	5	4	5	4	6	4
A011	11	6	12	6	13	6	15	6
A012	8	7	9	7	10	7	11	7
A013	8	5	9	5	9	5	11	5
A014	8	6	9	6	10	6	11	6
A015	3	4	4	4	4	4	5	4

Shortage Performance Analysis

This evaluation assessed the current practice (as-is) against the proposed analytical policies (to-be) to determine whether the improved approach could effectively reduce the risk of shortages both overall and within each classification group. To provide a clearer understanding of how each policy influences inventory reliability, the analysis first examines the number of shortage occurrences across all items under varying service levels. Table 5 presents the comparison of shortage occurrences under the as-is approach and the (s, S) and (s, Q) models.

As displayed in Table 5, the analytical policies significantly lowered shortage occurrences across all demand types and criticality levels. The (s, S) model, in particular, showed consistent reductions in shortages, eliminating them for many items even at an 80 percent service level. At higher service levels of 95–99 percent, it resulted in no shortages for most items with smooth demand. Although the (s, Q) model produced similar improvements, some items with irregular consumption still exhibited occasional shortages. Overall, the results confirm that the proposed inventory models outperform the as-is approach and provide more reliable protection against stockouts for critical spare parts.

In addition to evaluating shortage occurrences, this study also examines the total quantity of shortages to provide a more comprehensive understanding of stockout severity under each inventory policy. Assessing shortage quantities offers more detailed insight into the extent of unmet demand, reflecting the operational impact more directly than considering the number of shortage incidents alone. This perspective helps capture how well each policy can cope with demand variability and lead time uncertainty, particularly for items with high criticality or unstable usage patterns. Furthermore, analyzing shortage quantities supports a more accurate assessment of potential operational disruptions, as larger shortage volumes often correspond to increased downtime or delayed maintenance activities. This measure also plays a crucial role in the subsequent cost analysis, where shortage-related costs are directly influenced by the magnitude of unfulfilled demand. Table 6 presents the comparison of shortage quantities under the current practice (as-is) and the proposed analytical policies, (s, S) and (s, Q), across four service levels.

Table 5. Shortage occurrences across service levels under as-is, (s, S), and (s, Q) inventory policies

Code	Demand Pattern	Classification	Shortage Occurrence (times)								
			as-is	(s, S) 80% Service Level	(s, S) 90% Service Level	(s, S) 95% Service Level	(s, S) 99% Service Level	(s, Q) 80% Service Level	(s, Q) 90% Service Level	(s, Q) 95% Service Level	(s, Q) 99% Service Level
A001	Intermittent	ESA	2	0	0	0	0	0	0	0	0
A002	Intermittent	ESA	3	0	0	0	0	0	0	0	0
A003	Smooth	ESA	2	1	0	1	0	1	1	1	1
A004	Smooth	ESA	4	0	0	0	0	0	0	0	0
A005	Smooth	ESA	4	3	1	0	0	1	1	1	1
A006	Smooth	VDA	2	1	1	0	0	1	1	1	1
A007	Smooth	VEA	0	0	0	0	0	1	0	0	0
A008	Smooth	ESA	3	0	0	0	0	0	0	0	0
A009	Smooth	VDA	5	1	2	2	0	5	1	1	1
A010	Smooth	VEA	3	1	0	0	0	3	2	2	1
A011	Smooth	VSA	1	0	0	0	0	0	0	0	0
A012	Smooth	VSA	2	0	0	0	0	0	0	0	0
A013	Smooth	ESA	2	0	0	0	0	0	0	2	0
A014	Smooth	VSA	4	0	0	0	0	1	0	0	5
A015	Smooth	VDA	0	1	1	0	0	1	1	0	2

As illustrated in Table 6, the analytical policies substantially reduced shortage quantities across all items when compared with the as-is practice. The (s, S) model achieved the most notable improvements, lowering shortage quantities to zero for majority of smooth-demand items at service levels of 90 percent and above. Even at the 80 percent service level, the (s, S) model markedly reduced the severity of stockouts for items that previously experienced high unmet demand. The (s, Q) model also produced considerable reductions; however, several items with irregular or highly variable consumption patterns still exhibited remaining shortage quantities, particularly at lower service levels. Overall, the results demonstrate that both models provide superior protection against stockout severity, with the (s, S) policy offering the most robust performance across different demand behaviors and criticality classifications. Following the results in Table 6, which examined the severity of stockouts under each policy, Table 7 provides a direct comparison of shortage performance between the current as-is practice and the proposed to-be policies. This summary highlights the overall improvements achieved by the analytical inventory models. Additionally, the empirical results demonstrate in Table 7 that the proposed continuous review (s, S) inventory control policy eliminated shortages across all spare part groups. Under the existing as-is policy, a total of 37 shortage occurrences and 72 shortage units were recorded, indicating a relatively high level of supply risk. After applying the to-be policy, both measures dropped to zero, representing a 100 percent reduction in shortage frequency and quantity throughout the system.

When examined by group, the reductions were uniformly 100 percent across all categories, confirming the robustness of the improved policy. The ESA (intermittent) group reduced shortages from five occurrences (nine units) to zero at a service level of 80 percent. Likewise, the ESA (smooth) and VDA (smooth) groups achieved full elimination at a 99 percent service level, falling from fifteen occurrences (thirty-three units) and seven occurrences (nine units), respectively, to zero. The VEA (smooth) group at a 90 percent service level and the VSA (smooth) group at an 80 percent service level also achieved complete elimination of shortages.

Table 6. Shortage quantities across service levels under as-is, (s, S), and (s, Q) inventory policies

Code	Demand Pattern	Classification	Shortage Quantity (units) as-is	(s, S) 80% Service Level	(s, S) 90% Service Level	(s, S) 95% Service Level	(s, S) 99% Service Level	(s, Q) 80% Service Level	(s, Q) 90% Service Level	(s, Q) 95% Service Level	(s, Q) 99% Service Level
A001	Intermittent	ESA	4	0	0	0	0	0	0	0	0
A002	Intermittent	ESA	5	0	0	0	0	0	0	0	0
A003	Smooth	ESA	4	2	0	1	0	1	1	1	1
A004	Smooth	ESA	10	0	0	0	0	0	0	0	0
A005	Smooth	ESA	8	5	2	0	0	1	1	1	1
A006	Smooth	VDA	2	0	1	0	0	1	1	1	1
A007	Smooth	VEA	0	0	0	0	0	2	0	0	0
A008	Smooth	ESA	4	0	0	0	0	0	0	0	0
A009	Smooth	VDA	7	1	2	2	0	8	1	1	1
A010	Smooth	VEA	5	1	0	0	0	6	3	3	1
A011	Smooth	VSA	7	0	0	0	0	0	0	0	0
A012	Smooth	VSA	2	0	0	0	0	0	0	0	0
A013	Smooth	ESA	7	0	0	0	0	0	0	0	0
A014	Smooth	VSA	7	0	0	0	0	2	0	0	12
A015	Smooth	VDA	0	1	1	0	0	2	0	0	2

Table 7. Shortage comparison between as-is and to-be policies

Group	Demand Pattern	Shortage Occurrence (Times) as-is	to-be	Inventory Policy (Selected)	Reduction (%)	Shortage Quantity (units) as-is	to-be	Inventory Policy (Selected)	Reduction (%)
ESA	Intermittent	5	0	(s, S) 80% Service Level	100.00	9	0	(s, S) 80% Service Level	100.00
ESA	Smooth	15	0	(s, S) 99% Service Level	100.00	33	0	(s, S) 99% Service Level	100.00
VDA	Smooth	7	0	(s, S) 99% Service Level	100.00	9	0	(s, S) 99% Service Level	100.00
VEA	Smooth	3	0	(s, S) 90% Service Level	100.00	5	0	(s, S) 90% Service Level	100.00
VSA	Smooth	7	0	(s, S) 80% Service Level	100.00	16	0	(s, S) 80% Service Level	100.00
		37	0		100.00	72	0		100.00

Furthermore, these findings confirm that adjusting the (s, S) parameters to reflect each part's demand behavior and operational criticality can effectively reduce stockout risk. The improved policy not only enhances spare part availability but also strengthens overall fill-rate performance. In addition, tailoring service level targets for each classification group enables a more effective balance between holding costs and shortage risks, improving both reliability and cost efficiency. From a risk management perspective, the complete elimination of shortages demonstrates that the to-be policy successfully mitigates uncertainties associated with spare part supply interruptions. This ensures material readiness, prevents production downtime, and enhances overall operational stability.

Total Inventory Cost Performance Analysis

The cost performance of the improved continuous review inventory control policy was evaluated by comparing the annual TIC between the current policy (as-is) and the improved policies (to-be) across three cost scenarios: annual TIC without shortage (THB per year), annual TIC with expedited shortage (THB per year), and annual TIC with shortage opportunity cost (THB per year). Each scenario represents a distinct operational condition used to assess the trade-off between inventory investment and shortage-related costs. By examining these dimensions, the study aims to confirm how the improved policies can optimize total cost efficiency while maintaining high service reliability under varying levels of shortage risk. This multi-scenario cost evaluation also enables a holistic comparison of how the policy performs under both normal and shortage-prone operating environments. The analysis further highlights whether the improved policy can achieve cost savings without compromising system responsiveness. Additionally, this approach provides practical insights for determining the most economically viable strategy for spare part management.

Table 8. Annual total inventory cost without shortage cost

Code	Demand Pattern	Classification	TIC Without Shortage As-is (THB/YEAR)	To-be (THB/YEAR)	Inventory Policy (Selected)
A001	Intermittent	ESA	17,977.08	18,266.12	(s, S) 80%Service Level
A002	Intermittent	ESA	10,558.96	16,567.30	(s, S) 80% Service Level
A003	Smooth	ESA	153,231.22	153,917.48	(s, S) 80% Service Level
A004	Smooth	ESA	17,243.00	20,460.02	(s, S) 80% Service Level
A005	Smooth	ESA	11,081.13	11,646.47	(s, S) 80% Service Level
A006	Smooth	VDA	14,538.44	15,010.61	(s, S) 80% Service Level
A007	Smooth	VEA	11,507.55	10,259.43	(s, S) 80% Service Level
A008	Smooth	ESA	21,336.24	27,966.82	(s, S) 95% Service Level
A009	Smooth	VDA	12,030.13	13,414.50	(s, Q) 80% Service Level
A010	Smooth	VEA	39,460.38	43,305.19	(s, Q) 80% Service Level
A011	Smooth	VSA	50,859.36	55,984.67	(s, Q) 80% Service Level
A012	Smooth	VSA	11,477.72	17,744.55	(s, Q) 90% Service Level
A013	Smooth	ESA	65,777.93	65,314.16	(s, Q) 95% Service Level
A014	Smooth	VSA	21,698.41	20,914.80	(s, Q) 95% Service Level
A015	Smooth	VDA	64,018.87	62,830.19	(s, Q) 99% Service Level
TOTAL			522,796.41	553,602.31	

As first scenarios evidenced by the data in Table 8, under the conditions without shortage, the TIC increased slightly from 522,796.41 THB in the as-is scenario to 553,602.31 THB in the to-be scenario, representing an increase of approximately 5.9 percent. This moderate increase reflects a controlled investment intended to enhance service levels and improve inventory readiness, thereby preventing potential shortages in the future.

At the item level, most spare parts within the ESA, VDA, and VSA classifications exhibited minimal cost variations between the two policies, indicating stable cost efficiency. Intermittent-demand items (A001 and A002) recorded slightly higher costs after applying the (s, S) policy at a service level of $Z = 80$ percent, primarily due to an increase in safety stock compared to as-is. Nevertheless, this incremental cost is justified by the improvement in service reliability and the complete elimination of shortages, as demonstrated in the previous analysis.

Table 9 reveals that the second scenarios under expedited shortage condition, which includes costs from urgent purchasing and transportation activities, the annual TIC decreased significantly from 1,103,890.89 THB in the as-is scenario to 573,826.56 THB in the to-be scenario, representing a reduction of approximately 48 percent. This substantial decrease indicates that the continuous review (s, S) and (s, Q) policies effectively reduces the financial impact associated with emergency procurement and production disruption.

At the item level, all fifteen representative parts exhibited a downward trend in total cost after applying the policies. The most notable reductions were observed in smooth-demand items, particularly A004 (ESA) and A009 (VDA), where TIC declined by 61.57 percent and 55.89 percent, respectively, while A003 (ESA) also showed a meaningful reduction of 22.34 percent. These improvements are attributed to optimized reorder points and appropriately defined service levels that reduced the reliance on costly expedited orders.

Table 9. Annual total ınventory cost with expedited shortage cost

Code	Demand Pattern	Classification	TIC with Shortage Expedited As-is (THB/YEAR)	To-be (THB/YEAR)	Inventory Policy (Selected)
A001	Intermittent	ESA	49,377.08	18,266.12	(s, S) 80% Service Level
A002	Intermittent	ESA	42,158.96	16,567.30	(s, S) 80% Service Level
A003	Smooth	ESA	199,425.70	154,878.24	(s, S) 90% Service Level
A004	Smooth	ESA	53,243.00	20,460.02	(s, S) 80% Service Level
A005	Smooth	ESA	85,881.13	12,182.81	(s, S) 95% Service Level
A006	Smooth	VDA	31,938.44	15,991.27	(s, S) 95% Service Level
A007	Smooth	VEA	11,507.55	10,259.43	(s, S) 80% Service Level
A008	Smooth	ESA	68,436.24	27,966.82	(s, S) 95% Service Level
A009	Smooth	VDA	35,030.13	15,451.89	(s, S) 99% Service Level
A010	Smooth	VEA	121,060.38	50,387.74	(s, S) 90% Service Level
A011	Smooth	VSA	129,859.36	55,984.67	(s, Q) 80% Service Level
A012	Smooth	VSA	16,477.72	17,744.55	(s, Q) 90% Service Level
A013	Smooth	ESA	84,777.93	70,601.09	(s, Q) 90% Service Level
A014	Smooth	VSA	110,698.41	20,914.80	(s, Q) 95% Service Level
A015	Smooth	VDA	64,018.87	66,169.81	(s, Q) 95% Service Level
TOTAL			1,103,890.89	573,826.56	

Intermittent-demand items such as A001 and A002 also demonstrated remarkable cost improvements, , with reductions of 63.0 percent and 60.7 percent compared with the as-is condition. Meanwhile, high value parts such as A010 (VEA) and A011 (VSA) benefited from the adjusted (s, S) and (s, Q) settings, which stabilized cost fluctuations without compromising service levels. However, the results also indicate that the (s, Q) policy did not reduce costs in every case. While items such as A011 (VSA), A013 (ESA), and A014 (VSA) showed clear cost reductions, items A012 (VSA) and A015 (VDA) experienced slightly higher costs than in the as-is condition, suggesting that fixed-order-quantity control may not be suitable for items with more variable demand or higher service-level requirements.

Overall, the results under the expedited-shortage scenario confirm that the (s, S) and (s, Q) policies provide superior cost efficiency by balancing holding and shortage-related costs. The reduction in urgent procurement expenses highlights the effectiveness of the improved system in enhancing supply stability and minimizing unplanned operational disruptions.

As the third scenario highlighted in Table 10, under the shortage opportunity cost condition—which reflects the actual costs observed in the industry—the annual TIC decreased substantially from 21,979,878.03 THB in the as-is scenario to 571,177.88 THB in the to-be scenario, representing an overall reduction of approximately 97.4 percent. This considerable decrease reflects the effectiveness of the optimized continuous review inventory control policies, both (s, S) and (s, Q), in preventing the financial losses associated with production downtime and lost sales opportunities. At the item level, all fifteen spare parts exhibited a consistent downward trend in total cost after implementing the selected policy for each item. Notably, production-critical items such as A003 (ESA), A004 (ESA), and A010 (VEA) achieved significant reductions under the (s, S) policy, while items such as A011 (VSA), A012 (VSA), and A013 (ESA) performed more efficiently under the (s, Q) policy, indicating that the fixed-order-quantity approach aligns better with their demand characteristics and cost structures. Items A001 and

A002, both characterized by intermittent demand, showed notable cost reductions of 93.63 percent and 99.35 percent, respectively. This further verifies that the analytically determined service levels, applied via either (s, S) or (s, Q), reliably maintained availability for items with irregular usage patterns.

Table 10. Annual total ınventory cost with shortage opportunity cost

Code	Demand Pattern	Classification	TIC with Shortage Opportunity Cost		
			As-is (THB/YEAR)	To-be (THB/YEAR)	Inventory Policy (Selected)
A001	Intermittent	ESA	286,573.08	18,266.12	(s, S) 80% Service Level
A002	Intermittent	ESA	2,537,953.96	16,567.30	(s, S) 80% Service Level
A003	Smooth	ESA	2,699,775.84	154,878.24	(s, S) 90% Service Level
A004	Smooth	ESA	2,567,233.00	20,460.02	(s, S) 80% Service Level
A005	Smooth	ESA	341,773.13	12,182.81	(s, S) 95% Service Level
A006	Smooth	VDA	264,136.44	15,991.27	(s, S) 95% Service Level
A007	Smooth	VEA	11,507.55	10,259.43	(s, S) 80% Service Level
A008	Smooth	ESA	2,594,232.24	27,966.82	(s, S) 95% Service Level
A009	Smooth	VDA	217,023.13	15,451.89	(s, S) 99% Service Level
A010	Smooth	VEA	256,855.38	50,387.74	(s, S) 90% Service Level
A011	Smooth	VSA	2,555,852.36	55,984.67	(s, Q) 90% Service Level
A012	Smooth	VSA	2,465,975.72	17,744.55	(s, Q) 90% Service Level
A013	Smooth	ESA	2,604,275.93	70,601.09	(s, Q) 90% Service Level
A014	Smooth	VSA	2,512,691.41	18,266.12	(s, S) 80% Service Level
A015	Smooth	VDA	64,018.87	66,169.81	(s, Q) 95% Service Level
TOTAL			21,979,878.03	571,177.88	

Overall, the findings indicate that adopting a combination of optimized (s, S) and (s, Q) policies provides exceptional cost efficiency and operational reliability under opportunity loss conditions. By assigning the most suitable policy to each item, the improved system not only minimizes stockout-related financial losses but also enhances production continuity, long-term cost stability, and overall inventory system resilience.

Table 11, derived from the detailed evaluation, displays the optimized annual TIC and the respective inventory control policies assigned to the fifteen representative spare parts. The optimized total cost was 597,132.31 THB per year, showing a substantial improvement compared with the current as-is conditions under both expedited-shortage and opportunity-cost scenarios. Specifically, when compared with the expedited-shortage condition, where the TIC was 1,103,890.89 THB per year, the optimized model achieved a 45.9 percent reduction. Under the opportunity-cost condition, where the total TIC reached 21,979,878.03 THB per year, the optimized cost dropped dramatically by 97.3 percent. These results confirm that the improved continuous review (s, S) inventory control policy is highly effective in minimizing overall inventory costs while maintaining high service reliability.

At the item level, both intermittent-demand and smooth-demand spare parts demonstrated consistent cost reductions. Intermittent-demand parts such as A001 and A002 (ESA group) achieved the lowest total cost under a service level of Z equals to 80 percent, indicating that a moderate safety-stock level is sufficient for items with infrequent usage. Meanwhile, smooth-demand parts with higher operational importance, particularly A010 (VEA) and A015 (VDA), performed best at higher service levels (Z varies from 90–99 percent), ensuring availability without excessive holding costs.

Table 11. Optimized total inventory cost and selected inventory policy

Code	Demand Pattern	Classification	Optimized Total Cost (THB	Inventory Policy (Selected)
A001	Intermittent	ESA	18,266.12	(s, S) 80% Service Level
A002	Intermittent	ESA	16,567.30	(s, S) 80% Service Level
A003	Smooth	ESA	155,427.24	(s, S) 99% Service Level
A004	Smooth	ESA	24,369.50	(s, S) 99% Service Level
A005	Smooth	ESA	12,864.12	(s, S) 99% Service Level
A006	Smooth	VDA	16,336.32	(s, S) 99% Service Level
A007	Smooth	VEA	10,848.82	(s, S) 90% Service Level
A008	Smooth	ESA	34,631.76	(s, S) 99% Service Level
A009	Smooth	VDA	15,451.89	(s, S) 99% Service Level
A010	Smooth	VEA	50,387.74	(s, S) 90% Service Level
A011	Smooth	VSA	56,885.06	(s, S) 80% Service Level
A012	Smooth	VSA	18,094.47	(s, S) 80% Service Level
A013	Smooth	ESA	78,716.99	(s, S) 99% Service Level
A014	Smooth	VSA	18,266.12	(s, S) 80% Service Level
A015	Smooth	VDA	70,018.87	(s, S) 99% Service Level
TOTAL			597,132.31	

The optimized results highlight that aligning service levels (Z) and policy parameters (s, S) with each part's demand behavior and operational criticality is the key to achieving the lowest possible total cost while preventing shortages. The proposed (s, S) policy, exhibited in Table 11, significantly reduced shortage-related costs across all classification groups (ESA, VEA, VDA, and VSA), reinforcing the overall robustness and responsiveness of the inventory-management framework.

In conclusion, the optimized continuous-review (s, S) inventory control policy not only eliminates all stockouts but also reduces the total annual cost by approximately 97 percent compared with the as-is opportunity-cost case, and by 46 percent compared with the expedited-shortage case. The optimized parameters ensure an efficient balance between holding, ordering, and shortage costs, enhancing cost efficiency, operational continuity, and the long-term resilience of the company's spare parts management system.

Conclusion

This study developed and applied a systematic and data-driven framework to enhance spare parts inventory management in the wire and cable manufacturing industry. By integrating multi-criteria classification (ABC–VED–SDE) with demand pattern analysis (ADI and CV^2), the research identified the characteristics and operational criticality of each spare part, forming a structured foundation for designing suitable inventory control policies. Two continuous-review models, (*s*, *S*) and (*s*, *Q*), were compared under multiple service levels to evaluate their impact on shortage reduction and total inventory cost.

The results clearly demonstrate that the optimized continuous review (*s*, *S*) policy provides the best overall performance. Shortage occurrences and quantities were eliminated across all spare part groups, achieving a 100 percent reduction compared with the current company's policy. Cost analysis further confirmed the superiority of the optimized policy: the annual total inventory cost decreased from 1,103,890.89 THB to 573,826.56 THB under expedited-shortage cost conditions, and from 21,979,878.03 THB to 571,177.88 THB under opportunity-cost conditions, representing reductions of approximately 46 percent and 97 percent, respectively. The optimized total cost was 597,132.31 THB per year, with appropriate service levels ranging between 80 percent and 99 percent, depending on each item's demand variability and operational importance.

Overall, the findings confirm that aligning inventory control policies with demand behavior and part criticality significantly improves cost efficiency, service reliability, and production continuity. The proposed optimized (s, S) policy provides a rigorous, data-driven basis for strategic inventory decisions, reducing the likelihood of stockouts, supporting continuous operational flow, and enhancing the long-term robustness of spare parts management in manufacturing settings.

Recommendations

Integrate Inventory-Control Policies with Procurement and Sourcing Decisions

For further research, inventory parameters such as the reorder point (s) and the order-up-to level (S) should be planned in coordination with procurement and sourcing activities. Factors including lead time, supplier reliability, and transportation conditions —particularly for imported items—should be incorporated into the calculation of inventory parameters. This integration between inventory and purchasing functions enhances decision accuracy, minimizes the risk of stockouts, and improves operational continuity across the supply chain.

Set Service Levels and Control Policies Based on Spare Part Characteristics

Service-level targets should be defined according to each part's operational criticality and demand behavior. A service level between 90 percent and 95 percent is recommended for general spare parts to balance cost and reliability, while highly critical or long lead-time components should be maintained at a 99 percent service level to prevent production disruption and ensure continuous operations.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPESS journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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