

Optimization of Spare Parts Inventory Management for Telescopic Forklift Maintenance in Port Operations

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Abstract

Maritime ports play a critical role in global supply chains by connecting land and maritime freight transportation, contributing directly to international trade efficiency and economic development. In this context, the operational performance of ports strongly depends on the availability and reliability of cargo-handling equipment, particularly reachstackers used in container operations. Due to the demanding operating conditions of these machines, effective maintenance management and adequate spare parts availability are essential to reduce downtime and ensure operational continuity. This study aims to support spare parts inventory management in the context of reachstacker maintenance in port operations. The work applies value analysis and demand classification to identify the most relevant spare parts and characterize their consumption patterns. Based on this classification, a periodic review inventory model is applied to selected items, allowing the definition of target stock levels and review periods according to different service levels. The study was developed in a real industrial context, considering the operational challenges associated with maintenance activities and spare parts replenishment. The obtained results provide a structured basis to support inventory replenishment decisions and contribute to balancing spare parts availability with inventory investment. The proposed approach may help improve maintenance planning and reduce the risk of prolonged equipment downtime in port logistics operations.

Keywords

Maintenance, Port Logistics, Stock Management, Spare Parts Management,

1. Introduction

Maritime ports play a fundamental role in global supply chains by ensuring the connection between land and maritime freight transportation. As such, they constitute strategic infrastructures for international trade, contributing directly to supply chain efficiency and economic development (Zhang et al., 2017; Camacho-Vallejo & González-Ramírez, 2026). In this context, the logistical and operational efficiency of a port strongly depends on the availability, integrity, and performance of port equipment, as well as on the adequacy of supporting infrastructures (Zhang et al., 2017).

Among the various types of equipment used in port operations, reachstackers play a particularly important role in horizontal container handling activities, including cargo transportation, loading, unloading, and maneuvering operations (Tchotang et al., 2020). These machines frequently operate under demanding conditions characterized by

high workloads, exposure to corrosive agents, space limitations, and the need for high operational availability (Zhang et al., 2017; Tchotang et al., 2020). Consequently, ensuring effective maintenance management becomes essential to minimize failures and guarantee operational continuity within port environments.

The effectiveness of maintenance activities strongly depends on the immediate availability of critical spare parts in inventory (Gan et al., 2026). Stockouts occurring during maintenance interventions may significantly delay repairs, increasing equipment downtime and negatively affecting the operational performance of port organizations. This issue becomes even more critical in geographically isolated contexts or in environments exposed to adverse weather conditions, where supply lead times tend to be longer and logistics costs higher (Gan et al., 2026).

In this sense, the integration between maintenance management and spare parts inventory management is particularly important to ensure equipment operational availability and reduce the risk of unexpected downtime. Furthermore, the complexity of port operations and associated decision-making processes reinforces the need for management and optimization tools capable of improving operational efficiency and supporting decision-making processes (Camacho-Vallejo & González-Ramírez, 2026).

1.1 Objectives

Therefore, the present study aims to support spare parts inventory management in the context of reachstacker maintenance in port operations. To achieve this, a case study was conducted at a port in the Azores, Portugal. A spare part value analysis and demand classification were applied to identify the most relevant spare parts and characterize their consumption patterns. Based on this classification, a periodic review inventory model was applied to a selected set of spare parts, allowing the definition of target stock levels and review periods according to different service levels.

2. Literature Review

2.1. Maintenance and Spare Parts Management

Maintenance plays a fundamental role in ensuring the reliability, safety, and availability of equipment and operational systems throughout their life cycle (Liang et al., 2012; IPQ, 2021). Modern maintenance management is no longer limited to corrective actions performed after failures occur, but increasingly integrates preventive, condition-based, and predictive approaches focused on reducing operational risk and improving equipment performance (O'Neil et al., 2025). In this context, maintenance management involves technical, administrative, and planning activities aimed at optimizing equipment availability while balancing operational and economic objectives (Hamasha et al., 2023; IPQ, 2021).

The effectiveness of maintenance activities is strongly associated with the availability of spare parts and support materials. Spare parts shortages during maintenance interventions may significantly increase equipment downtime and compromise operational continuity (Gan et al., 2026). This issue becomes particularly relevant in industrial systems operating under demanding conditions, where maintenance interventions must be carried out quickly and efficiently to avoid productivity losses. Therefore, integrating maintenance management with spare parts inventory management is essential to reduce failure risks, improve responsiveness, and support equipment availability.

2.2. Maintenance and Equipment Availability in Port Operations

Maritime ports play a strategic role in global supply chains by connecting maritime and land transportation systems, contributing directly to international trade and economic development (Zhang et al., 2017; Camacho-Vallejo & González-Ramírez, 2026). The operational performance of ports strongly depends on the availability and reliability of specialized equipment used in cargo handling and container operations.

Among these assets, reachstackers are widely used in horizontal container handling activities, including loading, unloading, transportation, and stacking operations (Tchotang et al., 2020). These machines frequently operate under harsh environmental and operational conditions, characterized by high workloads, exposure to corrosive agents, limited operational space, and strict availability requirements (Zhang et al., 2017; Tchotang et al., 2020). Consequently, maintenance management becomes essential to ensure operational continuity and reduce unexpected failures.

In addition, port operations are often exposed to logistical challenges associated with long supply lead times, geographical isolation, and adverse weather conditions, which may affect the availability of critical spare parts (Gan

et al., 2026). Therefore, efficient maintenance planning and adequate spare parts management are essential to minimize downtime and support the reliability of port logistics systems.

2.3. Spare Parts Inventory Management and Classification Methods

Spare parts inventory management presents particular challenges due to the intermittent and uncertain nature of demand, the high diversity of items, and the operational criticality associated with maintenance activities (Mehdizadeh, 2020; Pahl et al., 2024). Efficient inventory management aims to ensure spare parts availability while minimizing storage costs and avoiding excessive stock levels (Babai et al., 2025).

To support inventory decision-making, several classification methods have been proposed in the literature. Among them, ABC analysis is one of the most widely used approaches for inventory prioritization. Based on the Pareto principle, this method classifies items according to their financial importance, distinguishing high-value items (Class A), medium-importance items (Class B), and low-value items (Class C) (Stojanović & Regodić, 2017; Mehdizadeh, 2020; Pahl et al., 2024). This classification supports differentiated inventory control policies according to the relevance of each group.

Since ABC analysis considers mainly the economic dimension of inventory, it is often combined with demand classification methods. The XYZ classification evaluates demand variability through the coefficient of variation, distinguishing stable, variable, and uncertain demand patterns (Stojanović & Regodić, 2017; Zenkova & Kabanova, 2018). For spare parts inventories, additional classifications based on ADI (Average Demand Interval) and CV² are particularly relevant, allowing demand to be categorized as smooth, erratic, intermittent, or lumpy (Syntetos et al., 2005; Cavalieri et al., 2008; Heinecke et al., 2013). These methods are especially useful in maintenance environments where demand is irregular and characterized by long periods without consumption.

2.4. Inventory Replenishment Models

Inventory replenishment models are essential to define ordering policies capable of balancing spare parts availability with inventory investment. Among the most common approaches are the Continuous Review Model (Q), the Periodic Review Model (P), and Material Requirements Planning (MRP) systems (Assis, 2014; Amaral, 2016). The Continuous Review Model establishes a fixed reorder quantity whenever inventory reaches a predefined reorder point, requiring continuous inventory monitoring (Assis, 2014). In contrast, the Periodic Review Model (P) performs inventory reviews at fixed intervals, with replenishment quantities varying according to the target stock level defined for each review period (Carvalho, 2023).

Due to the characteristics of spare parts demand, particularly its uncertainty and intermittence, the Periodic Review Model (T,S) is considered suitable for maintenance inventory management contexts (Carvalho, 2023). In this model, T represents the fixed review period and S the target stock level to be reached after replenishment. The determination of these parameters depends on expected demand during the protection period, which includes both the review interval and lead time, as well as the safety stock required to achieve the desired service level (Carvalho, 2023). Additionally, the Naddor heuristic provides an alternative approach for determining the parameters of the Periodic Review Model by incorporating demand variability, lead times, and the probability of zero demand periods, making it particularly suitable for intermittent spare parts demand patterns (Naddor, 1975; Babai et al., 2010).

3. Methods

The study was conducted at the Port of Horta, located in the Azores, Portugal. It focused on reachstackers, as these are critical pieces of equipment for container handling operations in the port. This research adopted a mixed-methods approach, combining quantitative and qualitative methods (Creswell, 2009). The quantitative component was based on the analysis of historical maintenance and consumption data, including the number of failure occurrences, spare parts consumption records, and maintenance performance indicators (KPIs), such as failure rates, repair times, and equipment availability (Creswell, 2009). In turn, the qualitative component aimed to understand current practices, operational constraints, and the specific characteristics of the studied context through observation and interpretative analysis (Creswell, 2009). As shown in Figure 1, the study was conducted in three main steps. First, data related to maintenance records, spare parts consumption, costs, lead times, and maintenance indicators were collected. Second, the spare parts were classified according to their economic value and demand behaviour. Finally, based on this

classification, the inventory management policy was defined, including the replenishment model, target stock levels, review periods, and ordering rules.

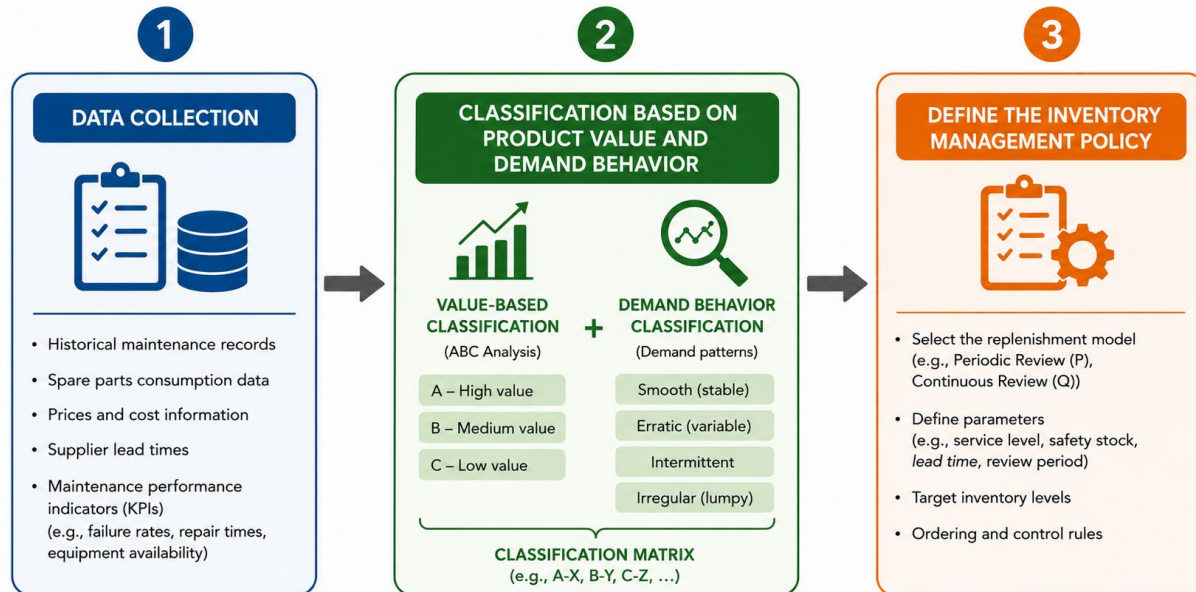


Figure 1. Methodological Steps

4. Data Collection

Data collection was carried out during a four-month internship at the organization. During this period a series of document it was analysis to carry out the research. Data collection was carried out during a four-month internship at the organization. During this period, several documents were analysed to support the research. First, a total of 531 records corresponding to corrective work orders registered between 2021 and March 2026 were examined. These records were categorized to identify the most critical equipment systems in terms of failure occurrence. After classification, the total number of occurrences was calculated for each category.

Second, the spare parts of the most critical system were classified according to their economic value using the ABC method. This analysis was applied to a random sample of 50 spare parts with at least one consumption record between 2023 and 2025. The classification was based on the unit price of each item and its average demand during the analysed period, allowing the identification of the spare parts with the greatest economic impact on the total inventory value. For demand classification, consumption data from 2023 to 2025 were used. The classification was based on the ADI and CV^2 indicators, which allow spare parts to be grouped according to both the frequency and variability of demand. This method was selected because it is more suitable for spare parts with low, irregular, and discontinuous consumption patterns. Based on the calculated ADI and CV^2 values, the items were classified into five demand categories: smooth, erratic, intermittent, lumpy, and sporadic. Items with only one unit consumed during the analysed period were directly classified as sporadic demand. The remaining items were classified using the theoretical cut-off values of $ADI = 1.32$ and $CV^2 = 0.49$.

To calculate the inventory policy parameters, demand data from 2023 to 2025 were analysed. These data were used to determine the mean demand and the standard deviation for each component. Lead time was calculated by reviewing the procurement orders for each component during the same period.

5. Results and Discussion

5.1 Numerical Results

Table 1 shows that the Lifting System recorded the highest number of corrective work orders during the period under study, with 128 occurrences. This was followed by the Engine, with 93 occurrences, and Bodywork, Chassis and Accessories, with 76 occurrences. Together, these three categories account for more than half of the corrective work orders analysed. Therefore, these systems can be considered the most critical in terms of equipment downtime

associated with corrective maintenance. This result is consistent with the operational role of the lifting system, since it is continuously exposed to high mechanical loads during container handling activities. Failures in this subsystem may directly compromise reachstacker availability and consequently affect port operational capacity and container flow continuity.

Table 1. Criticality-Based Prioritization of Equipment Systems

Description	No. of Corrective Work Orders	Relative Frequency (f%)	Cumulative Frequency (F%)
Lifting System	128	24.11%	24.11%
Engine	93	17.51%	41.62%
Bodywork, Chassis and Accessories	76	14.31%	55.93%
General Electrical System	54	10.17%	66.10%
Suspension and Wheels	47	8.85%	74.95%
General Hydraulic System	42	7.91%	82.86%
Transmission	28	5.27%	88.14%
Control System	27	5.08%	93.22%
Brakes	19	3.58%	96.80%
Steering System	16	3.01%	99.81%
Engine and General Hydraulic System	1	0.19%	100.00%
General Pneumatic System	0	0.00%	100.00%
Total	531		

For the lifting system, the components were classified according to their economic value and demand behaviour. Table 2 presents the classification of the main components of the lifting system. Based on this classification, the most suitable inventory management model was defined for each component. The adoption of differentiated inventory policies according to spare part criticality and demand behaviour may contribute to reducing unnecessary inventory investment, especially for sporadic-demand and high-value items, while still ensuring the availability of critical components required for maintenance activities.

Table 2. Integration of classification methods and matching with the appropriate Inventory Management Model.

Reference Spare Parts	ABC	Demand Classification	Inventory Management Model
GEAR MOTOR 3010052	A	Sporadic	Order-on-Demand
PIN 4016004	A	Lumpy	Periodic Review P (T, S) (Strict Control)
SUPPORT 6028424	A	Intermittent	Periodic Review P (T, S) (Strict Control)
ICOM RADIO IC F6022 + ANTENNA	B	Intermittent	Periodic Review P (T, S) (Medium Control)
SKF BEARING 32028X-61260280	B	Sporadic	Order-on-Demand
SHAFTS A025100300	B	Lumpy	Periodic Review P (T, S) (Medium Control)
T ACCESSORY 9217860039	C	Intermittent	Periodic Review P (T, S) (Light Control)
WIPER BLADE 81966040	C	Sporadic	Order-on-Demand
WASHER 2607036	C	Lumpy	Periodic Review P (T, S) (Light Control)

As shown in Table 2, similar with other studies most of the analysed spare parts present intermittent or lumpy demand behaviour. The predominance of these demand patterns highlights the complexity of spare parts inventory management in maintenance environments. Unlike production inventories, which often have more stable and predictable demand, spare parts consumption is strongly associated with unexpected failures and irregular maintenance interventions, making forecasting and replenishment decisions more uncertain.

Class A items, due to their high economic impact on inventory investment, were associated with stricter inventory control policies. For the item “GEAR MOTOR 3010052”, classified as A with sporadic demand, an order-on-demand strategy was selected to avoid high holding costs for a low-demand and high-value spare part. The items “PIN 4016004” and “SUPPORT 6028424”, classified as having lumpy and intermittent demand, respectively, were associated with the Periodic Review Model P (T,S), allowing stricter inventory monitoring and reducing stockout risk. Class B items were associated with intermediate control policies according to their economic relevance and demand behaviour. Items with intermittent or lumpy demand were managed through the Periodic Review Model P (T,S), while sporadic-demand items were assigned an order-on-demand strategy to reduce unnecessary inventory costs and obsolescence risk.

For Class C items, which present lower economic impact, lighter inventory control policies were adopted. Intermittent and lumpy demand items were associated with the Periodic Review Model P (T,S) under a lighter control approach, while sporadic-demand items were managed through order-on-demand policies.

Overall, the combined use of ABC classification and demand classification provided a structured basis for selecting inventory management policies according to both the economic relevance and demand behaviour of each spare part. Since most analysed items presented intermittent or lumpy demand patterns, the Periodic Review Model P (T,S) was considered the most appropriate strategy for inventory management. In contrast, sporadic-demand items were managed through order-on-demand policies in order to minimize storage costs and obsolescence risk.

5.2 Spare Pare Stock Management

Since most of the analyzed spare parts presented intermittent and lumpy demand, the Naddor heuristic was used to calculate the target stock level (S). Similar to other studies focused on spare parts inventory management with intermittent demand patterns, the Naddor heuristic was considered suitable due to its ability to incorporate demand variability and periods with zero demand into the inventory calculations. The calculations were performed for different service levels (90%, 95%, and 99%). Using different service levels allows the company to choose the most suitable inventory policy according to the desired balance between spare parts availability, inventory holding costs, and replenishment costs.

The review periods (T) were defined based on the company’s current practices, the observed demand behaviour of each item, and the service level considered. For higher service levels, such as 99%, shorter review periods were defined, since higher service levels require a lower risk of stockout. By reviewing inventory more frequently, the company can respond earlier to demand variations and reduce the probability of shortages, without necessarily increasing the target stock level excessively. Conversely, for lower service levels, longer review periods may be accepted, as the company assumes a higher tolerance to stockout risk.

The Naddor Heuristic is applied to the Periodic Review Model P (T,S) to determine the Target Stock Level (S), considering the demand during the risk period. The method starts by calculating the average demand during the protection period, considering the average lead time and the review period:

$$\mu_{d(LT+T)} = \left(\mu_{LT} + \frac{T}{2} \right) \times \mu_d \quad (1)$$

Next, the standard deviation of demand during the same period is calculated by incorporating demand variability and the probability of zero demand, which is particularly important for intermittent demand patterns:

$$\sigma_{d(LT+T)} = \sqrt{\left(\mu_{LT} + \frac{T}{3} \right) \times \sigma_d^2 + \frac{(T \times \mu_d^2)}{12} \times \frac{1-P(0)^T}{6}} \quad (2)$$

Finally, the Target Stock Level (S) is obtained by combining the expected demand during the risk period with a safety factor associated with the desired service level:

$$S = \mu_{d(LT+T)} + N \sigma_{d(LT+T)} \Leftrightarrow S = \mu_{d(LT+T)} + z \quad (3)$$

This approach allows the model to consider both demand uncertainty and the risk of stockouts during the review and replenishment periods, making it suitable for spare parts with intermittent and irregular demand behavior.

Table 3 presents an example of the calculation of the inventory replenishment model parameters. The analysis focused on the spare parts considered most relevant to the company. Therefore, the Periodic Review Model P (T, S) was applied only to Class A items with intermittent or lumpy demand patterns.

Table 3. Calculation of the parameters required to determine the Target Stock Level using the Naddor Heuristic

Spare Part Reference	Service Level (N-z)	T (year)	μD	σD	μLT	$\mu(DL+T)$	P(0)	$\sigma(DL+T)$	S
PIN 4016004	N-99% z-2.3263	0.5	3	4.6188	0.2130	1.3890	0.9722	2.8792	9
HEADLIGHT 9217330026		0.25	10	4.3905	0.01142	1.3642	0.6667	1.5373	5
SUPPORT 6028424		0.5	2	2.3094	0.06849	0.6370	0.9722	1.1575	4
SPHERICAL BEARING 9214630008		0.5	2	2.3094	0.09315	0.6863	0.9722	1.2130	4
HYDRAULIC PIPE 7280374		0.5	2	2.3094	0.04384	0.5877	0.9722	1.0992	4
PIN 4016004	N-95% z-1.6449	1	3	4.6188	0.2130	2.1390	0.9722	3.5228	8
HEADLIGHT 9217330026		0.5	10	4.3905	0.01142	2.6142	0.6667	2.3552	7
SUPPORT 6028424		1	2	0.6667	0.0685	1.1370	0.9722	0.7187	3
SPHERICAL BEARING 9214630008		1	2	0.6667	0.0932	1.1863	0.9722	0.7263	3
HYDRAULIC PIPE 7280374		1	2	0.6667	0.0438	1.0877	0.9722	0.7111	3
PIN 4016004	N-90% z-1.2816	1	3	4.6188	0.2130	2.1390	0.9722	3.5228	7
HEADLIGHT 9217330026		1	10	4.3905	0.0114	5.1142	0.6667	3.8774	11
SUPPORT 6028424		1	2	0.6667	0.0685	1.1370	0.9722	0.7187	3
SPHERICAL BEARING 9214630008		1	2	0.6667	0.0932	1.1863	0.9722	0.7263	3
HYDRAULIC PIPE 7280374		1	2	0.6667	0.0438	1.0877	0.9722	0.7111	2

As previously mentioned, due to the more consistent consumption pattern of the item HEADLIGHT 9217330026, different review periods (T) were defined according to the considered service levels. Through the application of the Naddor Heuristic, different review frequencies and target stock levels were obtained for the analyzed spare parts. In practical terms, the target stock level represents the inventory level that the company should restore after each inventory review. Therefore, at each review period, the company should order only the quantity required to replenish the inventory up to the defined target level.

For the item PIN 4016004, a semi-annual review period and a target stock level of 9 units were proposed for a 99% service level. For a 95% service level, the review period becomes annual with a target stock level of 8 units, while for

a 90% service level the annual review period is maintained with a target stock level of 7 units. Therefore, a gradual reduction in the target stock level can be observed as the service level decreases.

For the item HEADLIGHT 9217330026, a quarterly review period and a target stock level of 5 units were proposed for a 99% service level. For a 95% service level, a semi-annual review period with a target stock level of 7 units was obtained, while for a 90% service level an annual review period with a target stock level of 11 units was proposed. In this case, a different behaviour was observed compared to the remaining items, since the target stock level increased as the service level decreased. This can be explained by the increase in the review period T , which changes from quarterly to annual, requiring the inventory system to cover a longer protection period and consequently maintain a higher target stock level.

For the items SUPPORT 6028424 and SPHERICAL BEARING 9214630008, similar results were obtained. In both cases, a semi-annual review period and a target stock level of 4 units were proposed for a 99% service level. For both 95% and 90% service levels, an annual review period with a target stock level of 3 units was obtained. Finally, for the item HYDRAULIC PIPE 7280374, a semi-annual review period and a target stock level of 4 units were proposed for a 99% service level. For a 95% service level, an annual review period with a target stock level of 3 units was obtained, while for a 90% service level the annual review period was maintained and the target stock level decreased to 2 units. Overall, the Naddor Heuristic appears to provide an inventory policy with relatively moderate target stock levels, contributing to the reduction of capital tied up in inventory while still maintaining the desired service level. However, the selection of the most appropriate inventory policy should ultimately depend on the company's operational priorities, desired service level, stockout risk tolerance, and inventory holding costs.

The results should also be interpreted considering the company's current inventory management practice. At present, inventory is mainly reviewed once a year, without systematically considering demand behaviour, service levels, lead times, or the economic relevance of each spare part. This practice may increase the risk of stockouts, especially for components with intermittent or lumpy demand, since the company may not detect replenishment needs in time. As a consequence, when a failure occurs and the required spare part is not available, the equipment may remain stopped for longer periods due to procurement and logistics lead times.

In this context, the proposed classification and periodic review approach provides a more structured basis for inventory decision-making. By defining review periods and target stock levels according to the demand behaviour, economic value, lead time, and desired service level, the company can reduce the probability of shortages and improve equipment availability. This is particularly relevant for critical systems such as the lifting system, where missing spare parts may directly increase downtime and affect port operations.

6. Conclusion

This study demonstrated that spare parts inventory management in port maintenance environments is strongly influenced by the irregular and intermittent nature of demand. Through the analysis of corrective maintenance records and spare parts consumption data from reachstackers operating in the Port of Horta, it was possible to identify the most critical systems and classify the spare parts according to their economic relevance and demand behaviour.

The application of the ABC classification method, combined with demand classification based on the ADI and CV² indicators, allowed the identification of different inventory profiles and supported the selection of more suitable inventory management policies for each type of spare part. The results showed that most of the analysed components presented intermittent or lumpy demand patterns, confirming the complexity associated with spare parts management in maintenance operations.

Based on these classifications, the Periodic Review Model P (T , S), supported by the Naddor Heuristic, was applied to the most economically relevant spare parts. The obtained results demonstrated that defining differentiated review periods and target stock levels according to service levels and demand behaviour may contribute to reducing stockout risk while avoiding excessive inventory levels. Furthermore, the proposed approach provides a more structured inventory management process compared to the company's current practice, which is mainly based on annual inventory reviews without considering demand variability or service level requirements.

Despite the contributions of this study, some limitations should be acknowledged. The analysis was conducted using data from a single port organization and focused only on reachstacker spare parts, which limits the generalization of

the results to other operational contexts. In addition, the study considered a relatively small sample of spare parts and relied on historical demand data between 2023 and 2025, which may not fully represent future operational conditions or unexpected changes in equipment usage patterns.

Future research may extend this work by analysing larger datasets, including additional types of port equipment and comparing different inventory management models for intermittent demand. Further studies could also incorporate cost analysis, simulation approaches, predictive maintenance data, and machine learning techniques to improve demand forecasting and optimize spare parts inventory policies in maintenance environments.

The adoption of differentiated inventory policies according to spare part criticality and demand behaviour may contribute to reducing unnecessary inventory investment, especially for sporadic-demand and high-value items, while still ensuring the availability of critical components required for maintenance activities.

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