Spare Parts Stock Management: Classification and Policy Assignment

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Spare parts management is a maintenance management function that aims to support maintenance activities. It intends to provide real-time information about the available quantities for each spare part and to adopt stock management policies that assure its availability at the lowest possible cost. This paper proposes a methodology for the stock management of spare parts that aims to assign stock management policies to each spare part in an industrial plant. Five groups and five associated stock management policies were defined. Considering that the policy to be allocated depends strongly on the characteristics of demand, two of the groups are intended for generic spare parts, and the other three for specific spare parts. The definition of the groups and the assignment method took into account the associated stock management policy, which in turn took into account the characteristics of the demand for the associated parts. A case study carried out in a manufacturing company that produces electronic systems for the automotive sector showed that the developed methodology allows, simply and intuitively, the assignment of policies that balance the cost of a part being out of stock and the cost of keeping it in stock, thus minimizing total cost.

Keywords: *Criticality; Maintenance management; Multi-criteria classification; Spare parts management; Stock management policies.*

1. INTRODUCTION

Maintenance management has gained a strategic role in organizations over the last decades. The competitiveness of markets and the need to quickly respond to demand have given the maintenance function a significant role in industrial units. To become or remain competitive in the market, organizations must invest in the continuous improvement of their processes; that is, they must invest in the efficient management of their resources and processes, including issues associated with maintenance.

Spare parts are used in many of the maintenance actions. According to EN 13306 [1], a spare part is an item intended to replace a corresponding item in order to retain or maintain the original required function. This paper uses the term spare to denote spare parts, i.e., parts/components that are not repairable after their failure.

On the one hand, there may be an excess inventory of spares, which means high holding costs for the organization. On the other hand, the absence of a spare can represent a high cost due to production stoppage. This makes the efficient and effective management of spares fundamental for maintenance management. Therefore, spare parts availability affects the performance of maintenance management and, consequently, the productivity of organizations by reducing downtime, which is particularly relevant in the context of Industry 4.0 [2].

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Spare parts are characterized by a wide variety, intermittent demand, and generally high shortage costs. As such, spare parts management models aim to improve availability and decrease investment in spare parts stocks [3]. In the literature, there are many works that focus on the definition of parameters of stock management policies, on the classification of spare parts, or on the analysis of demand, but there are few models focused on the allocation and definition of stock management policies to each spare part type of a given organization. These models or methodologies require the classification of spare parts.

Braglia, Grassi, and Montanari [4] present a case study where a matrix is developed, in which each type of spare (obtained through a classification) is assigned one of four possible stock management policies: Null stock, single-item inventory, just-in-time policy, and multiple item inventory. In this study, a large number of criteria are used, which makes the classification method complex. Furthermore, the policy to be adopted is not fully defined by the definition of the spare part type since more than one policy is suggested for the same type.

In the study of Bošnjaković [5], a multi-criteria ranking is also presented to aggregate spares into groups and to assign a stock management policy to each group. The stock management policies that the author chose are three: keep no spares in stock, keep one part in stock, and keep several spares in stock. Bošnjaković [5] starts by classifying spare parts using the ABC classification based on the value-usage, which does not seem appropriate for the type of parts under analysis since the impact of the absence of a spare part can be very significant despite its low value-usage. This is an approach that focuses on reducing the value of stock.

The policies considered by Braglia, Grassi, and Montanari [4] and by Bošnjaković [5] are the same, except for the just-in-time policy, which is only referred to in the study by Braglia, Grassi, and Montanari [4]. In these studies, it was not explained how the stock level and order quantity of the policy that aims to keep various spares in stock would be calculated.

The objective of this research was to develop a methodology for spare parts classification and policy assignment that takes into account the demand behavior of spare parts. It was also intended to first consider the perspective of maintenance (reducing impact on pro–ductivity) and then the perspective of stock management (reducing value in stock). Before starting the metho–dology development, it was defined that its implemen–tation should be simple and not require much infor–mation and that it should not only help in identifying the type of stock management policy to be used for a given spare part but also indicate how to determine its parameters when needed.

Initially, a study was conducted using forecasting models to verify if it was an added value in stock management policy definition. To this end, models based on time series that are the most referenced in studies on the demand for spare parts were tested with data from an industrial company, which are the moving average, the Simple Exponential Smoothing (SES), the Croston model, and the Syntetos-Boylan Approximation (SBA) or modified Croston [3]. The study revealed that it was not possible to assign only one forecast model to a part group. This analysis was important to rule out this hypothesis for the determination of the best stock management policy for each group.

Then, to achieve the intended result, the following steps were performed:

- Definition of possible groups and associated stock management policies depending on the severity of shortage and the demand characteristics of spare parts.
- Definition of the criteria that would allow the assignment of parts to groups, seeking to minimize holding costs and avoid shortages for the most critical parts for maintenance.
- Definition of decision trees for assigning groups to each part using three possible levels for each criterion, using the deductive method.
- Validation and adjustment of the method with data from the mentioned industrial company, as well as adjustment of stock management policies based on the historical demand for the studied spare parts.

The adopted approach is intended to minimize costs, including those associated with downtime (reflected by shortage costs), holding, and purchasing costs. Thus, although the analysis is mainly based on costs, it reflects the effect of various performance criteria, such as availability or downtime.

The paper is organized as follows. Section 2 presents a literature review of spare part management. In Section 3, the methodology for spare parts classification and stock management policy assignment is exposed. In Section 4, a case study is used to validate the methodology. Section 5 presents a discussion of the results. Finally, in Section 6, the main conclusions and further work are presented.

2. LITERATURE REVIEW

Spare parts are neither works in progress nor finished products that are intended for sale to an end customer. Spare parts stocks support maintenance activities, ensuring the operation of machines. Therefore, the stock management of spare parts differs from the stock management of finished products [6].

Spare parts inventory control is particularly chal–lenging due to the nature of the demand for spare parts. Since inventory management policies depend on the distribution of demand over the lead time, the selection of the policy will affect performance and costs to the organization, which may be high if the policy adopted is not adequate to fit demand [7].

Several areas support spare parts management, for which numerous works can be found in the literature:

- Classification, where several methods and multi-criteria models are used to classify the parts.
- Demand forecasting, where besides the more clas–sical forecasting methods, there are also specific methods and models developed for the case of spare parts.
- Stock management consists of policies, models, and methods to manage a particular type of parts.

The classification of spares is crucial for controlling the vast number and variety of parts. As such, the cate–gorization of spares is a way to control their diversity and specificity [8, 9]. Regarding the methods and models used in the classification of spare parts in the literature, the AHP is widely used for the multi-criteria classification, with several adaptations to the initial version [10]. Many of the analyzed methods or models have some implementation complexity, which, for practical application in organizations, can be disadvan–tageous. Yang et al. [11] proposed a multi-criteria spare parts classification using the deep convolutional Neural Network method.

According to Hu et al. [12], forecasting the demand for spare parts is a requirement in the management of this type of spare parts. However, given their charac–teristics, it is difficult to predict the demand for spares accurately. For this reason, many studies reported in the literature have been devoted to this area [13]. The demand for spares is characterized by sporadic behavior and high variability. Therefore, the consumption rate is not stationary, and the statistical properties of demand are not time-independent [14]. Typically, the demand is intermittent in nature and is characterized by long periods with zero demand [6, 15–22].

Four stock policies are normally used in spare parts management [13, 23]:

- Continuous review, with fixed reorder point (r) and fixed order quantity (Q), referred to as (r, Q).
- Continuous review, with fixed reorder point (s) and order quantity up to a level (S), referred to as (s, S).
- Periodic review, with fixed replenishment interval (T) and order quantity up to a level (R), referred to as (T, R).
- Continuous review with order quantity up to level (S) in a one-to-one replenishment mode, referred to as (S-1, S).

The continuous review (s, S) inventory policy has theoretically been shown to be the best for managing intermittent low-demand items [23].

Anglou, Ponis, and Spanos [24] performed a study on shipping companies operating fleets of vessels. They applied clustering in order to identify high-interest items and then focused stock management issues on these selected items. Milković, Lisjak, and Kolar [25] used a linear programming model to find optimal stocks for spare parts in the context of Railroad PassengerWagon Maintenance. Only a few works focus on the stock management of spare parts, which involves classifi–cation, demand forecasting, and the definition of the stock management model. The global stock manage–ment of spare parts, involving the management of all spare parts of a company, is addressed by [4] and [5].

3. METHODOLOGY FOR CLASSIFICATION AND POLICY ASSIGNMENT

The proposed multi-criteria classification methodology aims to group spares by taking into consideration their main characteristics and predefined stock management policies. Five stock management policies were defined to cover all groups with their respective characteristics.

3.1 Defining groups and assigning spare parts

Classification criteria and groups for classification

The selected criteria cover two perspectives that are directly related to the management of spare parts, namely, the maintenance perspective and the stock management perspective. These two perspectives are complementary when addressing spare parts manage–ment. The criteria defined for each perspective were the following: criticality for maintenance management and price and lead time for stock management. Criticality is obtained by combining two sub-criteria, the component function and the impact on production, which, com–bined through a matrix, allows for obtaining the vital, essential, and desirable result. Details can be found in [26]. The Price and Lead Time criteria are divided into three levels: high, medium, and low.

After defining the criteria from the maintenance and stock management perspectives, the groups of spares were defined. The process of defining the spare parts management methodology involved several iterations. In the first iteration, the demand behavior was not considered; that is, a spare part with a unitary demand was treated in the same way as a spare part with a variable lot demand (they could belong to the same group if they had the same characteristics, reflected in the criteria levels). It was realized, however, that a part that presents a unitary consumption and one that presents a variable batch consumption should not be treated in the same way.

Thus, we used the designation proposed by Cavalieri *et al*. [23], which divides maintenance materials into classes: consumables or auxiliary materials, generic spares, specific spares, and strategic spares. In the scope of this research, the auxiliary materials were not addres–sed. To adjust these classes to the intended purpose, only the concepts of generic spare and specific spare were used, since for strategic spare parts, the main issue to solve is whether to keep one in stock, given the high value and low consumption rate, or purchase when needed [23]. These concepts are defined as follows:

- Generic spares: These spares can be used in more than one type of equipment. They are usually easily found in the market.
- Specific Spare Parts: The spare is specific to a particular piece of equipment and/or is only available through a specific supplier.

Therefore, in addition to the classification of spares according to the criteria of criticality, lead time, and price, it was decided to analyze if the spare part is generic or specific and check if the demand for specific components is unitary or by lot. It should be noted that the number of machines of a certain type that are in operation in the organization can lead to a specific spare part being treated as generic. This happens when a part is specific to a type of machine, and there is a high number of machines of that type in operation in the factory. It was through this information that the groups were defined.

Five groups (A, B, C, D, and E) were defined in order to group the spares and assign them an appropriate stock management policy according to their charac–teristics. The characteristics of each group that allowed the classification are presented in Table 1.

After defining each group's characteristics, each part's classification process considering the criteria was determined. The classification method was intended to be easy to implement and intuitive for those involved.

The classification methodology consisted of combi–ning all the various criteria and their respective levels for the two classes of spares (generic and specific). Decision trees were used to represent and analyze these combinations.

The importance of the criteria was defined to determine the order of consideration of each criterion in the decision tree. The order considered the relevance of each criterion for the organization under study. Thus, the most important criterion is criticality, followed by lead time, and lastly, price. In the case of groups C and D, in addition to the previously defined criteria, a new criterion was added. This criterion refers to the probability of shortage within the lead time. Although the demand for the spare parts belonging to these groups is unitary, the probability of shortage within the lead time, originating stock-outs, tends to be higher the greater the number of machines that incorporate this part. When this probability is high, it is considered that the existence of a minimum stock of at least one unit is justified to avoid a shortage.

For the attribution of the groups, the costs that the company will have to bear in case of shortage of a part are considered. The non-existence in stock of a part classified as vital would bring the company higher shortage costs than those of the essential and desirable level, which are higher the longer the lead time. The values of the shortage cost of a part classified as essential tend to be lower than the previous ones, but they can be very close, depending on the associated lead times. In the case of a spare part classified as desirable, its shortage cost tends to be zero (its failure has no impact on production). These shortage costs are com–pared with the holding cost, knowing that this increases with the price of the part and with the quantity held in stock.

Table 1. Characteristics of spare parts groups.

Spare part Type	Group	Characteristics
Generic	A	Spare parts that are non-existent in stock cause high shortage costs. The parts belonging to this group are not allowed to be out of stock.
	B	Spare parts whose shortage costs tend to be lower and/or the holding cost tends to be high.
Specific	C	Spare parts whose absence causes high shortage costs and/or the fact that several machines use the spare, lead–ing to a higher probability of failure within the lead time. Therefore, shortages of spare parts belonging to this group are not allowed.
	D	Spare parts tend to have lower shor–tage costs than those in group C and/ or a smaller number of machines. Shor–tages are still not allowed in this group.
	E	Spare parts that are non-existent in stock cause no shortage costs. As such, this group includes spare parts for which shortages are allowed.

3.2 Assignment of spares to groups A and B

Combinations of the levels of the criteria for assigning groups A and B were analyzed. The analysis of the combinations begins with the criticality criterion; the highest level is vital. It is intended that for the spares classified as vital, the stock shortage is not allowed, as it causes high shortage costs. Therefore, combinations of the vital classification with the high and medium levels of the lead time criterion and all levels of the price criterion are assigned to group A (Figure 1).

In the case of the combination of vital, low lead time, and high price, the group that was considered to be assigned is B. In this case, although it is not intended that there is a shortage, it is necessary to take into account the cost of keeping it in stock despite the low lead time. The parts in this combination present a high holding cost since the price is high, and as such, group B was chosen. The combinations vital, low lead time, and medium or low price are assigned to group A because the shortage cost of spare parts with these combinations tends to be higher than their holding cost.

In case the level of criticality is essential (Figure 2) and the lead time is high or medium, group A is attributed to all price levels. The spares that are included in this classification present a high shortage cost since they have an intermediate level of criticality but present a high or medium lead time, which causes their shortage to translate into high losses for the organization. In the case of the essential combinations, low lead time and high, medium, or low price, group B is assigned because the lead time is low. Therefore, the costs caused by the shortage will have a lower impact on the organization. The assignment of this group also allows you to control the costs associated with high stock levels

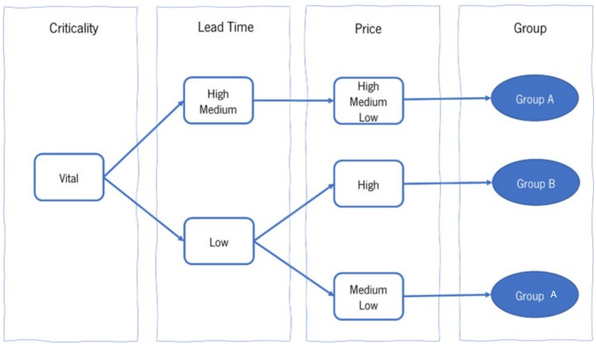

Figure 1. Decision tree for vital criticality level.

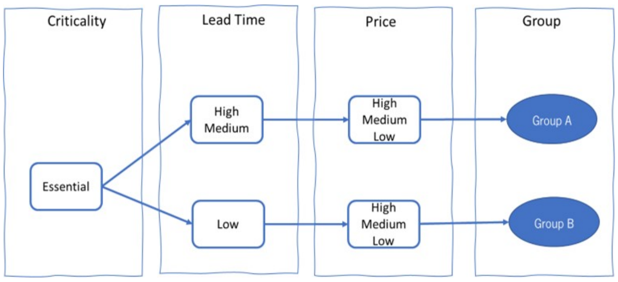

Figure 2. Decision tree for the essential criticality level.

In the case of the desirable criticality level, the group assigned to all levels of lead time and price is B (Figure 3). The spare parts with desirable criticality levels have zero shortage costs, and as such, there is no need to keep very large quantities in stock.

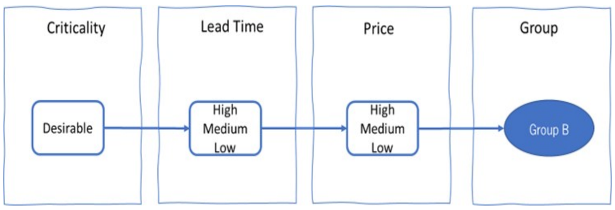

Figure 3. Decision tree for desirable criticality level.

3.3 Assignment of spares to groups C, D, and E.

For the specific spares, groups C, D, or E are assigned to each of the combinations. For groups C and D, the need was identified to include one more criterion that refers to the probability of breakdown within the lead time. This need arose after analyzing the number of machines with the same part. It was verified that the spare can be associated with only one machine, but it can also be associated with several machines. Although the demand is unitary, the probability of a shortage occurring within the lead time tends to be higher the greater the number of machines and the longer the lead time. In this way, this criterion helps define the values to be kept in stock. The combination of the various criteria allows for avoiding the risks of a shortage but also avoiding the risk of degradation or obsolescence since the specific parts have a unitary consumption and tend to be spaced over time.

For groups C, D, and E, the policies to be assigned were entirely defined simultaneously with the groups. As such, a policy (S-1, S) was defined for groups C and

D, and for group E, a no-stock-out policy. The minimum and maximum stock values were previously defined. In Table 2, the stock management policies defined for groups C, D, and E are presented. Group C has a policy assigned that consists of keeping a minimum stock of 1 unit and a maximum stock of 2 units. This is intended to ensure that there is no shortage during the lead time in case a part is associated with a very high number of machines, and the probability of shortage, i.e., the probability of 2 or more failures within the lead time, is high.

Group D has a policy assigned that consists of adopting a maximum stock of 1 unit and a minimum stock of 0 units. The policy of this group aims to keep in stock only 1 part because the probability of shortage, that is, the probability of 1 or more failures occurring within the lead time, is very low, thus increasing the holding cost by keeping more parts in stock is unnecessary. Group E is assigned a zero-stock policy since the failure of the spares assigned to this group does not cause any shortage costs for the organization.

Table 2. Group C, D, and E stock management policies.

Group	Stocks management policy
Group C	Policy (S-1, S) - Maximum stock: 2, minimum stock: 1, quantity to order: 1
Group D	Policy (S-1, S)- Maximum stock: 1, minimum stock: 0, quantity to order: 1
Group E	No-stock policy.

To determine the probability of shortage during the lead time, it was decided to use the Poisson distribution, and the average number of failures within the lead time (parameter of the distribution) was defined m_l; the Poisson distribution is often used in maintenance for modeling the number of failures. The Poisson process is suitable for determining the supply of spares whenever the failure rate is constant [27]. Guajardo *et al*. [28] reported that the Poisson distribution is suitable when dealing with spares with unitary demand.

The Poisson process with parameter λ>0 applies when the following conditions are met [29]:

- The number of events that occur in two disjoint intervals is independent;
- The probability of exactly one event occurring in any interval of arbitrarily small amplitude Δt is approximately $\lambda\Delta t$;
- The probability of two or more events occurring in any interval of arbitrarily small amplitude Δt is approximately equal to zero.
- The average number of failures within the lead time (ml) can be obtained through an expression (Eq. 1) that multiplies the failure rate of the part (the reciprocal of mean time to failure, MTTF) by the number of machines (N) and the lead time (L).

$$m_l = \frac{1}{MTTF} * N * L \tag{1}$$

For the assignment of Group C to the detriment of Group D, it was determined that a minimum limit of P would be defined for the probability of shortage in the lead time. The value of P should be defined according to the organization where the method is applied because each organization wants different service levels according to its area of activity and the rigor of its customers. Even within the same organization, the values should be reviewed regularly due to the need to adapt to the organization's production/customer changes.

Once this additional criterion was determined, the different combinations of criteria levels that lead to classification in each of the groups C, D, and E were defined. For the level of criticality vital (Figure 4), high lead time level, and high or medium price level, the criterion probability of failure is considered to select between group C or D.

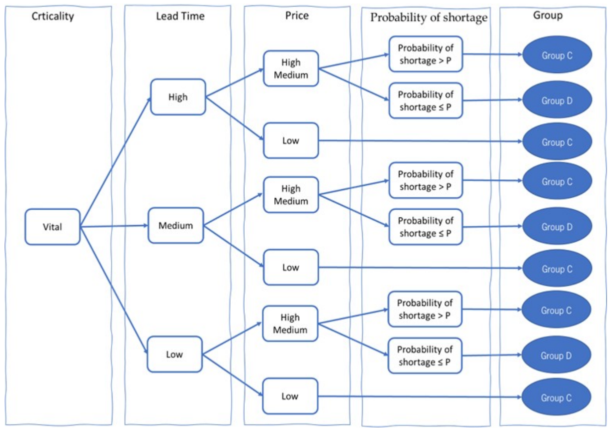

Figure 4. Decision tree for vital criticality level.

For situations where the probability is greater than P, group C is assigned, and for situations where the probability is less than or equal to P, group D is assigned. For the low-price level, group C is assigned, and the criterion of the probability of shortage in the lead time is not considered because holding costs, in this case, tend to be low, either by price or by the number of parts. The same situation repeats for the remaining levels of lead time (medium and low) in which the probability of shortage is considered for high or medium price levels. For spares where the probability is greater than P, group C is assigned, and for situations where the probability is less than or equal to P, group D is assigned, and for the low-price level, group C is assigned. The costs caused by stock-outs tend to be high given the criticality, but as the consumption of these spare parts is low when assigning different groups, it is intended to ensure that there are no stock-outs and, on the other hand, reduce the risk of degradation and,/or obsolescence.

For the criticality level essential (Figure 5), lead time level high or medium, and price level high or medium, the criteria probability of shortage in the lead time is considered. For situations where the probability is greater than P, group C is assigned, and for situations where the probability is less than or equal to P, group D is assigned. For the low-price level, group C is assigned. For the low lead time level and all price levels, the criterion - the probability of shortage in the lead time is considered, in which, as in the other combinations, for values of the probability of shortage higher than P, group C is assigned, and for values lower than or equal to P group D is assigned.

For the combinations with a desirable criticality level (Figure 6), a high lead time, and a high price, group E is assigned because a high price represents a high holding cost, and, in this case, the cost of shortage tends to be zero. However, in the case of a desirable level of criticality and a high lead time and medium or low price, group D is assigned because, although the cost of shortage tends to be zero due to the level of criticality (the failure of a spare has no impact on production), the price is medium or low, so the holding cost tends to be low.

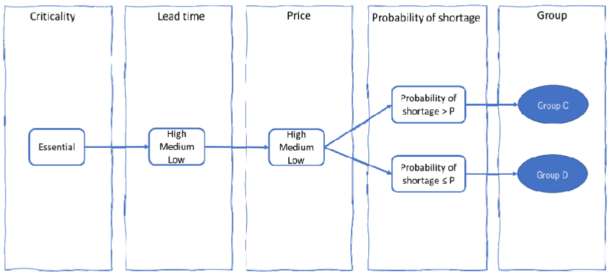

Figure 5. Decision tree for criticality level essential.

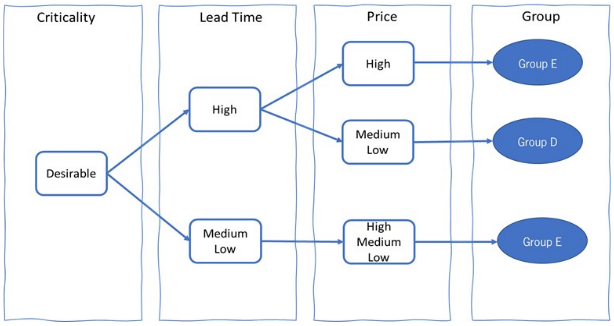

Figure 6. Decision tree for desirable criticality level.

The desirable criticality, combination of medium and low lead time levels, and all price levels are assigned group E since the shortage costs tend to be zero and the lead time is not high. The stock-out of spares with these characteristics does not imply costs, but keeping stock would imply holding costs that would be higher than the price.

In this subsection (2.1), the C, D, and E groups for specific spare parts and associated stock management policies were described. For generic spare parts, only the groups (A and B) and the process of assignment to these groups were presented. In the following subsec–tion, their stock management policies are defined.

a. Definition of the stock management policies for groups A and B

For generic spare parts, a demand study was performed to choose the stock management policy. This analysis aimed to verify if the demand follows a Normal distribution. This information is important because, for the spares that follow a Normal distribution, the continuous order level review – economic order quantity (EOQ) model is adequate to define the stock management parameters. For those that do not follow a Normal distribution, a method was defined that allows the definition of the policy and the respective parameters considering the demand. The defined stock management policy has a fixed order level (r) and a fixed order quantity (Q) (Table 3). The probability of shortage (or service level) is used to determine the order level using historical demand. To determine the order quantity, the approximation to EOQ is used. With this, the value that minimizes total costs is obtained.

Table 3. Goal and policy for groups A and B.

Group	Objective	Stocks management policy	
		Normally distributed	Non-Normally distributed
Group A	Maintain a very high service level.	Policy (r, Q) - EOQ is used. - r is determined based on Normal distribution	Policy (r, Q) - EOQ is used. - r is determined based on demand accumulated frequency.
Group B	Use a lower service level than group A.	Policy (r, Q) - EOQ is used. - r is determined based on Normal distribution	Policy (r, Q) - EOQ is used. - r is determined based on demand accumulated frequency.

3.4 The overall process of policy assignment

Figure 7 presents a graphical representation of the pro–posed methodology for spare parts classification and policy assignment, summarizing the steps to be follo–wed from the characterization of the spare part to the group assignment and determination of the policy para–meters.

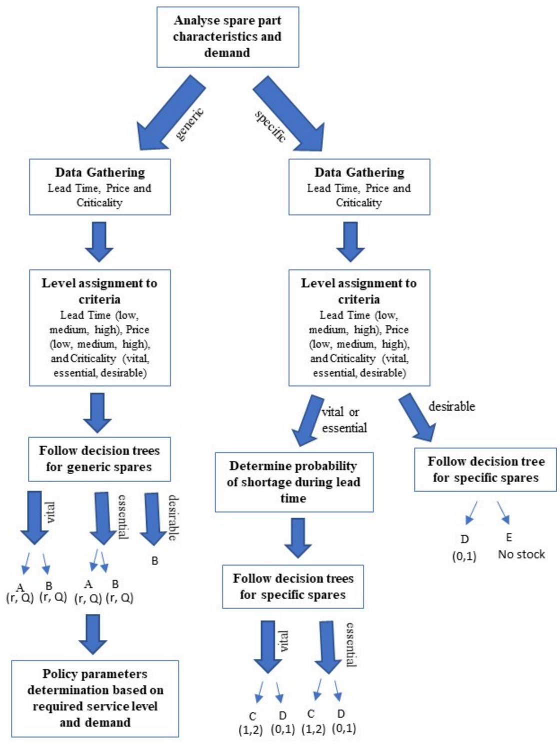

Figure 7. Policy assignment process.

4. CASE STUDY

A case study was conducted to validate the classifi–cation and policy assignment methodology. This study was conducted in a manufacturing company that pro–duces electronic components for the automotive indus–

try, a sector where the logistics of spare parts may be particularly complex [30].

To this end, a set of representative spares from each of the groups was used. The first step was to collect data regarding each of the criteria and to assign the spares to the groups. Then, as a second step, the stock manage– ment policies assigned to the groups were validated.

4.1 The approach

A set of spares were selected and classified according to the mentioned criteria. In Figure 8, the sample of spare parts used in the analysis is presented, as well as the results of the first step of the validation process.

The process of validation of the policies was diffe– rent for generic parts (groups A and B) and specific parts (groups C, D, and E) due to the specificities of the parts and the type of policy to be applied.

Spare part	Criticality	Lead time (days)	Level	Price (€)	Level	Prob. of shortage	Group
Fuse	Vital	2	Low	0.90	Low	-	A
Cap coupling	Vital	15	Medium	46.79	Low	-	A
KF-center ring	Essential	2	Low	11.68	Low	-	B
Round belt	Essential	15	Medium	79.77	Low	0.00279	C
Clamping blade	Essential	15	Medium	3 314.0	High	0.03018	D
Cap round vinyl	Desirable	15	Medium	0.70	Low	0.00012	E

Figure 8. Spare parts sample.

A set of data was required for the analysis. The orga– nization provided the estimated value for the provi–sioning cost, which corresponds to 15.34 € per order. Holding a part in stock costs the company money that is proportional to the part price. For the annual holding rate used to calculate the holding cost, since it was not possible to obtain a value from the organization, it was decided to use a spectrum of values for this rate varying between 10% and 30% for groups A and B and between 15% and 40% for groups C, D, and E, with intervals of 5%.

The value of the shortage cost was calculated considering the cost of lost production and does not consider the time to receive the part or the time to replace it in the equipment. In Table 4, estimates of the cost of lost production are presented for the levels of the impact on production (the sub-criteria used to obtain the criticality criterion level), namely, no impact, quality losses, productivity reduction, and sudden stop. This cost was obtained by considering the cost associated with the production loss of the company in the study, and, in the case of quality loss and productivity reduction, it was considered that this cost is a percentage of the production loss cost. The values for the lead time are those contracted with the supplier since it was not possible to obtain the actual values.

It has been assumed for this analysis that a machine continues to run when it is producing defective parts (quality losses). This can happen in situations where the quality losses are one-off. In cases where there are high-quality losses, the machine is considered to have a sudden stop, as production is immediately stopped, to avoid too high costs.

In the case of groups A and B, the parameters and respective total annual stock management costs were calculated. For the spares that do not follow the Normal distribution, the quantity to be ordered was determined using EOQ, and to determine the order level, demand accumulated relative frequency was used. The order level for each spare part was defined by the value of demand associated with a cumulative relative frequency equal to or greater than the value of the desired service level. In the analyzed sample of spares, only the demand for one spare follows the Normal distribution, which was expected given the typical behavior of the demand for spares. For the spares that follow the Normal distribution, the EOQ approximation was also used to determine the quantity to be ordered that minimizes total costs. The determination of the order level was based on the Normal distribution.

Table 4. Production loss cost values per hour for each level of production impact.

Sub-criteria	Percentage of production loss cost	Lost production Cost (€/hour)
No impact	0	0
Quality losses	5 - 50	5.24 - 52.40
Productivity reduction	40 – 75	41.92 - 78.60
Sudden Stop	100	104.80

For the sample of spare parts used to test the approach, a period of 3 years was selected (2018, 2019, and 2020), and the demand was grouped into monthly periods. It was found that the demand is irregular, with, in some cases, many periods of zero demand. For each of the spares, an analysis of the demand was performed, and the corresponding frequency table was built. To calculate the EOQ, the average demand for the period under analysis was determined.

As defined in Table 1, the spares of groups A and B differ in terms of the desired service level, so for each of the groups, two levels of service were tested. In the case of group A, service levels of 95% and 98% were tested, and the costs that each one entails were evaluated. For group B, two levels of service were also tested, 90% and 95%. This analysis was intended to evaluate the impact on costs of using these levels of service to define which is more advantageous to the organization. For the spares that follow a Normal distribution, two levels of admissible shortage were also tested to define the level of service that is intended to be achieved in each group. In the case of group A, two values were used for the allowable risk of failure: 2% and 5%.

For groups C, D, and E, since the quantities to be kept in stock for each group are already defined, the costs associated with the holding and shortage of each spare part were compared for the defined group, and a simulation of the application of the results to the period under analysis was also performed. The study consisted of analyzing holding costs and shortage costs, consi– dering different policies. Besides the costs associated with the policy chosen for the spare part by the group assignment, the costs associated with alternative policies resulting from the hypothesis of a different classification for the spare part were also calculated. For example, for a part classified in group C, the costs resulting from the adoption of the policy associated with groups D and E were analyzed. The purpose of this study was to validate the policy associated with the spare parts obtained through the group assignment.

The annual holding cost (Cp) was obtained through the expression in eq. 2 that multiplies the annual holding rate (i) by the spare part unit cost (c) and the quantity of the maximum stock defined for each group (Q). The average stock is expected to be very close to the maximum stock since the occurrence of demand is much spaced in time, and lead times are usually much shorter than the interval between demands.

$$Cp = c * i * Q \quad (2)$$

Shortage costs are extremely difficult to estimate since the impact of the absence of a spare can bring several costs to the organization, some of them unquantifiable. The failure of a spare part does not always cause a production stop, so it is necessary to obtain an estimate for the shortage cost of each spare part. To obtain a shortage cost as close as possible to reality, the approach followed consisted of considering the level of "impact on production" of each spare (a sub-criterion used in obtaining criticality). The approach to defining the cost of production loss used to determine the cost of stock-outs is identical to that used for groups A and B.

The shortage cost is obtained by considering the cost of lost production, the lead time, the probability of shortage in lead time, and the number of orders, as presented in the expressions (3), (4), and (5).

For group D, the probability of shortage is given by P(X≥1) because the policy of this group is to keep in stock 1 units, so for a shortage to occur, there must be one or more failures within the lead time. For group C, P(X≥2) is considered because the policy associated with this group is a maximum stock equal to 2 and a minimum stock equal to 1, so to a shortage within the lead time, 2 or more failures within the lead time have to occur.

The expression to determine the value of the group D shortage cost for the period under analysis is as follows:

$$Cr = Cpp * \left(\frac{L}{2}\right) * P\left(X \geq 1\right) * N_E \quad (3)$$

Cr - Shortage cost of a spare for the period under analysis;
Cpp - Cost of lost production according to the impact on the production of the spare per day;
L- Lead time of the spare in days;
P(X≥1) - Probability of one or more failures occurring during the lead time;
X - Number of occurrences of failure of a spare;
N_E - Number of orders in the period under review.
Every time an order is placed, a shortage may happen. Therefore, the expression considers the number of orders made in the period.

To determine the shortage cost of group C for the period under analysis, the expression is as follows:

$$Cr = Cpp * \left(\frac{L}{3}\right) * P\left(X \geq 2\right) * N_E \quad (4)$$

in which, P(X≥2) - Probability of 2 or more failures occurring during the lead time.

For group E, since as soon as a failure of the spare occurs, it is stock-out, the expression for the shortage cost was defined as follows:

$$Cr = Cpp * L * N_E \quad (5)$$

The lead time is divided by two in the case of group D because it is considered that the probability of demand occurring on any of the days is equal, so it was assumed that, on average, the failure during the lead time occurs in the middle of the interval. In the case of group C, when an order is triggered, there is still one part in stock, so if a shortage happens, the lead time for the first part is already elapsing. In the case of group E, a shortage with a duration L occurs every time the part failure happens since the policy associated with this group is to keep no stock.

To determine the probability of a shortage occurring within the lead time, we used the Poisson distribution with mean m_L (value obtained through the expression (1), which represents the average number of failures within the lead time when the part is used in N machines. The replacement process time of the part in the equipment is not considered, as this will be the same regardless of whether the part is in stock or not. The next section presents the application of the policies to each of the spare parts.

4.2 Groups A and B

Spares that do not follow the Normal distribution

The analysis of each of the spares is presented next, starting with the analysis of the accumulated relative frequencies, which allowed the value of the order level to be defined for each of the service levels under analysis. Subsequently, the value of the EOQ and the costs associated with the estimated parameters are presented. Then, the difference in total costs between the defined service levels is analyzed. The first spare to be analyzed is the "Cap coupling," which belongs to group A, and then the "KF-center ring," which is assigned to group B.

Cap coupling

Table 5 presents the values of the absolute and relative cumulative frequencies (2018, 2019, and 2020) of demand that allowed the parameter value of the order level to be defined. As mentioned, the values corresponding to the service level values under analysis were selected. Thus, the value of demand that guarantees at least a 95% service level is 11 units (97.22%), and the value that guarantees a 98% service level is 15 units (100%).

After defining the value of the order level, the EOQ was calculated, and then the values of holding costs, order cost, and total cost for the 3 years. For the EOQ calculation, the value of the average demand used was 2.1 units a month. The result of the order level policy for a 95% service level is presented in Table 6.

Table 5. Frequency table for spare part cap coupling.

Demand	Absolute Frequency	Cumulative relative frequency
0	24	66.67%
1	3	75.00%
2	1	77.78%
6	3	86.11%
8	1	88.89%
10	2	94.44%
11	1	97.22%
15	1	100.00%

Table 6. Results of the order level policy for a 95% service level of cap coupling.

Annual holding rate (i)	EOQ	Order level	Holding cost (€)	Order cost (€)	Total cost
10%	22	11	308.81	52.71	361.53
15%	18	11	421.11	64.43	485.54
20%	16	11	533.41	72.48	605.89
25%	14	11	631.67	82.84	714.50
30%	13	11	736.94	89.21	826.15

In Table 6, the parameters and the total annual cost for the order level policy are presented, considering a service level of 98%. It was found that the percentage increment in total cost decreases as the annual holding rate increases.

Table 6. Results of the order level policy for a 98% service level of cap coupling.

Annual holding rate (*i*)	EOQ	Order level	Holding cost (€)	Order cost (€)	Total cost
10%	22	15	364.96	52.71	417.68
15%	18	15	505.33	64.43	569.76
20%	16	15	645.70	2.48	718.18
25%	14	15	772.04	82.84	854.87
30%	13	15	905.39	89.21	994.59

Analyzing the difference between the total cost that exists for the two values, 95% and 98%, it was found that the total cost is higher for all levels of the holding cost rate, showing a difference in costs ranging from 15.5% to 20.4%, with the lowest value concerning the lowest annual holding rate and the highest value concerning the highest annual holding rate (Figure 9).

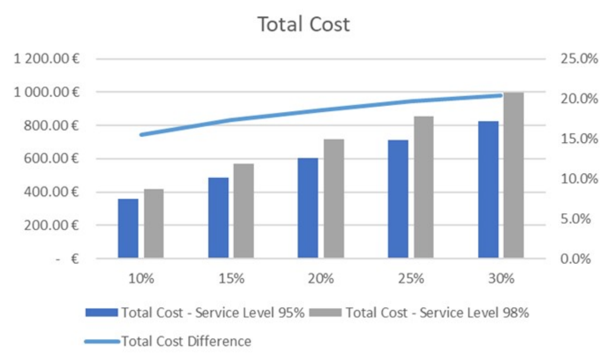

Figure 9. Difference between the total cost for the service level of 95% and 98% of cap coupling.

KF-center ring

Table 7 shows the values of the cumulative relative fre– quencies that allowed the parameter value of the order level to be set. For a service level of 90%, the order level set is 0 units (91.67%), and the value that guaran– tees at least a 95% service level is 4 units (97.22%).

Table 7. The frequency table is for the spare part of the KF-center ring.

Demand	Absolute Frequency	Cumulative relative frequency
0	33	91,67%
2	1	94,44%
4	1	97,22%
6	1	100,00%

As with the previous spare, the result of the appli– cation of the order level policy for a service level of 90% is presented in Table 8. For the EOQ calculation, the value of the average demand rate used was 0.3 units a month. In Table 9, the parameters and total annual cost for the order level policy are presented, considering a service level of 95%.

Table 8. Results of the order level policy for a 90% service level for the KF-center ring.

Annual holding rate (*i*)	EOQ	Order level	Holding cost (€)	Order cost (€)	Total cost
10%	17	0	29.78	9.75	39.53
15%	14	0	36.79	11.83	48.63
20%	12	0	42.05	13.81	55.85
25%	11	0	48.18	15.06	63.24
30%	10	0	52.56	16.57	69.13

Table 9. Results of the order level policy for a 95% service level for the KF-center ring.

Annual holding rate (*i*)	EOQ	Order level	Holding cost (€)	Order cost (€)	Total cost
10%	17	4	43.80	9.75	53.55
15%	14	4	57.82	11.83	69.65
20%	12	4	70.08	13.81	83.89
25%	11	4	83.22	15.06	98.28
30%	10	4	94.61	16.57	111.18

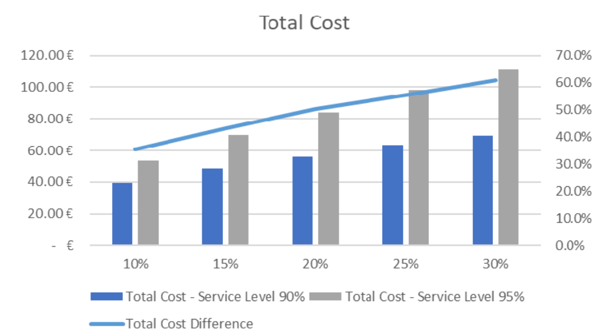

Figure 10. Difference between the total cost for 90% and 95% service levels of the KF-center ring.

To understand the impact on total costs of the two levels of service, the differences between total costs for 90% and 95% service levels were analyzed. The total cost for the 95% service level is higher for all levels of holding rates, presenting a difference in costs that varies between 35.5% and 73.0%, with the lowest value for the lowest annual holding rate and the highest value for the highest annual holding rate (Figure 10).

4.3 Spares that follow the Normal distribution

The spare part analyzed next belongs to group A. No spare parts following the Normal distribution were found with group B assigned.

Fuse

The average demand value used was 33 units, and the standard deviation was 15 units. After identifying the necessary data, the policy parameters associated with this type of spare were calculated. Table 10 presents the results for EOQ, safety stock, and order level, as well as the total annual cost for the different holding rates (i) (between 10% and 30%), considering an allowable shortage risk of 2%.

The change in total cost for the various values of the annual holding rate was also calculated. The percentage increase in total cost drops as the annual holding rate increases.

Table 10. Order-level policy results in an allowable 2% shortage risk of the spare part fuse.

Annual holding rate(i)	EOQ	Safety Stock	Order level	Total cost (€)
10%	367	8	10	33.79
15%	300	8	10	41.58
20%	260	8	10	48.20
25%	232	8	10	54.08
30%	212	8	10	59.43

In Table 11, the parameters and total annual cost for the order level policy are presented, considering an admissible shortage risk of 5%. It was found that the percentage increment in total cost decreases as the annual holding rate increases.

Table 11. Order-level policy results in a 5% allowable shortage risk of the spare part fuse.

Annual holding rate (i)	EOQ	Safety Stock	Order level	Total cost (€)
10%	367	7	9	33,70
15%	300	7	9	41,44
20%	260	7	9	48,02
25%	232	7	9	53,86
30%	212	7	9	59,16

To understand the impact of the allowable failure risk on total costs, the difference between the total cost that exists for the two values of the allowable failure risk, α=2% and α=5%, was analyzed. It was found that for α=2%, the total cost is higher for all levels of holding rate, showing a difference in costs ranging between 0.3% and 0.5%, with the lower value corres–ponding to the lower annual holding rate and the higher value to the higher annual holding (Figure 11).

After obtaining the results, it was possible to define that for the spares belonging to this group (in which demand follows the Normal distribution), the level of admissible failure risk to be used is α=2% because, as expected, the total cost value is higher than for an α=5%, but the difference in cost is very low, not reac–hing 1%. And since it is estimated that the costs of stock-outs of parts belonging to this group can reach very high values for the organization, it is acceptable to support the difference in the total cost since it is quite low.

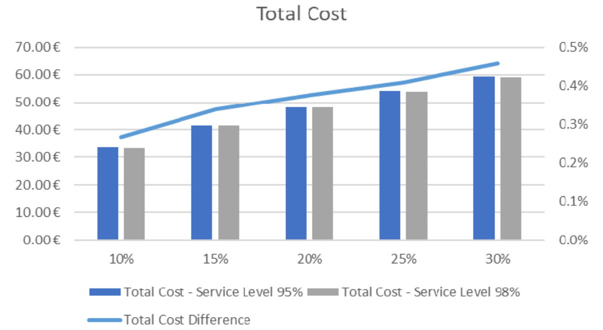

Figure 11. Difference between the total cost for the 2% and 5% allowable shortage level for the fuse.

4.4 Groups C, D, and E

Round belt

The spare part under analysis is assigned to group C. The holding cost for the period under analysis was calculated considering it belonged to groups C and D. The shortage cost was also calculated for the two groups and group E. In Figure 12, the holding cost values for the two groups are presented. The holding cost for group C amounts to 71.79 € for a 15% rate and 191.45 € for a 40% rate. For group D, these values are 35.90 € for a 15% rate and 95.72 € for a 40% rate.

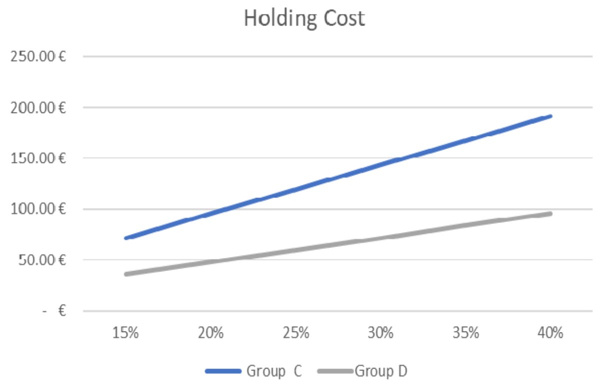

Figure 12. Holding cost for groups C and D of the spare part round Belt.

This part has a production impact level of "quality losses"; as such, the shortage cost was calculated assu–ming several values (Table 4). The value of the shortage cost varies with the annual holding rate between 2.68 € and 21.44 € for group C. For Group D, the shortage costs are between 106.27 € and 850.19 €, and for Group E, they vary between 25,938.00 € and 86,460.00 €.

The shortage cost of group E is much higher than the shortage costs of groups C and D, and in the case of group C, the shortage cost value is extremely low. Comparing the shortage costs with the holding cost, it can be concluded that the holding cost of groups C and D is much lower than the shortage cost of group E, so it can be concluded that group E policy is not suitable for this spare.

The holding costs for Group C are lower than the shortage costs of group D, and the total cost given by the sum of the holding and shortage costs shows that the total cost of group C is also lower than that of group D, so it is advantageous to keep a minimum stock of 1 part instead of a minimum stock of 0 (Figure 13)After this cost analysis, it can be concluded that the group assig–ned by the procedure (group C) is the most advanta–geous for the organization.

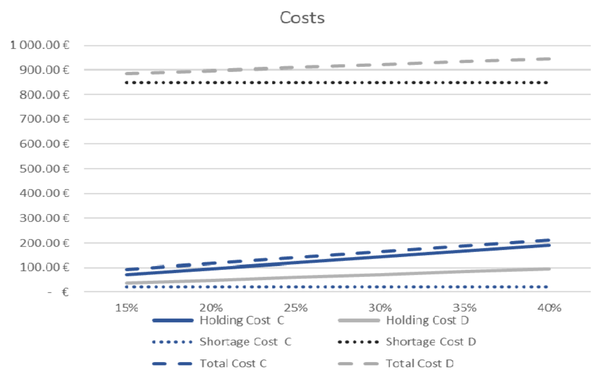

Figure 13. Holding, shortage, and total cost of groups C and D for the round Belt.

Clamping blade

The spare under analysis was assigned to group D. In the cost of holding for group C amounts to 2,982.60 € for a 15% rate and 7,953.60 € for a 40% rate (Figure 14). For group D, these values are 1,941.30 € (15% rate) and 3,976.30 € (40% rate).

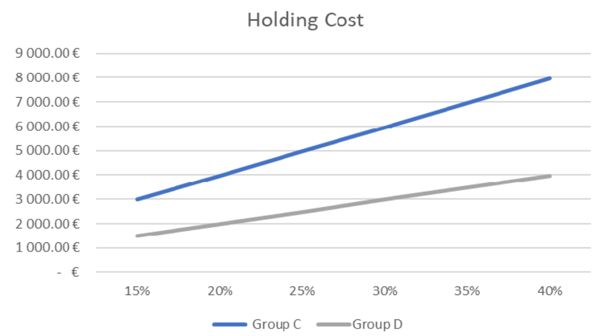

Figure 14. Cost of holding for groups C and D of the spare part clamping blade.

This part has "quality losses" as its production impact level. The value of the shortage cost varies between 0.18 € and 1.41€ for group C. For group D, the shortage costs are between 17.40 € and 139.17 €, and for group E, they vary between 10,375.20 € and 34,584.00 €.

Similarly to what was already mentioned for the previously analyzed spare part, the shortage cost of group E is much higher than the shortage costs of groups C and D and much higher than the holding cost of groups C and D. Therefore, it was concluded that group E policy is not adequate for this spare part. The holding costs of group C are much higher than the shortage costs of that group, so it is not advantageous to keep 2 parts in stock to the detriment of 1 part. After this cost analysis, we can conclude that the group assigned by the decision tree (group D) is the most advantageous for the organization (Figure 15).

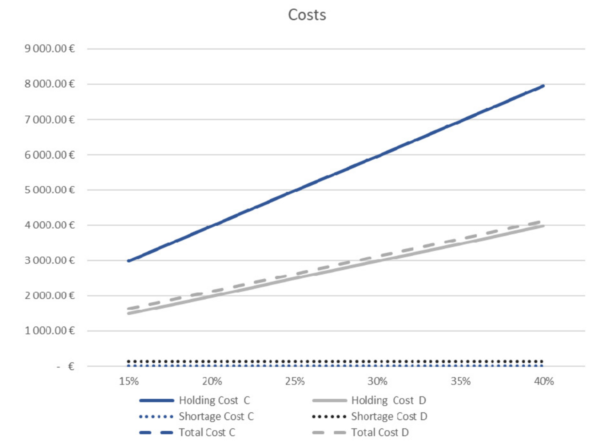

Figure 15. Costs of holding, shortage, and total for groups C and D of the clamping blade.

Cap round vinyl

Cap round vinyl was assigned to group E. Since its production impact level is "no impact", no shortage cost is calculated. In Figure 16, the holding costs for groups C and D are presented. The holding cost for group C ranges from 0.63 € for a 15% rate to 1.68 € for a 40% rate; for group D, the holding cost is 0.32 € for a 15% rate and 0.84 € for a 40% rate. The holding costs are quite low; nevertheless, given that the failure of the spare does not entail any shortage costs, it is advantageous to assign group E.

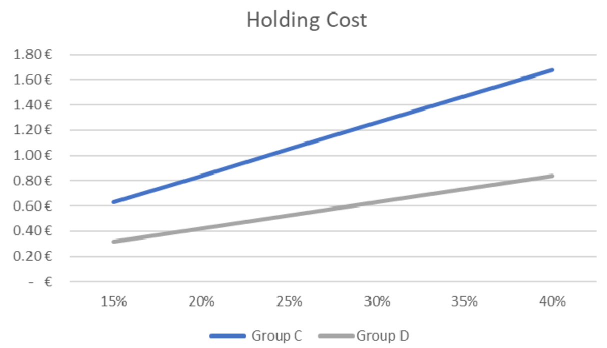

Figure 16. Holding cost for groups C and D of the spare part cap round vinyl.

In summary, for the spare parts in groups C, D, and E, it was found that the group assigned through the classification methodology and the respective stock management policy assigned to the group presented good results since they minimized the holding and shortage costs.

5. DISCUSSION

This paper reports a multi-criteria methodology for classifying spare parts and assigning predefined stock management policies. For validation, a case study was used, which consisted of using a sample of spare parts and comparing the costs associated with each policy.

Members of the company's maintenance department participated in this classification. The methodology was easily transmitted and perceived by company members, and despite the necessary information being dispersed across two computer systems, the classification of the considered sample was carried out easily.

Through the analysis of the spare parts of groups A and B, whose demands do not follow a Normal distribution, it was observed that the assigned policy presents good results, minimizing the associated costs. The holding costs tend to be higher than the ordering costs because these spare parts present a great disparity in terms of consumption, so a high reordering level is maintained.

For group A, with demands following a Normal distribution, we conclude that this model is suitable for this type of spare parts because the EOQ allowed us to determine the fixed size order quantity that minimizes costs. This inventory management model can also be used for other maintenance management-related materi–als such as consumables.

The analysis of the spare parts for groups C, D, and E led to the conclusion that the allocation of the groups was the most advantageous, so the allocated policy minimized the associated costs.

In this study, the parameter values were obtained for a range of the annual holding rate. For the implemen–tation of this methodology, it is important that this rate is defined and that different spares may have different holding rates, according, for example, to the risk of deterioration and/or obsolescence. Spare parts of groups A and B present a lower risk of deterioration and/or obsolescence because they present more recurrent consumption. The spare parts of groups C, D, and E will have attributed a higher annual holding rate since the occurrence of long periods in which there is no demand entails risks of obsolescence and/or deterioration.

In summary, for the spare parts analyzed, it was found that the group assigned through the classification methodology and the respective stock management policy associated with the group presented good results. In the case of groups C, D, and E, the stock manage–ment policies are effective in balancing the costs of the non-availability of a part and the cost of keeping it in stock, thus minimizing total costs. Therefore, it is concluded that the classification methodology and the procedure for policy assignment are adequate for the inventory management of spare parts.

6. CONCLUSIONS

Manufacturing organizations depend on their equipment to produce. Spare parts are fundamental to maintaining the efficiency and good functioning of the equipment, avoiding production losses. Spare parts management represents a complex problem for organizations due to the large number of parts involved, the amount of information that must be considered, and the difficulties in collecting this data. Keeping high stock levels leads to high costs for the organization. A spare part plays a key role in maintenance management and, therefore, can have a strong impact on production. However, the criteria and methodologies used for its classification and management must be different from those usually used in stock management.

In this paper, the proposed methodology aims to classify spare parts into five groups that have an asso–ciated predefined stock management policy. For this classification, the methodology considers the demand characteristics of spare parts. It is also noteworthy that the combination of the maintenance management and stock management perspectives in the classification methodology allows a wide view of the characteristics of each part, allowing the adequate stock management policy to be assigned. The criticality classification criterion reflects the importance of the spare part for production and maintenance, and the lead time and price criteria reflect the vision of stock management. The intention was not only to select the most relevant criteria but also to take into account their applicability in companies due to the ease of access to data. Compared to [4] and [5], the methodology proposed in this paper requires few data to perform the classification and also presents an additional stock management policy to better meet the demand characteristics.

The distinction between the defined groups, A and B, and C, D, and E, is related to the fact that the demand for these spares presents various behaviors. Therefore, generic spares and/or those with a variable batch demand are distributed among groups A and B, and specific spares and/or those with a unitary demand are distributed among groups C, D, and E.

The policies assigned to each of the groups aim to respond in the best way to their specificities. Therefore, for groups A and B, the parameters of the stock mana–gement policy are calculated for each of the spares to obtain the lowest total cost to guarantee the desired level of service for each group and thus avoid or reduce the costs of shortage. In groups C, D, and E, the assig–ned policies have the parameter values previously de–fined since the demand is unitary. In the case of specific spares, an extra classification criterion, which is the probability of shortage within the lead time, was considered to assign group C instead of group D due to the number of identical machines that use the same spare part.

The multicriteria methodology for classifying spare parts and assigning stock management policies was validated through a case study, which showed its adequacy for assigning policies that minimize total costs in an intuitive and fast way. Since the effect of impro–ved stock management policies on maintenance indi–cators is hardly noticeable in the short term, indicators such as Mean Downtime or Equipment Availability will be monitored and analyzed in the media term in the case study company to better understand the impact of the proposed approach.

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УПРАВЉАЊЕ ЗАЛИХАМА РЕЗЕРВНИХ ДЕЛОВА: КЛАСИФИКАЦИЈА И ДОДЕЛА ПОЛИТИКЕ

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Управљање резервним деловима је функција управљања одржавањем која има за циљ да подржи активности одржавања. Намера је да обезбеди информације у реалном времену о расположивим количинама за сваки резервни део и да усвоји политике управљања залихама које обезбеђују његову доступност по најнижој могућој цени. Овај рад предлаже методологију за управљање залихама резервних делова која има за циљ да додели политике управљања залихама сваком резервном делу у индустријском постројењу. Дефинисано је пет група и пет повезаних политика управљања залихама. С обзиром на то да политика која се додељује у великој мери зависи од карактеристика тражње, две групе су намењене за генеричке резервне делове, а друге три за специфичне резервне делове. Дефинисање група и метода доделе узели су у обзир придружену политику управљања залихама, која је заузврат узела у обзир карактеристике потражње за припадајућим деловима. Студија случаја спроведена у производној компанији која производи електронске системе за аутомобилски сектор показала је да развијена методологија омогућава, једноставно и интуитивно, додељивање политика које балансирају између цене дела који нема на лагеру и трошкова његовог одржавања у залихе, чиме се минимизирају укупни трошкови.