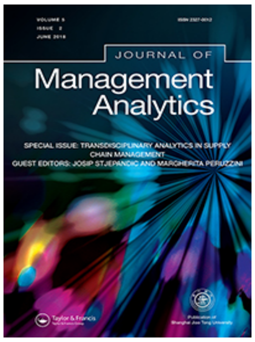

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Classification methodology for spare parts management combining maintenance and logistics perspectives

Catarina Teixeira*, Isabel Lopes and Manuel Figueiredo

ALGORITMI Research Centre, Department of Production and Systems, University of Minho, Guimarães, Portugal

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Spare parts management is a function of maintenance management that aims to support maintenance activities, giving real-time information on the available quantities of each spare part and adopting the inventory policies that ensure their availability when required, minimizing costs. The classification of spare parts is crucial to control the vast number of parts that have different characteristics and specificities. Spare parts management involves mainly two areas, maintenance and logistics. Therefore, the integration of both input information is recommended to make decisions. This paper presents a multi-criteria classification methodology combining maintenance and logistics perspectives that intends to differentiate and group spare parts to, subsequently, define the most appropriate stock management policy for each group. The methodology was developed based on a case study carried out in a multi-national manufacturing company and is intended to be included in its computerized maintenance management system to support decision-making.

Keywords: criticality; maintenance management; multi-criteria classification; spare parts management

1. Introduction

Up until 1940, maintenance activities were not planned, they were only performed when a failure occurred (Murthy, Atrens, & Eccleston, 2002). Between 1950 and 1960, the first scientific approach to maintenance management emerged, moving from the corrective maintenance paradigm to the preventive maintenance paradigm, reducing unplanned downtime in production (Dekker, 1996).

With maintenance planning, maintenance costs are more easily controlled and reduced. Maintenance costs include not only the cost of labor and spare parts (Chen, Ren, Bil, & Sun, 2015) but also the costs of equipment downtime due to breakdowns. An efficient and effective spare parts management is essential for maintenance management since it influences the downtime of equipment. Therefore, management of spare parts of manufacturing equipment affects the performance of maintenance management and, consequently, the productivity of organizations. In organizations with high dependence on production equipment, high equipment availability is required. Therefore, spare parts are an important resource to ensure availability (Roda, Macchi, Fumagalli, & Viveros, 2014). Spare parts inventory management

*Corresponding author. Email: B7236@algoritmi.uminho.pt

has the functionality of providing support to maintenance service, such as to ensure operability of the installed systems. However, spare parts management is a critical issue as maintaining high inventories of spare parts ties up capital and often results in relevant costs consuming a significant part of capital investments. Spare parts are used in a large number of maintenance interventions and associated inventory costs may be of two types: costs of holding stock and costs of the non-existence of a spare part associated with production stoppages.

Spare parts inventories diverge from inventories of manufactured products and materials in many aspects (Kennedy, Wayne Patterson, & Fredendall, 2002). Spare parts are characterized by a large cost magnitude and by intermittent and highly erratic demand and inventories are determined by the demand, instigated by preventive and corrective maintenance interventions.

The availability of spare parts should be directly related to maintenance in order to reduce failure downtime and costs. Inventory and maintenance management must be seen as parts interconnected for optimizing company's operations (Van Horenbeek, Buré, Cattrysse, Pintelon, & Vansteenwegen, 2013). Computerized maintenance management system (CMMS) is now a central component of many companies' maintenance departments, and they offer support on a variety of activities related to maintenance. Concerning spare parts, they can track the movement of spare parts and their requisition when necessary (Labib, 2004) and facilitate the integration of logistics and maintenance perspectives (Cavalieri, Garetti, Macchi, & Pinto, 2008). The integrated logistics and maintenance decisions will allow a more efficient maintenance programming and execution.

According to Molenaers, Baets, Pintelon, and Waeyenbergh (2012), the classification of spare parts is a relevant research area due to the financial resources and service requirements involved. In literature, although there are already several models that aim at the management of spare parts, frameworks that gather all the aspects related to this subject are lacking. Through literature review, opportunities were found to develop a spare parts management methodology that covers various aspects of spare parts management.

This paper presents a multi-criteria classification to be included in the spare parts management methodology that also will include demand forecasting and definition of the inventory policy. The objective of the spare parts management methodology is to group the spare parts (using the classification) and assign to each group the more appropriate stock management policy according to the spare parts specificities.

Regarding spare parts classification methodologies, techniques that just consider one criterion and also techniques that consider several criteria can be found in the literature. The large number of criteria used in some techniques makes them complex and difficult to apply to the reality of industrial organizations. The presented methodology uses criteria that are easily obtained and generally gathered by organizations.

The criteria involved in the classification should consider the maintenance and logistic perspective since both functions are involved in decision-making concerning spare parts stock levels. In this way, the methodology includes the evaluation of the criticality of the spare parts and the most relevant and easily measurable logistics criteria.

The paper is an extended version of the research presented by Teixeira, Lopes, and Figueiredo (2017). This research work about spare parts management was performed in the scope of a project that aimed to upgrade the CMMS of a company. This upgrade consists of software architecture redesign, adding a set of advanced management maintenance methodologies and functionalities (Lopes et al., 2016). Hence, the classification methodology for spare parts will be integrated in the developing CMMS.

The paper is organized as follows. In Section 2 a literature review is presented about spare parts management, classification techniques, and criteria selection. Section 3 presents the multi-criteria classification methodology. In Section 4, an example is used to validate the methodology. Finally, in Section 5, the main conclusions and further work are presented.

2. Literature review

2.1. *Spare parts management*

In NP EN 13306 (2007) spare part is defined as an "item intended to replace a corresponding item in order to restore the original required function of the item". According to Gopalakrishnan and Banerji (2015) some of the specificities of spare parts are: spare parts have a high tendency for obsolescence; stock out cost is greater than the spare part price; spare parts are critical from an operational point view; number of suppliers is small; there is a lack of information system.

Kennedy et al. (2002) refer that the stock management of spare parts has peculiars characteristics, such as:

- The decision of whether to repair or replace has profound implications on maintenance inventory levels;
- The information about reliability is generally not available to the degree needed for the prediction of failure times;
- When certain spare parts no longer take place in the system (because they are no longer used for maintenance) it creates an obsolescence problem.
- The costs of breaking a spare parts inventory are difficult to quantify because it includes costs associated the production losses.

Cavalieri et al. (2008) state that a large number of organizations have problems related to maintenance management due to the lack of adequate inventory management policies in accordance with maintenance needs.

According to Lynch, Adendorff, Yadavalli, and Adetunji (2013) to determine which parts are critical to the maintenance process, the following features must be considered:

- **Process and control of criticality:** The criticality of the process is related to the cost of inactivity, that is when a part fails and a replacement part does not exist in stock. The control of criticality quantifies the reaction time, by taking into account factors such as the availability of spare parts, the probability of failure, the repair times, among many others.
- **Specificity:** Spare parts need categorization in order to distinguish generic and exclusive parts. Generic parts usually have no supply problems, as there are several suppliers available. On the other hand, the exclusive parts tend to have a single supplier and an irregular lead time.
- **Demand patterns:** Spare parts usually have a low demand volume. This type of demand pattern results in high storage costs, especially storing critical items at high prices.
- **Product value:** Unlike finished products, spare parts do not create value, their function is to prevent or reduce the downtime of production equipment.

Stock management of spare parts plays an increasingly central role in modern operations management. The tradeoff is clear: on the one hand, a large number of spare parts represents a large amount of capital tied up, on the other hand, its inexistence causes costs by stopping production (Aronis, Magou, Dekker, & Tagaras, 2004; Zhu, Dekker, van Jaarsveld, Renjie, & Koning, 2017).

Huiskonen (2001) asserts that spare parts logistics differ from other materials since the demand for spare parts is characterized by sporadic behavior and a potential variability when it occurs. The consumption rate is not stationary; therefore, the statistical properties of demand are not independent of time (Cavalieri et al., 2008). According to Syntetos, Babai, and Altay (2012), the demand for parts replacement is related to the failure or replacement and as such the relevant patterns are different from those associated with 'typical' stock keeping units (SKUs). Typically, the demand has a large variance in frequency and quantity and is of intermittent nature which is characterized by several periods of zero demand. Consequently, this type of demand is hard to predict (Zorgdrager, Verhagen, & Curran, 2014). In order to categorize demand, the model proposed by Ghobbar and Friend (2002) uses two variables, the coefficient of variability and the intervals between consumptions.

According to Cavalieri et al. (2008), spare parts management should be inserted in CMMS. The authors suggest the integration of logistics and maintenance perspectives. Therefore, the authors proposed a decision-making framework composed of five sequential steps (Figure 1).

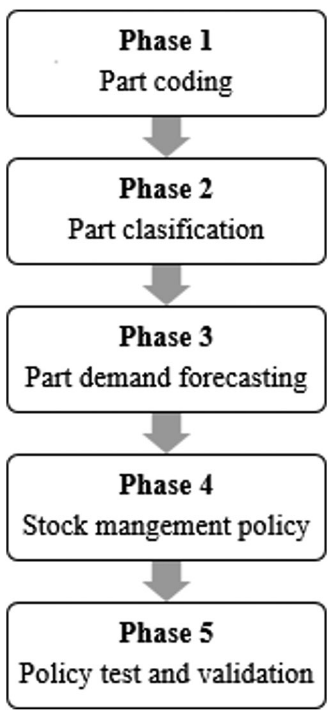

Figure 1. Steps for spare parts management (Cavalieri et al., 2008).

The framework applications aim to sequence spare parts management. In each step, it is necessary to define the appropriate methodologies and techniques to each company. The framework application may eventually lead to fulfilling the gap of the low level of usage of tools to manage spare parts in the industry based on a factual and quantitative assessment (Cavalieri et al., 2008).

Spare parts classification is a relevant step to guide the whole management process. Many advantages can be achieved by proper classification. The demand forecasting process may be driven by data collected for different classes allowing performance improvement measures to focus on the more critical classes (Roda et al., 2014).

With the classification, a suitable management of spare parts can be obtained. It supports the choice of demand forecast and inventory control methods and establishes different performance targets in service levels and turnover for each category (Huiskonen, 2001).

The classification of spare parts, and therefore groups' constitution, follows the Group Technology (GT) concept. According to Shtubt (1989), GT is a manufacturing concept based on the assumption that by decomposing a manufacturing system into subsystems, overall performance improvement can be achieved. This concept has been successfully employed in cellular manufacturing in which, parts with similar processing requirements are identified and grouped into part families, and then machines with different processing capacities are placed within a cell (Shahin & Janatyan, 2010). GT principles have been applied in other areas beyond production, including in maintenance. In the approach developed by Talukder and Knapp (2002), GT concept was applied to the problem of grouping equipment into blocks for the application of preventive maintenance. A heuristic for optimally grouping equipment into multiple blocks within a system for block preventive replacement was developed. Almomani, Abdelhadi, Seifoddini, and Xiaohang (2012) propose a platform to conduct planning of preventive maintenance actions by using clustering, based on the GT concept, to create preventive maintenance virtual cells of machines.

According to Huiskonen (2001) and Molenaers et al. (2012), there are two types of criteria to classify spare parts. Those that evaluate the criticality of spare part for the process and those that evaluate the criticality of control. Process criticality is concerned with the consequences of failure or malfunctions for the plant (for example, consequences related to loss of lives, environmental contamination or production loss). Regarding control criticality, a spare part is considered critical if the possibility to ensure immediate availability of the part is difficult to control. To assess the criticality, spare parts classes should be defined based on quantitative and qualitative criteria (Molenaers et al., 2012).

2.2. *Classification techniques*

The classification of spare parts is crucial due to a large number of parts and their variety. As such, the categorization of spare parts is a way of controlling their diversity and specificity (Molenaers et al., 2012). A classification of spare parts is generally based on administrative efficiency considerations (such as inventory costs, usage rates, etc.) derived from historical data of the company.

According to Dekker, Kleijn, and de Rooij (1998), the classification of spare parts serve to highlight the most critical spare parts that must be kept in stock to ensure production.

Lenard and Roy (1995) identify that the segmentation of materials is indicated by the following reasons:

- It is possible to evaluate the results of each group and to see if they fit the objectives of management.
- Since the final decision on the policy to be adopted must remain in the hands of management, the segmentation of the items allows the analysis of the effects of each decision to be fast and intuitive;
- Segmentation of materials allows the same restrictions to be applied to materials that have similar parameters, allowing the choice of parameters (service rate, the frequency of Stock review) appropriate to each group and allows adjusting the stock management policy which best suits each group of materials.

Two types of methods can be applied to classify spare parts: quantitative methods and qualitative methods (Cavalieri et al., 2008).

In industry, the traditional classification method is ABC analysis, which is widely used to determine service requirements of spare parts (Molenaers et al., 2012). The classification helps companies to simplify stock management. The objective of ABC analysis is to classify the inventory items or SKUs into three classes, namely: A (very important items); B (moderately important items) and C (relatively unimportant items) (Hatefi, Torabi, & Bagheri, 2014; Prakash & Chin, 2017). ABC analysis is easy to use and supports the inventory management of materials that are fairly homogenous in nature (Flores, 1987). The criteria used to classify are product annual demand and average unit price (Ramanathan, 2006). According to Braglia, Grassi, and Montanari (2004) ABC classification is the most well-known and used classification scheme to manage the spare parts inventory management problems.

Huiskonen (2001) mentions that as the variety of control characteristics of items increases the one-dimensional ABC classification does not include all the control requirements of different types of items. In the literature, it has been generally recognized that a "classical" ABC analysis may not be able to provide a good classification in practice (Altay Guvenir & Erel, 1998).

Another quantitative method is FSN, which classifies items into three categories: fast-moving, F, slow-moving, S and non-moving, N. The method is based on the analysis of the demand patterns and leads to a different kind of classification, that is focused on the moving rates of spare parts (Bosnjakovic, 2010; Cavalieri et al., 2008). This classification is useful when it is desirable to put in evidence that the obsolescent spare parts are non-moving after many years (Cavalieri et al., 2008).

The qualitative methods normally used for spare parts classification are based on rough judgment or in scoring methods (Cavalieri et al., 2008). The VED (Vital, Essential, Desirable) classification is a qualitative method (Mukhopadhyay, Pathak, & Guddu, 2003). The VED classification system is based on the maintenance expert's knowledge. Spare parts can be classified as vital, essential or desirable. Although its apparent simplicity, the structuring can be a difficult task because its implementation can suffer from subjective judgments of users (Cavalieri et al., 2008). Gajpal, Ganesh, and Rajendran (1994) suggested the application of VED classification with an Analytic Hierarchy Process (AHP) procedure to limit the problem of subjective judgments.

The other qualitative method that is normally reported in the literature for spare parts classification is AHP. AHP has been considered as a leading and one of the most popular multi-criteria decision-making techniques. AHP attracts the attention of researchers due to the fact that normally the input data are easy to obtain (Triantaphyllou & Mann, 1995). Thus, this methodology is presented in the literature as a possible option to create performance rankings. It is used in a wide range of fields, especially in operations management, to solve complex decision problems by the prioritization of alternatives (Gass & Rapcsák, 2004; Subramanian & Ramanathan, 2012; Wang, Ji, & Chaudhry, 2014). This technique can be used when the consideration of qualitative and quantitative factors are required and it helps to define the critical factors through the definition of a hierarchical structure similar to a family tree (Bevilacqua & Braglia, 2000).

In AHP, the relevant data are obtained from the use of a set of pairwise comparisons. The application of AHP helps to reduce the complex decisions to a series of simple comparisons and consequently, it helps to synthesize results showing the best decision and the clear reason for the choice (Bevilacqua & Braglia, 2000). AHP uses a multi-level hierarchical structure of objectives, criteria, subcriteria, and alternatives. These comparisons are used to define the weight of each criterion and the relative performance measures of the alternatives for each criterion. This method also verifies the comparisons consistency and provides a mechanism to improve it in the cases where the comparisons are not consistent (Triantaphyllou & Mann, 1995; Viriyasitavat, 2016; Xu, Da, & Chen, 2003).

AHP implementation can be structured in three steps (Bevilacqua & Braglia, 2000):

(1) Define decision criteria in the form a hierarchy of objectives, this means structured on different levels;
(2) Weight the criteria, subcriteria, and alternatives as a function of their importance for the corresponding element of the higher level;
(3) After a judgment matrix has been developed, a priority vector to weight the elements of the matrix is calculated.

According to Roda, Macchi, Fumagalli, and Viveros (2012), for the classification of spare parts to be carried out in a well-structured way, it cannot be based only on a single criterion nor on qualitative judgments, then in the literature emerging research reveals the need for a multi-criteria perspective to classify spare parts.

The classification methodology proposed by Braglia et al. (2004), called Multi-Attribute Spare Tree Analysis (MASTA), uses several criteria based on the criticality of the item. The method presents two sequential steps. The first step proposes the identification of four classes of spare parts using a logical tree. In the second step, the appropriate stock management strategies are defined for each of the four defined classes. The AHP method is used to support the decision on each node of the logical tree. For each factor used to make the classification (criticality of spare parts for the factory, spare parts supply characteristics, inventory problems and usage rate) a set of criteria that are measured considering three levels (critical, important and desirable) are considered (Braglia et al., 2004).

In the methodology presented by Braglia et al. (2004) a classification is performed considering a wide range of criteria. The chosen classification technique, AHP, uses a comparison of criteria that presents as an end result, an orderly ranking of spare parts based on the weights assigned to each criterion.

Using only one criterion to classify spare parts is not appropriate considering all their characteristics and specificities. In this way, multi-criteria classification should be used. However, the use of too many criteria makes the model complex and difficult to apply to the reality of industrial organizations since a large set of information needs to be available and easily updated.

2.3. *Criteria selection*

The first stage of multi-criteria classification methods is the definition of significant criteria.

According to Roda et al. (2014) maintenance managers consider the most important spare parts those which their unavailability would result in severe consequences for the production. On the other hand, inventory management and logistics managers consider other parameters as more important, such as holding costs and demand patterns that are important for the choice of a stock management policy. From a financial point of view, the value of spare parts and the investment questions are the most significant to define the importance of a spare part.

The most frequently used criteria are lead time, price, probability of failure and number of potential suppliers (Bosnjakovic, 2010; Botter & Fortuin, 2000; Braglia et al., 2004; Cakir & Canbolat, 2008; Molenaers et al., 2012; Stoll, Kopf, Schneider, & Lanza, 2015), as indicated in Table 1.

The approach developed by Botter and Fortuin (2000) presents a case study in which a pragmatic but structured approach is followed. The goal is to present a

Table 1. Criteria selection in case studies.

Criteria	Botter and Fortuin (2000)	Braglia et al. (2004)	Cakir and Canbolat (2008)	Bosnjakovic (2010)	Molenaers et al. (2012)	Stoll et al. (2015)
Lead time	X	X	X		X	X
Price	X	X	X			
Probability of failure		X			X	X
Number of potential suppliers		X		X	X	
Annual demand	X		X			
Availability of equipment					X	X
Inventory problem		X		X		
Availability of technical specifications					X	
Installation time						X
Others	X	X	X	X	X	X

solution to the control of service parts for the repair of professional electronic systems on customer sites.

The method MASTA developed by Braglia et al. (2004) presents a model for inventory management of spare parts. The model takes into account a set of attributes for the classification of the parts in the paper industry. The model uses several criteria, grouped into four types (spare part plant criticality, supply characteristics, inventory problems and usage rate) each criterion has three levels: critical, important and desirable.

In the study of Cakir and Canbolat (2008) a multi-criteria inventory classification applied in a small electrical company is proposed. The classification combines the potency of recent information technologies such as Java Servlets, MySql database and the modeling principles of the fuzzy AHP methodology.

In the study of Bosnjakovic (2010) a methodology for spare parts inventory control applying multi-criteria inventory model is proposed. It is based on ranking and classifying the spare parts in groups according to similar attributes. The used criteria for classification are value-usage, criticality of spare parts (measured using four criteria: plant production, supply, safety and inventory) and frequency of demand.

In the case study proposed by Molenaers et al. (2012) a multi-criteria classification method based on spare parts criticality is presented. The contribution of their research work was actual implementation of a classification method in an industrial environment.

The approach developed by Stoll et al. (2015) was intended to evaluate spare parts based on real inventory in cooperation with an industrial company. The goal was to solve the problem of stockage of spare parts.

In the literature, several criteria have been used for the classification of spare parts. But the wider the number of criteria considered to classify them, the greater the possibility of the lack of recorded data for an adequate classification.

3. Research approach and methodology

In this section, the development of the multi-criteria classification methodology is presented. Initially, reference is made to the management of spare parts in the organization in order to understand the main difficulties and problems that exist in the management of spare parts. Subsequently, the main steps of the development of a multi-criteria classification methodology are presented.

The spare parts management is carried out by a purchasing department (which is not related to the maintenance department), that manages the spare parts stocks to ensure the plant's needs. The quantities of parts to order and the safety stock value is defined by the information provided by the suppliers of the machines, the experience of the maintenance department and the consumption history of spare parts. These values are thus obtained taking into account criteria such as the criticality of the machines (defined subjectively by the maintenance department) or the unit cost.

The classification of the spare parts is carried out using two methods, the ABC analysis based on a parameter, the consumption, and through the classification FSN that analyzes the frequency of movements of the parts. At present, 18% of the items in stock are classified as non-moving (FSN Classification). This classification highlights spare parts that have not been moved for many years.

The classifications based on ABC and FSN serves to identify the most important spare parts and with greater inventory rotation. The information obtained from the classification serves to put more attention on the parts, controlling the value in the stock and the quantities to order. It is also used to analyze the performance of the maintenance department regarding the consumption of spare parts.

Nevertheless, a single classifying criterion cannot generally represent the criticality of an item. The classification only considers information related to the management of inventories, namely it is not possible to know the information related to maintenance management, the consequences that the inexistence of the spare part cause on production. For instance, the lack of a slow-moving item can have a major impact on productivity. Therefore, in the context of spare parts logistics, an approach that includes criticality for the process as a fundamental criterion should be developed. Spare parts management is not currently supported by the CMMS of the company. The inventory management of spare parts is done by the enterprise resource planning system using a "supermarket" of material that is used for maintenance actions.

The multi-criteria classification of spare parts was developed in order to assign an adequate inventory policy to each spare part, combining a set of criteria.

The methodology for spare parts classification is divided into two steps (Figure 2), the division is related with the fact that the purchasing department has insufficient information about spare parts importance to maintenance and its impact on production. The first step consists of defining criticality of spare parts for the process. The criticality of spare parts is defined identifying the importance and need of spare parts for production. In this case, it is intended to evaluate the consequences that the lack of the spare part can bring to production. The main goal is to assign to

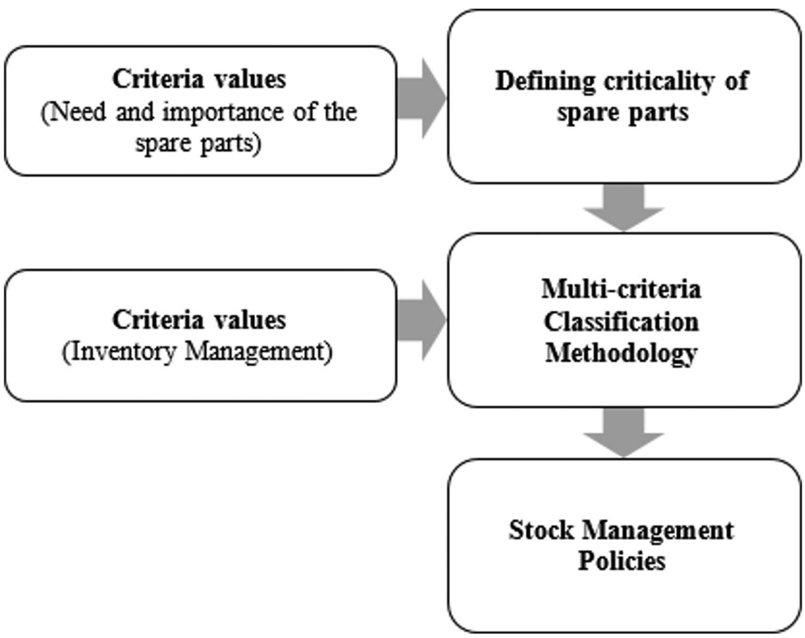

Figure 2. Inputs and outputs of the classification methodology.

each spare part a level of criticality using three categories: Vital, Essential and Desirable. These terms have already been used in previous works. In this case, the meaning of each category is the following:

- Vital: Part failure have a great impact on production processes;
- Essential: Part failure have a middle impact on production processes;
- Desirable: Part failure poses no risk to the production processes.

Therefore, the result of this step is to assign the spare parts to one of three levels of criticality. This will be used in a second classification that aims to create groups of spare parts sharing the same stock management policy.

Before defining the rules for criticality assignment, the most appropriate criteria were selected. Two criteria, namely Function and Impact on Production, were defined.

The choice of the criteria was based on the analysis of the literature. This allowed to know the importance of measuring the criticality of the spare parts, that is, to know the impact that the failure of a certain spare part has on the productive process. The case study showed that it was possible to obtain measurable information for each criterion.

The Function criterion is divided into three levels and the criterion Impact on Production in four levels. Table 2 presents the description of the criteria and respective levels.

In the second step criteria related to inventory management are added. With this step, the methodology considers issues not only related to maintenance and production but also issues related to inventory management.

The information related to the price and lead time criteria is obtained from the department responsible for the purchase and management of spare parts. In this way, it is intended to aggregate the information of this department to the maintenance department in the same methodology of classification of spare parts.

Lead time is a relevant aspect to consider in spare parts classification. Logistically, there are delays between the order of spares and their arrival. This situation is even

Table 2. List e description of criteria.

Criteria	Description
Function	**The function performed by the spare part in the production process**
1. Auxiliary function	The spare part function consists on supporting the equipment operation, it does not interfere directly on production (e.g. control, comfort, structural integrity, economy, prevent misuse).
2. Safety function	The spare parts function is to preserve operator safety, it may not directly interfere on production
3. Indispensable function	The spare part is involved in a primary function of the equipment
Production Impact	**Impact of the spare part failure on the production process**
0. No Impact	The spare part failure has no impact on production.
1. Quality losses	The spare part failure causes defective products.
2. Productivity reduction	The spare part failure causes a reduction in production rate.
3. Sudden stop	The spare part failure causes an immediate stop of the machine, causing the total equipment shutdown.

more crucial when spare parts are vital since spare parts are not always available at the supplier (Godoy, Pascual, & Knights, 2013).

Part cost (unit or inventory cost) is the most popular criteria (Bacchetti, Plebani, Saccani, & Syntetos, 2010). In this case, the unit price is used for the classification.

4. Industrial case study

Spare parts management is not currently included in the CMMS of the company. Management of spare parts is performed by a department that ensures all the plant's needs. For a more efficient and effective use of CMMS, it is intended that CMMS be able to provide information relevant to the inventory management of spare parts.

In this section, an application example of the classification methodology is presented. The development of the classification methodology was based on the information and data made available by the organization. In this case, there are 16,094 spare parts registered in the organization's information system. For the study of the Price and Lead Time criteria, the information regarding the 16,094 spare parts was used.

The first step of the classification process, the identification of spare parts criticality, is validated using a set of spare parts. In the second step of the classification, the criteria and methodology are presented.

4.1. *Criticality of spare parts*

After defining the criteria and the respective levels, a method should be used to obtain the three levels of criticality. In this case, a matrix of combinations that aims to associate the levels of the two criteria (function and impact on production) was used. It was verified that both criteria have the same importance, therefore, the levels of the Function criterion were ordered from 1 to 3, and the levels of the Impact on Production criterion were ordered from 0 to 3. In both cases, the smaller number represents the less relevant level. The matrix considers the 12 possible combinations (Figure 3). The combination matrix has been validated, with the help of the company, by analyzing several different parts. This study reveals that among the 12 possible combinations, 3 never occur. For this reason, the combination matrix may have combinations that do not occur depending on the organization where it is applied.

The result of this first step is the assignment of three levels of criticality to spare parts: Vital, Essential and Desirable. The distribution of the 12 combinations for the three categories was performed taking into account what is considered vital, essential and desirable for the organization.

Table 3 presents a sample of the analyzed spare parts, each one corresponding to the nine existing combinations, as well as the corresponding level of criticality.

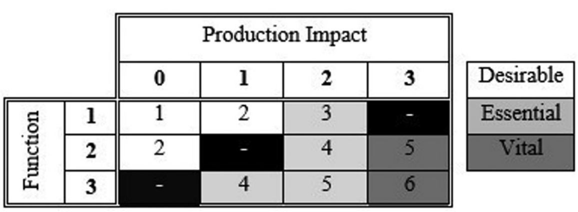

Figure 3. The combinations matrix.

Table 3. Spare parts classification example.

Description	Function	Production Impact	Sum	Classification
Cable M12	3	2	5	Essential
Grippe finger – milling cutters	3	3	6	Vital
Vacuum cleaner bag Ringler	1	0	1	Desirable
Emergency button – ASI	2	3	5	Vital
ET-30 Emergency (stop)	2	0	2	Desirable
Interlock switch	2	2	4	Essential
Needles ICT	3	1	4	Essential
Support scanner	1	2	3	Essential
Glass selective	1	1	2	Desirable

4.2. *Multi-criteria classification*

After defining the criticality of the spare parts, it is necessary to analyze their prices and lead times. Therefore, a study was carried out taking into account all the spare parts to define the most appropriate intervals.

The definition of the levels related to the lead time was performed using an analysis of the lead time values observed in the organization. Table 4 shows the absolute and relative frequencies for the lead time values. Through this table and the experience of the maintenance team, the three levels were defined. The low level represents 28.71%

Table 4. Lead time levels.

Lead time (Days)	Absolute frequency	Accumulated absolute frequency	Accumulated relative frequency (%)	Levels
0	1	1	0.01	Low
1	53	54	0.34	
2	2375	2429	15.09	
3	59	2488	15.46	
5	2201	4689	29.14	
8	114	4803	29.84	Medium
10	369	5172	32.14	
14	2	5174	32.15	
15	7520	12,694	78.87	
20	52	12,746	79.20	High
21	11	12,757	79.27	
25	3	12,760	79.28	
30	2938	15,698	97.54	
35	1	15,699	97.55	
40	16	15,715	97.65	
50	2	15,717	97.66	
60	57	15,774	98.01	
75	1	15,775	98.02	
90	319	16,094	100.00	

Table 5. Price levels.

	Low	Medium	High
Levels	≤300€	>300€ and ≤1500€	>1500€
Percentage	87	10	3

of the lead time values, the mean level represents 49.6% and the high level represents 21.69% of the values.

The levels of the price criterion were defined according to what the organization considers to be a high, medium or low price.

Table 5 shows that a large percentage of spare parts is contained at the low level (87%) so the price criterion is intended to be crucial only when the value of the spare part is medium or high.

To analyze the distribution of spare parts according to the unit price, a histogram of unit prices was built and is presented in Figure 4. The histogram shows that prices are mostly in the first class, i.e. 77.70% of prices are in the range [0; 84]. The remaining 22.3% of the spare parts prices are distributed in the remaining classes. The last class has a range of values included in [1955; 35,677]. The minimum price registered for spare parts is € 0.01 which is the unit price of Spotlight Bearing Ball, Bit Holder, among others. The maximum price registered is 35,676.07€ which is the price of the Head unit – High-Speed.

Next, ranges for the possible quantitative and qualitative results of each criterion are defined in Table 6. The levels assigned to price and lead time criteria are adjustable to the organization where this methodology may be applied.

After the definition of criteria and respective levels, it is necessary to select the method for their comparison. Thus, the use of a decision tree is proposed. Figure 5

Figure 4. Distribution of spare parts unit prices.

Table 6. Criteria levels.

Criteria /Levels	Criticality	Lead time	Price
High	Vital	>3 weeks	>1500 €
Medium	Essential	>5 days and ≤3 weeks	>300 € and ≤1500€
Low	Desirable	≤5 days	≤300 €

shows an example. In this case, the first criterion to be taken into account is criticality, the second is the lead time and the third is the price of the spare part.

Therefore, each spare part is assigned to one of four different groups designated by A, B, C and D. For each group, the stock management policy most appropriate to the characteristics of the spare parts will be assigned.

Table 7 shows an example of spare parts classification through a small sample. The table shows the information about the three criteria (Criticality, Lead time and Price) used in the multi-criteria classification for a small sample and in the column "inventory policy" is the group that would be assigned to the spare part. This result is achieved using the decision tree mentioned above.

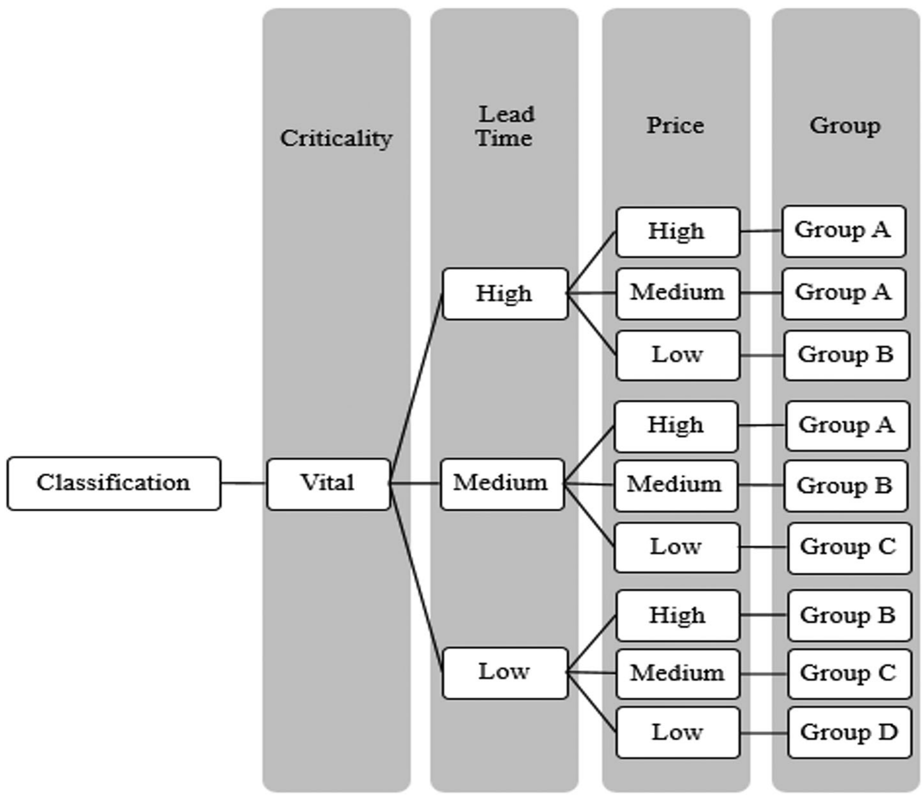

Figure 5. Decision tree for the classification example.

Table 7. Spare parts multi-criteria classification example.

Material	Description	Criticality	Criticality level	Lead time	Lead time level	Price	Price level	Annual consumption 2016	Inventory policy
8600 862,658	Gripper finger – milling cutters	Vital	High	15	Medium	32.53 €	Low	13	Group C
8600 862,886	Light bulb 24 V/2.6 W	Desirable	Low	15	Medium	2.00 €	Low	0	Group C
8600 859,133	Ultrasonic sensor microsonic	Vital	High	15	Medium	152.10 €	Low	1	Group C
8600 857,167	Interlock switch – AB1450	Essencial	Medium	15	Medium	80.45 €	Low	0	Group D
8600 859,400	Needles ICT	Essencial	Medium	2	Low	0.46 €	Low	26,987	Group A
8600 856,903	PRINTHEAD 300 DPI, W-6308;20-2195-01	Essencial	Medium	2	Low	694.00 €	Medium	13	Group B
8600 863,419	Pump 9.7 mm; 231,976	Vital	High	5	Low	4,330.68 €	High	3	Group B

Table 8. Inventory policies.

Inventory policy	Description
No stock	Unavailability of a spare part is a conscious decision
One spare part in stock	This management policy implies ordering just when the spare part is taken from stock.
Multi spare part inventory • Model 1 • Model 2	It implies stocking more than one piece of a particular item. Inventory reorder level, safety stock and the size of replenishment orders have to be calculated. More than a model can be settled down.

Finally, it is important to define the most appropriate stock management policy for each group of spare parts. In this case as an example, four stock management policies may be proposed, as explained in Table 8.

In defining the parameters associated with the stock management policy, two aspects should be taken into account: the number of machines for which the spare parts are used and the demand for spare parts. To determine spare parts demand, reliability studies should be performed. In the case of parts that are periodically replaced (preventive interventions), it will be necessary to know the probability of failure for the item during the preventive maintenance interval.

5. Conclusions

Manufacturing organizations depend on the availability of their equipment to produce. Spare parts are important to maintain the efficiency and the good functioning of the equipment, avoiding losses of production.

The management of spare parts represents a complex problem for organizations due to the large number of items involved, the amount of information to be considered and the difficulties in collecting this data.

High inventory levels are very expensive due to both capital immobilization and storage space. Thus, many studies are conducted in an attempt to optimize the number of spares to be stored. For this, the factors affecting the decisions concerning acquisition and storage must be known.

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 their classification and management should be different from those commonly used for the management of finished goods inventories.

This paper presents a multi-criteria classification methodology for spare parts management which combines maintenance and logistics perspectives and uses information that is generally available in most organizations.

The first step intends to assign a level of criticality to each spare part. For this, two criteria were used: function and production impact. The second step aims to classify each spare part using two more criteria: lead time and price.

This multi-criteria classification methodology was validated through a case study using a sample of spare parts made available by an automotive company.

In the future, it is necessary to assign the most appropriate stock management policies to each group of spare parts that resulted from the classification and choose the adequate values for the parameters associated with each policy.

The development of this multi-criteria sorting tool will help the organization to make better decisions concerning management of spare parts based on the quantitative and objective information.

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ORCID

Isabel Lopes http://orcid.org/0000-0002-8958-449X

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