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RESEARCH ARTICLE

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A NEW COMBINED SPARE PARTS CLASSIFICATION METHOD AND A CRITICALITY ANALYSIS: AN IRON ORE MINING COMPANY STUDY CASE.

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ABSTRACT

Spare parts are important to maintain mining operations, which made necessary the development of consolidated classification methods, to help in the decision-making process. The management of spare parts aims to reduce the unnecessary inactivity time arising from the component failures and represent a significant part of the total operational cost. A way to manage the inventory of these materials is its classification. This work presents a new spare parts categorization method based on multi-criteria classification for managing the spare parts inventory using the approaches cut-off point, XYZ, ABCD, Kraljič matrix, Analytical Hierarchical Process (AHP), and Bottom-up to categorize in the sectors of production, maintenance, and supply. The study was realized with real data from a mining company composed of 40,002 stored materials, and the results showed an abridgment of the management models. This new categorization contributes to the literature of spare parts inventory management, once there are few studies of practical applications in mining industries besides conducting a literature review regarding relevant criteria and methods used to classify spare parts.

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INTRODUCTION

Spare parts perform an important role in several sectors like automobile, aviation, and manufacture industries, in support of operational and maintenance activities (Nurcahyo *et al*., 2018). Items are strategic for the continuity of the operations, and a stock-out can directly affect the production process (Conceiçao *et al.*, 2015; Nurcahyo *et al*., 2018; Zhang and Zeng, 2017). It is not unusual that the companies keep dozens of thousands of spare parts (Babai *et al*., 2015; Cavalieri *et al*., 2008; Kennedy *et al*., 2002). The unnecessary acquisition paralyzes a significant part of the organizational capital (Downing *et al*., 2014). Thus, the classification of spare parts is useful to determine the requirements of the services and to aid management decisions (Bacchetti and Saccani, 2012). There are different methods of classification of stocked materials. (Bacchetti and Saccani, 2012) revised twenty-eight papers and twenty one adopted a multi-criteria classification of which only three used study cases. (Roda *et al*., 2014) analyzed 48 works highlighting that 71% of the companies adopt the rules of thumb, 60% VED methodology, summarises the three categories, namely, Vital, Essential, and Desirable, 17% bi or multi-criteria classification, and 31% ABC classification as a mono criterion. (Hu *et al*., 2017) synthesized thirty-three studies related to the classification of stocked materials, as eight of them, were applied to real spare parts case studies, including the own work of the authors. The classification issue did not receive as much academic attention as its implications for spare parts management would require (Bacchetti and Saccani, 2012). (Roda *et al*., 2014) detach the gap between the scientific theory and industrial application, stating that most of the companies do not have a quantitative method of classification, and they barely utilize multi-criteria classification methods. (Hu *et al*., 2017) highlight that few papers are applied to the classification of spare parts, besides do not utilize a huge number of materials, and that most works do not realize real case studies, they use examples or data extracted from other works. Of the several studies analyzed in the works of (Bacchetti and Saccani, 2012; Hu *et al*., 2017; Roda *et al*., 2014) the mining sector is studied only in (Roda *et al*., 2014) with an exploratory case study about two copper mining companies in Chile, and the barriers in the use of multi-criteria methods and how to overcome them. There is a need for studies on the classification of spare parts, as well as case studies in the important mining sector that has not yet been studied. The mineral sector is characterized by location rigidity, the large scale of its operations and logistics, and substantial impact on the territories in which it operates (Matlaba *et al*., 2017), significant contribution to the economic development of many countries (Luthra *et al*., 2015), producing jobs and wealthy (Shen *et al*., 2015). In Brazil, the sector generates around 180 thousand direct employments with a production value superior to US$ 32 billion in 2017 and 2018 (IBRAM, 2018). The maintenance of the mineral sector can represent between 40-50% of the total operational cost (Murthy *et al*., 2002), of which 25-30% are spare part costs (Hu *et al*., 2015). In Brazil, 4.69% of its GDP is spent on maintenance, which represents 21.96% of the total costs (ABRAMAN, 2013). Thus, it is necessary to study the classification of spare parts in the mineral sector, so the efficiency of management and availability of spare parts can be facilitated by the grouping, which allows applying specific inventory policies to each group (Hu *et al*., 2017).

This work contributes to the development of a four-phase multi-criteria classification method. In phase I, the applicable classification criteria are selected for the iron ore mining industries utilizing the cut-off point. Phase II defines the categories of the criteria based on the classification methods XYZ, ABCD, and Kraljič matrix. During phase III the AHP and bottom-up process are used to quantify the relevance of production, maintenance, and supply sectors, besides the general priority of the spare parts independently. Phase IV highlights the proposed model of comparison with the current classification methods adopted in the organization and the proposition of management models for each ranking of spare parts. The data set was acquired from a huge iron ore mining company from Brazil. The company name is being withheld for data protection and business ethics reasons. As far as we know, there are no previous studies that combine the methods of phases I, II, and III in the development of a classification model of phase IV. The paper is organized as follows. Literature review and spare parts classification are in Section 2. In Section 3 the proposed classification model is presented. The comparison among the current classification methods is in Section 4. Section 5 presents the main discussions and conclusions of the research.

Background: The contemporaneous inventory basis comprises thousands of different items which makes individualized attention to each item an impossible task (Ladhari *et al*., 2016). The efficient management of inventory systems and their classification are crucial elements in the operation of any manufacturing company (Kabir and Hasin, 2012). With the classification of materials, different forms of inventory control can be applied to different groups (Syntetos *et al*., 2009). Spare parts inventories differ from other manufacturing inventories in several aspects (Kennedy *et al*., 2002). (Kennedy *et al*., 2002; Roda *et al*., 2014) cite as peculiar aspects the demand being managed by the maintenance policy; poor reliability of failure predictability information, the lack of a spare part that can impact other components, quality or loss of production; risk of obsolescence.
There are several ways to classify spare parts (Ayu Nariswari *et al*., 2019) and the use of only one criterion may not be efficient in making decisions (Kabir and Hasin, 2012). Recently, the multi-criteria inventory classification (MCIC) approach has been increasingly considered in the academic literature (Babai *et al*., 2015). The existing literature in inventory classification using two or more criteria is summarized in Table 1, indicating the number of criteria, the main method used, if it is a real case study, the field, and if it is applied to spare parts. We analyzed forty-eight articles, and the number of criteria adopted by them varies between two and twenty-two, of which nineteen studies used four criteria, and nine of them applied three criteria. Regarding the methods used, there is a great variety. AHP was the most adopted method with seven applications, and the VED method was the most frequently combined with AHP in five works. It is noteworthy the occurrence of other methods as well as the combination of several methods in several studies being applied only once. Case studies with real data were carried out in twenty-three works with an emphasis on the industrial sector with applications in several segments: automotive, paper, energy, electrical circuits, food, petrochemical, pharmaceutical, semiconductors, drinks, and sports. The pharmaceutical industry had the largest number of case studies with three works, followed by automotive with two. It is also worth mentioning that only one of the works was carried out in the mineral sector using the AHP and VED methodologies. This work was based on the AHP criteria and analyzes of the article Muniz *et al*., (2020), the VED classification was replaced by the methods XYZ, ABCDE and Kraljič Matrix. Thus, a more consistent analysis of the classification model used in the company and the proposed approach was carried out.

Twenty works proposed classifications developed especially for spare parts using between three and twenty-two criteria, of which seven adopted four criteria, and the other four studies embraced six criteria. The most used method was the AHP in six studies and combined with VED in three of them. Three studies combined AHP and VED with other methods. The methodology of the remaining works was applied in a single study. Case studies were applied in sixteen works, and the pharmaceutical industry is the only one presented in two case studies. The industrial sector had fourteen studies in various sectors such as automotive, electronic devices, paper, heavy industry, petrochemical, and food. Seven of them were carried out on spare parts case studies.
Six works specified the number of materials analyzed with a range of pieces between 500 and 50,000. The works of (Botter and Fortuin, 2000; Stoll *et al*., 2015) developed a case study of over 50,000 spare parts, and the others developed the study in less than 10,000 materials. The aforementioned authors highlighted the difficulty of obtaining data, and limited information (Roda *et al*., 2014; Zeng *et al*., 2012), on the other hand, Stoll *et al*. (2015) used only data obtained automatically from the systems. Ayu Nariswari *et al*., (2019) highlighted that finding suitable criteria for the classification of spare parts is crucial since there is no consensus in the literature on the most appropriate ones. A substantive number of such criteria are considered in the literature research works or used in practice (Roda *et al*., 2014). Table 2 presents the criteria, the articles in which they were used, in addition to quantifying the occurrence of the use of the criterion. Many articles do not detail the meaning of the criteria. There are criteria with different nomenclature and the same meaning, for example, Demand, Demand Volume, Demand Rate, Storage space, Limitation of space, and Space required only one name is presented per criterion. Accordingly, to Table 2, many criteria are recurrently used for the classification of inventories, among which we highlight the Lead time, Price, and Usage value criteria, used in more than 85%, 72%, and 55% of the works, respectively.

In twenty-three analyzed articles with a case study, the lead time criterion occurred nineteen times, price in fifteen, and demand rate in twelve. Considering twenty spare parts studies, the most adopted criteria were the lead time, price, demand rate, stock-out cost, and usage value, with sixteen, eleven, ten, nine, and eight applications, respectively. Seeing the sixteen spare parts works with a case study, the most used criteria were lead time, demand rate, price, stock-out cost, and Tailor-made aspect, with twelve, nine, eight, seven, and six applications, respectively. When comparing the occurrence of the criteria with the most used methods (AHP and VED) in seven studies, lead time was adopted six times, the stock-out cost was used five, and price and Tailor-made aspect assumed in four works. In the six case studies with the application of AHP and VED, the main criteria used were lead time with five applications, and both stock-out five, and Tailor-made aspect with four. Considering the six spare parts case studies using AHP, the most used criteria were lead time and stock-out cost with five occurrences and Tailor-made aspect with four. There was no relationship between the adoption of the most-cited criteria with the use in a case study, application in spare parts, and methods used. The recurring criteria were lead time and price. The other criteria were used less frequently and it was not possible to define a usage relationship.

Method and implementation: To address a multi-criteria classification problem in a mining company, a combined methodology is proposed that allows the classification of spare parts without relying on historical data. The proposed methodology combined the cut-off point selection approaches, obtaining the hierarchy and weights by the AHP, classifying the categories into three specific classes in each sector, and the bottom-up process. Table 3 presents the steps, and methods applied through the case study in a mining company. Phase I selects criteria found in the literature suitable for the mineral sector, as per section 3.1. Phase II details the classification categories, see section 3.2. Phase III calculates the weights of each criterion selected in phase I, and the classification categories of phase II by AHP and performs the bottom-up process, presented in section 3.3. Phase IV shows the classification model based on fourteen criteria and the management proposal for each group of material, highlighted in Section 3.4. The classification model allows an assessment by organizational sectors differently from traditional approaches focused on one or two criteria. The approach can indeed be used in other mining companies or other sectors. Companies can include, exclude or change criteria, as well as categories of evaluation, being necessary to carry out Phases I, II, III, and IV.

Criteria selection: A detailed and extensive review was carried out to identify the criteria used in the literature, see Table 2. Duplicate or redundant criteria were excluded and without the possibility of evaluation in the classification openings. The criteria with the need for historical data were not considered, as the inclusion and exclusion of spare parts are routine, which makes it impossible to evaluate all materials with the same historical database. Next, the cut-off point method (Tam and Tummala, 2001) was used to select the most important criteria. The twenty selected criteria were individually assessed by eighteen specialists in the areas of production, maintenance, and supplies, to avoid influencing judgments. The score for each criterion and the cutoff value of 2.3 as in Muniz *et al*., (2020), are shown in Figure 2. The fourteen selected criteria were gathered into three groups production, maintenance, and supplies, see Table 4, based on the literature and the organizational structure of the case study company. Once the most suitable criteria are selected, it is necessary to define the classification openings for them.

Criteria categories: The categorization of spare parts used in the organization was maintained to facilitate understanding by specialists and to speed up the classification of materials. In the organization, the production, maintenance, and supply sectors adopt different classifications to support decision making. The maintenance sector uses the ABC / ABCD classification for equipment, in which the machines classified as A are the most critical (Deshpande and Modak, 2002; Ramli and Arffin, 2012), and this classification is generally carried out using multiple factors (Márquez *et al*., 2009). The maintenance sector uses the ABCD classification including class E, where it compares the probability of failure with the impacts of failure in production, safety, environment, maintenance cost, and quality. Each of these analyzes with five classifications related to the consequences in case of failure; small, significant, serious, very serious, or catastrophic which generates a final 5x5 evaluation matrix based on 30 different information. Values and rating ranges are assigned where A represents the most critical item, and E the least critical. The company's system presents the equipment in which each spare part is installed and was used to classify the materials. The classification used in the supply area for the purchase of spare parts is the Kraljič matrix, one of the most used methods to manage the purchase of different types of materials or the relationship between buyer and supplier (Hesping and Schiele, 2016). The Kraljič matrix distinguishes non-critical, leveraged, critical, and strategic purchases in two dimensions: “strategic importance” and “supply risk” (Kraljič, 1983).

For the classification, the organization uses a questionnaire evaluated by experts analyzing market complexity, impacts for the company and processes, and annual purchase value. The main criteria impact on product quality, the criticality of the item in the process, the number of processes impacted, and environmental impact. Finally, the groups of materials are classified in the quadrants of the Kraljič Matrix, each spare part belongs to a group of materials defined by the organization, and in this way, it is possible to classify each spare part. The production sector uses the XYZ classification adopted in the organization. The XYZ classification is related to the demand characteristics of the materials (Babai *et al*., 2015; Petropoulos *et al*., 2018; Stoll *et al*., 2015). In the organization, the classification is similar to that presented in (Gasnier, 2002), where X represents low criticality, Y medium, and Z high, related to the impact of the lack of material. For this classification, the organization uses a decision tree based on the factors: criticality of the equipment, impact on production, impact on quality, impact on the environment and safety, failure predictability, lead time, and the existence of an alternative resource. Thus, each material has its final category, which allowed the classification of the materials. Table 5 shows the classification categories used in the company. The collection of information was hampered by the lack of integration of systems used in the company. Only 4 criteria were obtained directly from the SAP™ system, the others through proprietary software and data manipulation from different databases such as MS Excel ™. The data used in the research despite the difficulty of obtaining it are validated by the specialists. Classifications can be redefined for applications in other organizations or sectors.

Hierarchy and weights: The criteria were evaluated by the company's specialists to carry out a peer-to-peer comparison in the Production, Maintenance, and Supplies sectors. Table 6 presents an example of the pairwise comparison matrix for the maintenance sector criteria, to Production and Suppliers matrix and more details of consistency ratios are found in (Muniz *et al*., 2020). In this case, the Spare parts reliability criterion is 7 times more relevant than the Machine priority criteria. The comparison matrix was also developed for production, supplies, and classification categories. The details of the AHP are found in the works of (Saaty, 2008, 1990, 1977). The consistency ratio verifies the consistency of the judgment, being the parameter that guarantees the precision of the obtained result. For values below 0.1 it implies that the judgments are consistent (Saaty, 1990), and the relative weights obtained can be used. Table 7 presents the results of the consistency index obtained in the study. Figures 4 to 6 show the hierarchies and weights for classifying the spare parts of the case study. The production area has the highest number of criteria, and consequently lower relative weights, compared to the areas of maintenance and supplies. In this study, the AHP was used by the Rating model and the calculations were performed using the software (Super Decisions.Ink Software, 2013).

The criticality of each material in the sectors is calculated by the bottom-up process based on (Stoll *et al*., 2015). The calculations are performed in two levels. The first level is defined by the criteria, and the second by the weights of the classification openings. The areas of production, maintenance and supply represent the general objective, that is, the assessment of the criticality of each area. The global priority ($P_{h,i}^{g}$) of category based on the criterion is computed by multiplying the weights of the rating categorywith the weight of the criterion , stated in the equation . The sum of global priorities ($P_{h,i}^{g}$) at the hierarchy levels, which consists of several criteria , resulting in the general priority (P_{h}^{t}) of spare parts of production, maintenance, and supply categories, according to the equation $P_{h}^{t} = \sum_i P_{h,i}^{g}$ (Stoll *et al*., 2015). An example is shown in Table 8 for items X1, X2, X3, and X4 in the maintenance sector.In the example, item X1 is the most relevant among the four materials, and spare part X3 is the least relevant in the analysis of the maintenance sector. Material X4 represents one of several classification possibilities when the material has different classifications in each criterion. The proposed model allows quantifying the criticality difference between the materials.

Table 1. Classification methods for stocked materials

	Number of criteria	Main method used	Real case study	Field	In Spare Parts
(Flores and Clay Whybark, 1986)	02	Bi-criteria matrix	Yes	Manufacturing company	Yes
(Duchessi *et al*., 1988)	04	Bi-criteria matrix	No	None	Yes
(Ernst and Cohen, 1991)	04	Operations Related Groups	Yes	Automotive company	No
(Flores *et al*., 1992)	04	AHP	No	Hospital	No
(Partovi and Burton, 1993)	07	AHP, ABC, VED	Yes	Pharmaceutical company	Yes
(Gajpal *et al*., 1994)	03	AHP and VED	Yes	Manufacturing company	Yes
(Botter and Fortuin, 2000)	06	VED and Decision support	Yes	Electronic devices	Yes
(Partovi and Anandarajan, 2002)	04	Artificial Neural Network	Yes	Pharmaceutical company	Yes
(Altay Guvenir and Erel, 1996)	05	Genetic Algorithms	Yes	University inventory	Yes
(Suryadi, 2003)	09	AHP and cut-off point	No	None	No
(Braglia *et al*., 2004)	22	AHP	Yes	Paper industry	Yes
(Ramanathan, 2006)	04	R-model	No	Hospital	No
(Bhattacharya *et al*., 2007)	05	TOPSIS	Yes	Pharmaceutical company	No
(Suryadi, 2007)	08	AHP and NON-AHP	No	Manufacturing company	Yes
(Ng, 2007)	03	Ng-model	No	Hospital	No
(Zhou and Fan, 2007)	05	ZF-model	No	Hospital	No
(Cakir and Canbolat, 2008)	05	Fuzzy AHP	Yes	Energy company	No
(Cavalieri *et al*., 2008)	04	AHP and VED	Yes	Heavy Industries	Yes
(Çelebi *et al*., 2008)	06	Ng-model revision	No	Light rail system	Yes
(Chu *et al*., 2008)	06	Fuzzy Classification	Yes	Keelung Port	Yes
(Chen *et al*., 2008b)	04	Case-based distance	No	Hospital	No
(Chen *et al*., 2008a)	04	DRSA	No	Hospital	No
(Jamshidi and Jain, 2008)	02	Exponential Smoothing Weights	No	Hospital	No
(Tsai and Yeh, 2008)	03	Multiple objective particle swarm optimization	Yes	Printed circuit board manufacturer	Yes
(Bosnjakovic, 2010)	11	ABC, VED, FSN	No	None	Yes
(Çebi *et al*., 2010)	06	Fuzzy AHP	Yes	Distributor company	No
(Hadi-Vencheh, 2010)	03	Extended Ng-model	No	Hospital	No
(Rezaei and Dowlatshahi, 2010)	04	Fuzzy logic	Yes	Food Manufacturing company	Yes
(Wong, 2010)	04	AHP	Yes	Semiconductor Firm	Yes
(Hadi-Vencheh and Mohamadghasemi, 2011)	03	Fussy AHP-DEA	Yes	Soft-drink production line	No
(Yu, 2011)	04	Artificial Intelligence	No	Hospital	No
(Chen, 2012)	04	TOPSIS	No	Hospital	No
(Kabir and Hasin, 2012)	06	Fuzzy AHP	No	None	No
(Mohammaditabar *et al*., 2012)	03	Simulated annealing (SA)	No	Hospital	No
(Molenaers *et al*., 2012)	07	AHP and VED	Yes	Petrochemical plant	Yes
(Torabi *et al*., 2012)	04	Modified DEA	No	Hospital	No
(Zeng *et al*., 2012)	10	AHP, fuzzy comprehensive evaluation and GRA	Yes	Power plant	Yes
(Keskin and Ozkan, 2013)	04	Fuzzy c-means	No	Automotive company	None
(Kabir and Hasin, 2013)	05	Fuzzy AHP and ANN	No	Energy company	No
(Hatefi *et al*., 2014)	04	Linear optimization	No	Hospital	No
(Lolli *et al*., 2014)	04	AHP and K-means algorithm	Yes	Engineering firm and hospital	None
(Park *et al*., 2014)	03	CE-WLO	No	Hospital	No
(Soylu and Akyol, 2014)	03	UTADIS	No	Hospital	No
(Stoll *et al*., 2015)	06	AHP and VED	Yes	Automotive company	Yes
(Liu *et al*., 2016)	04	Clustering Analysis and SA	Yes	Sports apparatus manufacturer	No
(Ladhari *et al*., 2016)	03	Hybrid weighted linear optimization	No	Hospital	No
(Hu *et al*., 2017)	04	DRSA	Yes	Manufacturing company	Yes
(Muniz *et al*., 2020)	14	AHP, VED	Yes	Mining company	Yes
This paper	14	AHP, XYZ, ABCDE and Kraljič Matrix.	Yes	Mining company	Yes

Table 2. Criteria

Criteria	Applied by	Times cited
Lead time	(Altay Guvenir and Erel, 1996; Bhattacharya *et al*., 2007; Bosnjakovic, 2010; Braglia *et al*., 2004; Cakir and Canbolat, 2008; Cavalieri *et al*., 2008; Çebi *et al*., 2010; Çelebi *et al*., 2008; Chen *et al*., 2008a, 2008b; Chu *et al*., 2008; Duchessi *et al*., 1988; Ernst and Cohen, 1991; Flores *et al*., 1992; Gajpal *et al*., 1994; Hadi-Vencheh and Mohamadghasemi, 2011; Hatefi *et al*., 2014; Hu *et al*., 2017; Keskin and Ozkan, 2013; Ladhari *et al*., 2016; Liu *et al*., 2016; Lolli *et al*., 2014; Mohammaditabar *et al*., 2012; Molenaers *et al*., 2012; Muniz *et al*., 2020; Ng, 2007; Park *et al*., 2014; Partovi and Anandarajan, 2002; Partovi and Burton, 1993; Ramanathan, 2006; Soylu and Akyol, 2014; Stoll *et al*., 2015; Suryadi, 2007, 2003; Torabi *et al*., 2012; Yu, 2011; Zeng *et al*., 2012; Zhou and Fan, 2007)	41
Price	(Bhattacharya *et al*., 2007; Bosnjakovic, 2010; Botter and Fortuin, 2000; Braglia *et al*., 2004; Cakir and Canbolat, 2008; Cavalieri *et al*., 2008; Çebi *et al*., 2010; Çelebi *et al*., 2008; Chen, 2012; Chen *et al*., 2008b, 2008a; Chu *et al*., 2008; Ernst and Cohen, 1991; Flores *et al*., 1992; Hadi-Vencheh, 2010; Hatefi *et al*., 2014; Hu *et al*., 2017; Kabir and Hasin, 2012, 2013; Keskin and Ozkan, 2013; Liu *et al*., 2016; Lolli *et al*., 2014; Muniz *et al*., 2020; Ng, 2007; Park *et al*., 2014; Partovi and Anandarajan, 2002; Partovi and Burton, 1993; Ramanathan, 2006; Soylu and Akyol, 2014; Suryadi, 2007; Torabi *et al*., 2012; Wong, 2010; Yu, 2011; Zhou and Fan, 2007)	35
Usage value	(Braglia *et al*., 2004; Çelebi *et al*., 2008; Chen, 2012; Chen *et al*., 2008b, 2008a; Duchessi *et al*., 1988; Flores *et al*., 1992; Hadi-Vencheh, 2010; Hadi-Vencheh and Mohamadghasemi, 2011; Hatefi *et al*., 2014; Hu *et al*., 2017; Keskin and Ozkan, 2013; Ladhari *et al*., 2016; Liu *et al*., 2016; Lolli *et al*., 2014; Mohammaditabar *et al*., 2012; Molenaers *et al*., 2012; Park *et al*., 2014; Ramanathan, 2006; Soylu and Akyol, 2014; Torabi *et al*., 2012; Tsai and Yeh, 2008; Yu, 2011; Zhou and Fan, 2007)	26
Demand rate	(Altay Guvenir and Erel, 1996; Bhattacharya *et al*., 2007; Botter and Fortuin, 2000; Braglia *et al*., 2004; Cakir and Canbolat, 2008; Çebi *et al*., 2010; Çelebi *et al*., 2008; Chu *et al*., 2008; Kabir and Hasin, 2012, 2013; Ng, 2007; Partovi and Anandarajan, 2002; Partovi and Burton, 1993; Rezaei and Dowlatshahi, 2010; Tsai and Yeh, 2008; Wong, 2010; Zhou and Fan, 2007)	17
Criticality of the function to be performed	(Chen, 2012; Chen *et al*., 2008b, 2008a; Chu *et al*., 2008; Flores *et al*., 1992; Kabir and Hasin, 2012, 2013; Keskin and Ozkan, 2013; Mohammaditabar *et al*., 2012; Muniz *et al*., 2020; Rezaei and Dowlatshahi, 2010; Torabi *et al*., 2012; Yu, 2011)	17
Stock-out cost	(Braglia *et al*., 2004; Cakir and Canbolat, 2008; Cavalieri *et al*., 2008; Çelebi *et al*., 2008; Duchessi *et al*., 1988; Ernst and Cohen, 1991; Flores and Clay Whybark, 1986; Gajpal *et al*., 1994; Jamshidi and Jain, 2008; Molenaers *et al*., 2012; Partovi and Burton, 1993; Ramanathan, 2006; Wong, 2010; Zhou and Fan, 2007)	14
Equipment availability	(Bosnjakovic, 2010; Botter and Fortuin, 2000; Chu *et al*., 2008; Hidayat and Suryadi, 2007; Muniz *et al*., 2020; Stoll *et al*., 2015; Zeng *et al*., 2012)	07
Spare parts reliability	(Braglia *et al*., 2004; Duchessi *et al*., 1988; Jamshidi and Jain, 2008; Molenaers *et al*., 2012; Muniz *et al*., 2020; Stoll *et al*., 2015; Suryadi, 2003; Zeng *et al*., 2012)	08
Tailor-made aspect	(Braglia *et al*., 2004; Cavalieri *et al*., 2008; Gajpal *et al*., 1994; Muniz *et al*., 2020; Partovi and Burton, 1993; Suryadi, 2003; Wong, 2010; Zeng *et al*., 2012)	08
Number of potential suppliers	(Bosnjakovic, 2010; Braglia *et al*., 2004; Kabir and Hasin, 2012; Molenaers *et al*., 2012; Muniz *et al*., 2020; Suryadi, 2007, 2003; Zeng *et al*., 2012)	08
Demand predictability	(Braglia *et al*., 2004; Çelebi *et al*., 2008; Ernst and Cohen, 1991; Molenaers *et al*., 2012; Zeng *et al*., 2012)	05
Durability	(Kabir and Hasin, 2012, 2013; Rezaei and Dowlatshahi, 2010; Suryadi, 2007, 2003)	05
Obsolescence rate	(Braglia *et al*., 2004; Molenaers *et al*., 2012; Partovi and Burton, 1993; Zeng *et al*., 2012)	04
Turnover rate	(Botter and Fortuin, 2000; Liu *et al*., 2016; Suryadi, 2003; Tsai and Yeh, 2008)	04
Shift plan	(Braglia *et al*., 2004; Muniz *et al*., 2020; Stoll *et al*., 2015; Zeng *et al*., 2012)	04
Storage space	(Bosnjakovic, 2010; Braglia *et al*., 2004; Hadi-Vencheh and Mohamadghasemi, 2011)	03
Ensuring safety	(Muniz *et al*., 2020; Suryadi, 2007, 2003)	03
Loss of product quality	(Bosnjakovic, 2010; Braglia *et al*., 2004; Muniz *et al*., 2020)	03
Internal safety and environmental damage	(Bosnjakovic, 2010; Braglia *et al*., 2004; Muniz *et al*., 2020)	03
Production failure (downtime)	(Bosnjakovic, 2010; Braglia *et al*., 2004; Muniz *et al*., 2020)	03
Ordering cost	(Partovi and Anandarajan, 2002; Partovi and Burton, 1993)	02
Interchangeable parts	(Altay Guvenir and Erel, 1996; Çebi *et al*., 2010)	02
Replaceability	(Altay Guvenir and Erel, 1996; Çebi *et al*., 2010)	02
Last use date	(Kabir and Hasin, 2012, 2013)	02
Domino effect	(Bosnjakovic, 2010; Braglia *et al*., 2004)	02
External safety and environmental	(Bosnjakovic, 2010; Braglia *et al*., 2004)	02
Installed population of the same material	(Braglia *et al*., 2004; Cakir and Canbolat, 2008)	02
Deterioration problems	(Bosnjakovic, 2010; Braglia *et al*., 2004)	02
Possibility of the internal maintenance	(Botter and Fortuin, 2000; Braglia *et al*., 2004)	02
Lifecycle stage	(Suryadi, 2003; Zeng *et al*., 2012)	02
Trading time	(Botter and Fortuin, 2000; Muniz *et al*., 2020)	02
Machine priority	(Muniz *et al*., 2020; Stoll *et al*., 2015)	02

Continue ….

Perishability	(Bhattacharya *et al*., 2007)	01
Storage cost	(Bhattacharya *et al*., 2007)	01
Payment terms	(Çebi *et al*., 2010)	01
Current item status	(Chu *et al*., 2008)	01
Expiration date	(Suryadi, 2007)	01
Masked time	(Braglia *et al*., 2004)	01
Cannibalism	(Braglia *et al*., 2004)	01
Standard parts	(Zeng *et al*., 2012)	01
Installations time	(Stoll *et al*., 2015)	01
Consumable	(Suryadi, 2003)	01
Maintenance cost	(Suryadi, 2007)	01

Table 03. Steps of the proposed approach

Steps	I – Criteria selection	II – Criteria categories	III - Hierarchy and weights	IV – Classification model
Methods	cut-off point	XYZ, ABCDE, and Kraljič Matrix	AHP and bottom-up process	Developed model

Table 4. List of criticality criteria

Department	Criticality criteria
Production	Internal safety and environmental
	Ensuring safety
	Production failed (downtime)
	Equipment availability
	Loss of product quality
	Criticality of the function to be performed
	Shift plan
Maintenance	Machine priority
	Tailor-made aspect
	Spare parts reliability
Supply	Trading time
	Lead time
	Price
	Number of potential suppliers

Table 5. Summary of ratings used in the company

Sector	Classification openings		
Production	X	Y	Z
Maintenance	A	BC	DE
Supply	Strategic (S)	Leverage and bottleneck (LB)	Non-critical (NC)

Table 6. Criticality criteria and classification (Muniz *et al*., 2020)

Maintenance	Spare parts reliability	Tailor-made aspect	Machine priority
Spare parts reliability	1	3	7
Tailor-made aspect	1/3	1	1/3
Machine priority	1/7	3	1
Relative weights	0.67	0.24	0.09

Table 7. Consistency ratios (Muniz *et al*., 2020)

Comparison level	Consistency ratio
Production criteria	0.03042
Maintenance criteria	0.00675
Supply criteria	0.01629
Classification categories	0.00000

Table 8. Detailed global priority calculation

Item	Class	Criteria	Category weight (v^h)	Criteria weight (v^i)	$P^g_{h,i}$	P^t_h
X1	A	Spare parts reliability	0.57	0.67	0.382	0.570
	A	Machine priority	0.57	0.24	0.137	
	A	Tailor made aspect	0.57	0.09	0.051	
X2	BC	Spare parts reliability	0.29	0.67	0.194	0.290
	BC	Machine priority	0.29	0.24	0.070	
	BC	Tailor made aspect	0.29	0.09	0.026	
X3	DE	Spare parts reliability	0.14	0.67	0.094	0.141
	DE	Machine priority	0.14	0.24	0.034	
	DE	Tailor made aspect	0.14	0.09	0.013	
X4	BC	Spare parts reliability	0.29	0.67	0.194	0.243
	DE	Machine priority	0.14	0.24	0.034	
	A	Tailor made aspect	0.57	0.09	0.015	

Table 9 – Classification bands and acronyms

Sectors	Class 2	Class 1
	$0{,}14 \leq P_h^t \leq 0{,}36$	$0{,}36 < P_h^t \leq 0{,}57$
Production	P2	P1
Maintenance	M2	M1
Supply	S2	S1

Table 10. Segments and management methods

Class	Priority	Management method
P1M1S1	High	Forecast model, replenishment point, and safety stock
P1M1S2	Medium	Forecast model and replenishment point
P1M2S1	Medium	Forecast model and replenishment point
P2M1S1	Medium	Forecast model and replenishment point
P2M2S1	Low	Minimum quantity
P2M1S2	Low	Minimum quantity
P1M2S2	Low	Minimum quantity
P2M2S2	Null	Zero stock

Table 11. Comparison between the proposed method and the XYZ classification

Production	Class 2	Class 1	Total
Proposed method	39,917	85	40,002
X	38,426	0	40,002
Y	1491	82	
Z	0	03	

Table 12. Comparison between the proposed method and the ABCDE classification

Maintenance	Class 2	Class 1	Total
Proposed method	39,331	671	40,002
A	3,111	669	40,002
B	2,411	2	
C	2,198	0	
D	974	0	
E	30,637	0	

Table 13 .Comparison between the proposed method and the ABC classification

Supply	Class 2	Class 1	Total
Proposed method	39,331	671	40,002
S	463	69	40,002
LB	813	75	
NC	38,055	527	

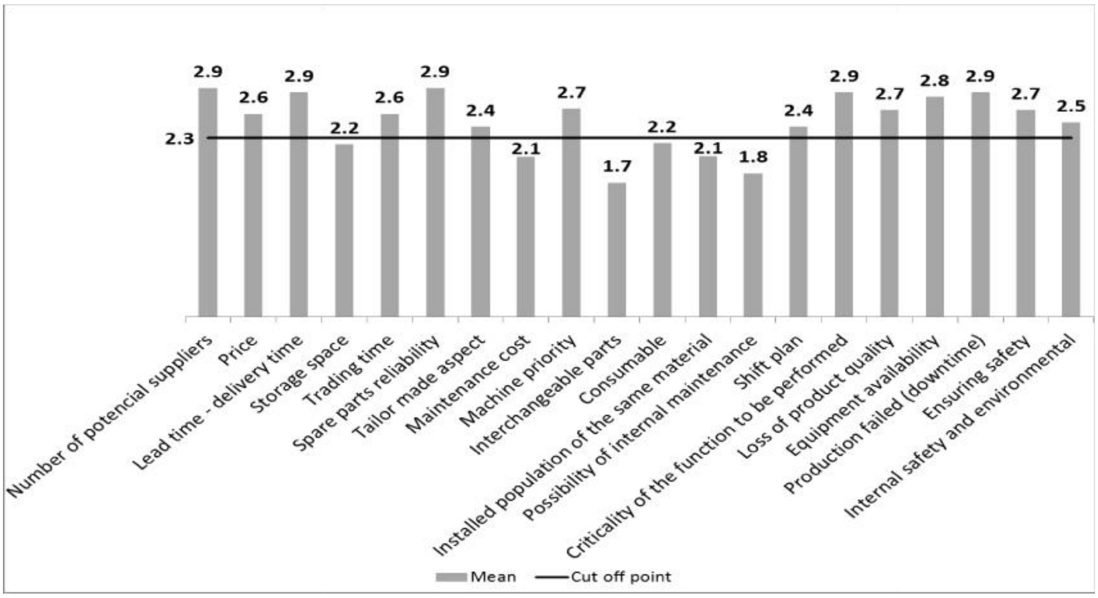

Figure 2. Selection of relevant criteria, adapted from (Muniz et al., 2020)

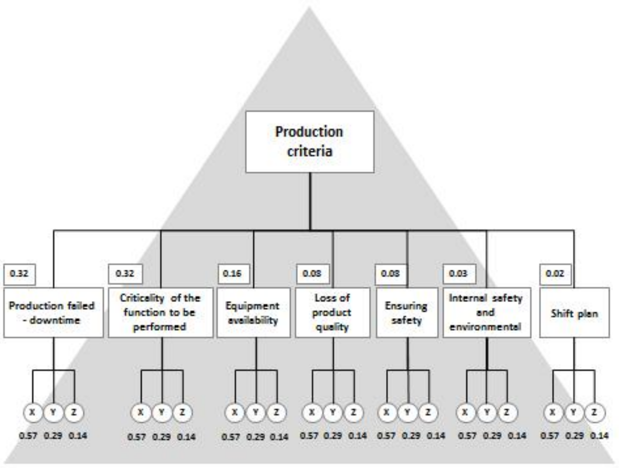

Figure 4. Hierarchy and weights (a), adapted from (Muniz et al., 2020)

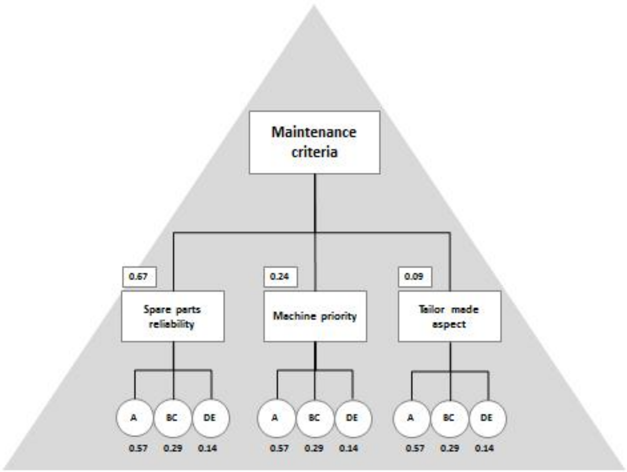

Figure 5. Hierarchy and weights (b), adapted from (Muniz et al., 2020)

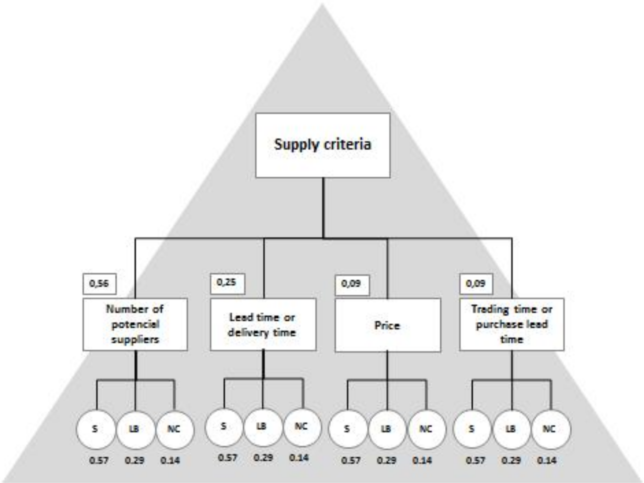

Figure 6 – Hierarchy and weights (c), adapted from (Muniz et al., 2020)

Classification model: A spare parts classification is useful for determining service requirements and inventory control decisions (Bacchetti and Saccani, 2012). In the current state of science, spare parts are divided into individual classes using different criteria from which stock strategies are derived (Stoll *et al*., 2015). This approach can be observed in the work of (Bosnjakovic, 2010; Botter and Fortuin, 2000; Molenaers *et al*., 2012; Stoll *et al*., 2015).

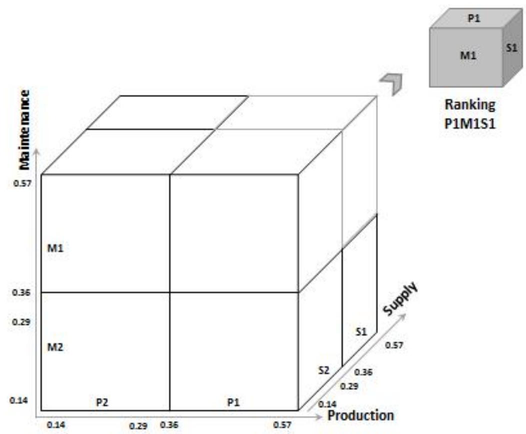

Figure 7. Classification model

The proposed model is based on the integrated classification approach as in (Bosnjakovic, 2010; Botter and Fortuin, 2000; Molenaers *et al*., 2012; Stoll *et al*., 2015) that represents the management model formed by axes as in Figure 7. The model developed in these works is strongly based on criteria. In the study of (Botter and Fortuin, 2000) the axes of the integrated classification are Price, Response Time, and Consumption; in (Bosnjakovic, 2010) the axes are Criticality, Frequency, and Value Usage; (Molenaers *et al*., 2012) uses the Probability of failure, Equipment criticality, and logistics characteristics axes; already in (Stoll *et al*., 2015) Criticality, Item Value and Predictability are adopted. To (Botter and Fortuin, 2000) the number of segments is arbitrary and the use of eight segments is manageable, in the work of (Bosnjakovic, 2010; Molenaers *et al*., 2012; Stoll *et al*., 2015) several segments are perceived with the same management, which makes twenty-seven segments unnecessary. In this work, the integrated classification model has the axes being represented by the criticality assessment of each area, that is, the general objective of the bottom-up with two segments as done by (Botter and Fortuin, 2000).

The classification axes are divided into two ranges by the midpoint between the highest and lowest axis value, Class 1 between 0.36 and 0.57 being more critical and Class 2 between 0.14 and 0.36 less critical, for nomenclature criticality is preceded by the initial letter of the sector, thus we have P1 and P2, M1 and M2, S1 and S2 according to Table 9. The combination of classes generates the integrated classification, so the most relevant items are the spare parts contained in cube P1M1S1, highlighted in Figure 7, the items of less relevance are found in cube P2M2S2. The integrated classification approach has eight segments distributed in priority: High, being the most important for the organization; Average, with relative significance; Low, where less control is applied; and Null, for non-stocked components.

The management methods defined for each segment are shown in Table 10. (Bosnjakovic, 2010) presents three basic spare parts management policies: without stock, one piece in stock, and more pieces in stock. These policies were the basis of the forms of management proposed in this work together with the management models proposed by (Botter and Fortuin, 2000; Molenaers *et al*., 2012; Stoll *et al*., 2015). The zero inventory management method represents items that are purchased after demand, without stock. The second method represents items that keep a minimum number of parts in stock to perform maintenance and the purchase is made after the consumption of these items, similar to one piece in stock. Finally, the method applied for the majority of parts in stock used forecasting models, replenishment points, with or without safety stock. Items with a forecast model are managed every week, those with a minimum quantity after consumption of the stocked materials, and those with zero stock after internal user's request. The details of the management models are not detailed due to confidentiality issues of the case study company.

Model results: The model was implemented in a database of 40,002 items from a large Brazilian mining company. The company stores the materials in a single location within its facilities. The analysis will be carried out with the comparison between the main classification parameter of the Production, Maintenance, and Supplies sectors used by the organization concerning the values obtained in the proposed method. This study assists in the management of spare parts and presents a new approach based on the sectors involved with the spare parts, and not only on criteria. Table 11 shows the comparison between the classification model of the production sector and the proposed method. There is a consistency between the methods since all items Z are in Class 1 and all items X in Class 2 and items Y present in both classes.

The comparison between the proposed method and the ABCDE is shown in Table 12. The 3,111 items that in the current classification of the organization are considered A are noteworthy and appear in Class 2 and the 2 items in Class 1 that in the organization's classification appear as B. All other items C, D, and E are classified in Class 2 because they are less relevant. It can be seen that the current complex classification system has been simplified and has become more suitable for the classification of spare parts using more objective and defined criteria. Allowing a better management effort in 671 items. Table 13 shows the comparison between the proposed method and the Kraljič matrix used by the supply sector. It is noticed that there are items classified in Class 1 of all dimensions of the Kraljič matrix, highlighting the 527 items classified as NC. These items represent the materials that have different characteristics from the current classification group in the company and require different management. For these materials, the current classification system is inadequate, it is worth mentioning that they represent a small part of the total of analyzed items. In general, the classification of maintenance and supplies has few items in Class 1, but a much larger amount compared to the production sector. There is a significant reduction in items that require more detailed management. Items classified as A in maintenance totaled 3,780 and in the proposed method are only 671 in Class 1, in production the classifications Y and Z totaled 1,576 and in the proposed method are 671, in the supply sector items S and LB were 1,276 and in the method proposed are 671.

Conclusions and future research

The method was successfully implemented in a database of 40,002 items from a large Brazilian mining company stored in a single location within the facilities. The methodology must be maintained with a constant update of the model parameters. The criteria and sub-criteria used and their openings can be revised whenever the organization deems necessary. The scope of research for spare parts management is very broad. The main theoretical implication of this work is the classification based on the sectors involved in the management of materials and not on criteria without the need for historical data and applied in a real case study of the mineral sector. The method highlights the use of cut-off point methods, classification openings, AHP, and Bottom-up that allow the quantification of the criticality of the pieces.

The approach answers the theoretical question presented in (Lolli *et al*., 2014) how should spare parts category clusters be built? This study presented a relevant bibliographic review on spare parts, characterized the state of the art, and closed gaps in academic studies and practical applications. It generated scientific contributions as a case study developed on spare parts of the mineral industry, helping in the gap of classification models tested in empirical data. Details of the procedure for choosing and selecting criteria and sub-criteria based on the literature applicable to iron ore mining companies. It shows that classifications used separately present divergences when compared to a consolidated approach. As future work, it is suggested the application of the same method in other sectors or comparative studies in other mining companies. The AHP and Bottom-up method can be expanded to one more level so that a single criticality value is obtained by consolidating the production, maintenance, and supply sectors to allow the assessment of price and criticality in material management. It is suggested that the criteria classification be opened in a more objective way to avoid the use of several methods, one should pay attention to the availability of data to avoid the impossibility of classification. Subsequently, optimization could be applied to decide whether to store an item or not, as well as to define the parts to be purchased after demand forecasts.

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