A review of multi-criteria classification of spare parts

From literature analysis to industrial evidences

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Abstract

Purpose – Spare parts management plays a relevant role for equipment-intensive companies. An important step of such process is the spare parts classification, enabling properly managing different items by taking into account their peculiarities. The purpose of this paper is to review the state of the art of classification of spare parts for manufacturing equipment by presenting an extensive literature analysis followed by an industrial assessment, with the final aim to identify eventual discrepancies.

Design/methodology/approach – Not only is the attention put on the literature about the subject, but also on an on-field analysis, that is presented comprehending an extensive survey and two in-depth exploratory case studies. The copper mining sector was chosen being representative for the case of capital intensive plants where the cost of maintenance has relevant weight on the total operating cost.

Findings – The paper highlights the status of the scientific literature on spare parts classification by showing the current situation in the real industrial world. The paper depicts the existing barriers that leave gaps between theory and real practice for the application of an effective multi-criteria spare parts classification.

Originality/value – The paper provides a review of the theory on spare parts classification methods and criteria, as well as empirical evidences especially for what concern current situation and barriers for an effective implementation in the industrial environment. The paper should be of interest to both academics and practitioners, since it provides original insights on the discrepancies between scientific and industrial world.

Keywords Maintenance, Spare parts, Classification criteria, Classification methods, Mining sector, Multi-criteria perspective

Paper type Research paper

1. Introduction

Equipment-intensive organizations are often challenged due to the requirements for high system availability. Spare parts are an important resource to this end.

The research work has been developed within the context of iMaPla (Integrated Maintenance Planning), an EU-sponsored project by the Marie Curie Action for International Research Staff Exchange Scheme (project acronym PIRSES-GA-2008-230814 – iMaPla).

Received 21 April 2013
Revised 1 October 2013
23 January 2014
Accepted 27 January 2014

One of the main problems is that the unavailability of a spare part can lead to long unproductive downtimes of the equipment with direct consequences on the company's profit (Sarker and Haque, 2000). Conversely, maintaining high inventories of spare parts ties up capital and often results in relevant costs and consuming a significant portion of capital investments. This makes the management of spare parts a critical issue that is worth studying carefully.

In many organizations in the manufacturing, services and defence sectors, there are opportunities for cost savings by engaging in a more efficient management of spare parts inventories, and the trend is that such issue is likely to become even more critical in the future (Díaz and Fu, 1997). As stated in the more recent work by Bacchetti and Saccani (2012), a major problem talking about spare parts stands in the paucity of research with an integrated perspective with regard to classification, demand management/forecasting, inventory management models and performance measurement. They conclude that the adoption of an integrated view is one of the main aspects affecting the overall effectiveness of spare parts management in companies. The management process can be organized in different steps, as it can be derived according to Cavalieri *et al.* (2008) into: identification of spare parts, through part coding and classification; forecasting of spare parts requirements (i.e. demand volume and pattern); identification and development of the stock management system, with the formulation of the inventory control policies and systems; implementation in a computerized maintenance management system, for spare parts information processing and inventory control systems' operation; and policy testing for continuous performance improvement.

This paper aims at focusing on spare parts classification as a relevant step for driving the whole management process. Many advantages can be achieved by proper classification, e.g. an organization may align the stock management system with the criticality of the spare parts (Macchi *et al.*, 2011); demand forecasting may be driven by part data collected for different classes and performance improvement may concern critical classes, easing the work of the analyst when concentrating on tests of currently running inventory control policies.

The paper presents an extensive review of the state of the art of spare parts classification. The literature analysis outcomes are presented and they are compared with the results coming from an empirical assessment, which is implemented with a survey and two exploratory case studies. Keeping both scientific and industrial focus, this research aims at answering two questions: "what kind of approaches for spare parts classification is currently proposed by literature?" and "which are the current industrial needs and barriers for spare parts classification?". To this end, literature investigation on spare parts has been implemented independently of specific industrial sectors. The focus was put on publications that keep the plant/equipment owners' point of view; even if other perspectives are discussed in the literature (i.e. after sales services). Regarding the empirical assessment, the authors decided to keep the focus on the Chilean copper mining sector before further extensions to other industries. The objective of this work is to reveal the existent discrepancies between literature and real industrial practice, and the preferred path chosen to this end considers the capital intensive industry as the initial focus, because of the relevant costs of spare parts with respect to the total cost of maintenance operations.

The specific choice to study the mining sector, while not other capital intensive industries, is fundamentally due to the fact that it is a sector where the annual cost of maintenance as a fraction of the total operating budget can be estimated between 40 and 50 per cent (Murthy *et al.*, 2002) and this is supposed to drive to high level of attention for maintenance optimization in general. This justifies the consideration of the sector as a good representative for advanced practices for what concern the spare parts management too. Further on, being the copper mining sector in Chile one of the pillars of the economy of the country (Lagos and Blanco, 2010); the focus has clearly been put on a top industry with high needs for continuity of operations. Hence, Chilean copper mining sector do represent a strong test-bed for the exploratory analysis. If such industry reveals discrepancies with the literature analysis outcomes, this would likely result in others industries.

The work is a further development of Roda *et al.* (2012) where a method for spare parts classification with a multi-criteria perspective was tested. The present paper provides more insights on the needs and barriers, identified thanks to industrial assessment of multi-perspective classification in general besides, literature review has been extended to cover more sources aiming at a general review of the state of the art on the topic.

The paper is organized as follows. After introducing the problem statement in the context of manufacturing industry (Section 2), the methodology and results from literature analysis are presented (Section 3). Then, empirical evidences from industry are gained through commenting the results of a survey and two case studies that are particularly useful for exploring the existing barriers with respect to what the scientific literature is recommending for use (Section 4). The conclusions in Section 5) provide final remarks on the present work and envisions the future needs for research to fulfil the requirements of practice, as elicited from the state of the art observed for scientific literature and real industry.

2. Problem statement

2.1 Spare parts peculiarities

The general function of spare parts inventories is to assist the maintenance staff in keeping equipment in an operating condition. Therefore, the policies that govern the spare parts inventories are different from those that govern other types of inventory such as raw material, work-in-process and finished goods inventories; this makes spare parts inherently specific to manage.

The conditions that make them different from production inventories are shown in the remainder as derived both from literature (Kennedy *et al.*, 2001; Cavalieri *et al.*, 2008) as well as from the direct experience of different auditing projects on spare parts management in the manufacturing industry:

- there is high uncertainty about when a part is required and also about the quantity of its requirement; indeed, part failures in the plant can be hardly predicted, particularly for new equipment and because of failures' dependencies;
- the number of spare parts is often too large making control tedious; for instance, in a medium scale engineering industry, it may be around 15,000;
- sourcing of spare parts is often limited to one or a few suppliers, causing constraints for the procurement lead time and the costs; or in the opposite case of multiple sourcing, the related risk of the variations of the quality of supplied materials can incur;
- obsolescence may be a problem; indeed, it is difficult to determine how many units of a spare part to stock for an obsolescent machine;

- high variety of spare parts' characteristics is normally observed; the rates of consumption for some parts are very high and for some others are very low; some parts are characterized by low purchasing costs, while others are characterized by high costs; eventually, procurement lead times are differentiated and may be high, especially in case of specific or on order parts; and
- the management process often lacks of information visibility; poor inventory data recordings in place, inefficient or ineffective ordering processes and inventory management hiding information in separated "silos" are only some typical reasons of scarce visibility.

2.2 Spare parts criticality

The parts classification is used in spare parts management as a step to focus on the most important items and facilitates the decision-making process (Syntetos *et al.*, 2009): classifying items allows making a so called criticality analysis to identify different classes of parts which will be managed differently, by adopting different control practices depending on the resulting criticality.

The criticality of a spare item is probably the first feature pronounced by practitioners. It is also clear that the term criticality can get different meanings based on the focus undertaken; critical items from a maintenance perspective are rather different compared to critical parts from a logistics or a financial point of view. Those parts for which their unavailability would result in severe consequences for the plant are perceived as important by maintenance managers but, from a logistics point of view, other parameters – like holding costs – are valuable issues for appropriateness of stocking policies for different parts classes and so on considering other perspectives. Although each of the parties cope with different goals, the link between them is crucial to solve the spare parts dilemma (Cavalieri *et al.*, 2008). Within this dilemma, one common issue is shared namely the function of holding spare parts in a stock is to support maintenance and ensure continuity of safe and reliable operations within the plant, not forgetting the need to control and optimize costs in the maintenance budget.

2.3 Multi-criteria classification of spare parts

The highly varied assortment of spare parts with their peculiarities (Section 2.1), and the diverse criticality perceptions by different functions (Section 2.2), make spare parts classification a crucial phase. Indeed, it is a main assumption of this work that spare parts classification is a fundamental step to enable further steps of decision making; literature suggests classification with a multi-criteria perspective to this end.

Interesting considerations are presented to this regard by Huiskonen (2001). He identifies two kinds of criticality: on the one hand, the criticality of a spare part is related to the consequences caused by the part failure in case a replacement is not readily available (process criticality); on the other hand, the possibilities to control the situation (control criticality) is related to lead times, availability of suppliers (one or more), predictability of failure, costs, type of materials (standard or specific parts), etc. To assess the criticality, spare parts classes should be created based on the use of several quantitative and qualitative criteria. A substantive number of such criteria is considered in the literature research works or used in practice. Some of them are summarized in Table I, grouped into four clusters.

Cluster	Criteria
Spare parts plant criticality	Quality problem Production loss (referred to as stock out cost when assuming an economic focus) Domino effect Environmental and safety aspects
Spare parts usage characteristics	Number of identical components in the plant Usage rate/usage value Frequency/probability of failure Demand volume/predictability Expiration date Redundancies
Spare parts inventory problems	Price Spaces required Turnover rate Obsolescence rate Deterioration problems
Spare parts supply characteristics	Lead time Number of potential suppliers Internal repair possibility/cost Substitution cost Masked time Cannibalism Standardization/standard parts (or, oppositely: specificity/specific parts can be used)

Source: (adapted from several literature references, especially Braglia *et al.* (2004))

Table I.
Criteria grouped in 4 thematic clusters

Both the literature analysis and the industrial assessment presented in the remainder of this paper will help identifying the most proper criteria to be considered when classifying spare parts and the methods to do it.

3. Literature analysis

3.1 Literature analysis methodology

The literature analysis has been implemented by an extensive research including papers from international journals, books and conference proceedings. Independently of the specific industrial sector, while keeping the perspective of plant/equipment owner, the main keywords for such investigation were: spare parts, spare parts classification, criticality criteria and classification criteria. Table II shows the literature sources and the number of papers taken into account from each of them. The review covers articles published from 1985 to 2012.

3.2 On the classification methods

Even if apparently part classification could seem an easily solvable problem, the discussion available in literature is a proof that there are more complications to be considered.

Traditionally, simple and straightforward procedures, such as quantitative ABC (Pareto like) and qualitative vital, essential and desirable (VED) analysis , have been the common “tools” used for part classification. ABC classification, forming three groups (A, B, C class), has been generally based on one criterion: for inventory items, often the annual dollar usage of the spare item (Partovi and Burton, 1993). ABC analysis on a

Source Title	*N* of papers
Applied Mathematical Modeling	1
California Journal of Operations Management	1
Computers & Industrial Engineering	2
Computers & Operations Research	1
Engineering Costs and Production Economics	1
European Journal of Operational Research	7
Expert Systems with Applications	1
Industrial Management & Data Systems	1
Journal of the Institution of Engineers (India)	1
International Journal of Fuzzy Systems	1
International Journal of Operations & Production Management	3
International Journal of Physical Distribution & Logistics Management	1
International Journal of Production Economics	6
Journal of Manufacturing Technology Management	2
Journal of Operations Management	2
Journal of Quality in Maintenance Engineering	2
Journal of the Operational Research Society	1
Omega	1
Production Planning & Control	1
Quaid-E-Awam University Research Journal of Engineering	1
Resources Policy	1
Tehnički vjesnik	1
Others (thesis, books extracts, conference proceedings)	9
Total	48

Table II.
List of sources analysed for the literature review and number of papers considered

single criterion is easy to use and serves well the inventory management of materials that are fairly homogenous in nature, differing from each other mainly by the unit price and demand volume. Therefore, ABC analysis has retained its popularity in directing control efforts without the need of item specific analysis (Flores and Whybark, 1985). For an application of ABC classification to spare parts, the works by Gelders and Van Looy (1978) and Tanwari *et al.* (2000) can be taken as references. However, as the variety of control characteristics of items increases, the one-dimensional ABC classification does not discriminate all the control requirements of different types of items (Huiskonen, 2001). Thus, it has been generally recognized that a "classical" ABC analysis may not be able to provide a good classification in practice (Guvenir and Erel, 1998; Partovi and Anandarajan, 2002; Celebi *et al.*, 2008).

Other commonly used "tools" are qualitative methods. The VED classification (Mukhopadhyay *et al.*, 2003) is a well-known qualitative method, based on the consultation with maintenance experts. According to their feedbacks, spare parts are classified as vital (V), essential (E) and desirable (D) items. Despite its apparent simplicity, structuring a VED analysis might be difficult, as its accomplishment may suffer from the subjective judgments of the users (Cavalieri *et al.*, 2008). As stated by Duchessi *et al.* (1988), standard methods for classifying spare parts usually require engineers, materials managers, quality control staff or other experts to evaluate subjectively the spare parts' importance. This may be acceptable because the evaluators are experienced; however, there may be a disagreement over a part's true importance. Therefore, a more rigorous method based on hard data is preferable.

More recently, the trend shows that researchers started to assess the necessity of considering factors that may be not easily measurable, either because of the difficulties to gather proper data or of the definition of the factor itself (see Table I for examples). Indeed, from the research discussion it has resulted that a well-structured classification of spare parts cannot be based neither just on one single criterion nor just on qualitative judgments or only quantitative measures; the need for a multi-criteria perspective for classifying the spare parts started to be disclosed in literature.

The first proposal citing a bi-criteria approach in order to classify spare parts can be dated back to 1985: Flores and Whybark proposed a cross-tabulate matrix methodology for implementing the bi-criteria approach. Being the first reference, this work has stimulated later discussions on some disadvantages. For example, as underlined by Celebi *et al.* (2008) and Ng (2007), it becomes impractical to use for more than two criteria.

Shortly after, Duchessi *et al.* (1988) proposed a top-down methodology relevant for two reasons. First, the authors foresee the need of multi-criteria classification methods for spare parts: a matrix-model classification is proposed based on two criteria, i.e. inventory cost and criticality, defined by considering simultaneously downtime cost, lead time and number of failures per unit time. A second relevance of the paper is the perspective given to the integration between classification and spare part management, laying a conceptual groundwork for effective spares management programmes. Although the strong conceptual contribution, the proposed method results difficult to be applied in industrial reality.

Other proposals for multi-criteria classification can be found in Nagarur *et al.* (1994) and Porras and Dekker (2008), who propose a hierarchical two- or three-dimensional quali-quantitative classification. Further on, Ramanathan (2006) proposed the use of a weighted linear optimization model for implementing a multi-criteria ABC classification. The model presents some limits because a linear optimization is required for each item and the processing time can be very long when the number of items is large, in scale of thousands of items (Ng, 2007). Moreover, an extended scheme was presented by Zhou and Fan (2007) to solve another problem of Ramanathan's model: the fact that this model could lead to a situation where an item, assigned with a high value in an unimportant criterion, is inappropriately classified as a class A item. Ng (2007) tried to overcome the problem of using an optimization model to find weights for each criterion, by introducing an algorithm for a multi-criteria classification converting all the measures of an inventory item into a scalar score. Hadi-Vencheh (2010) extends the Ng's method by using a non-linear programming model to determine a common set of weights for all the spare items, before proceeding with ABC classification of the calculated scores. Although the method is simple to implement, it does present some limits in its application since it can only be used with continuous-type criterions. Liu (2006) followed the same approach to address ABC inventory classification proposing a reduced data envelopment approach using repeatedly a linear programming model and employing simulation example to verify the efficiency of the model. The model presents the same disadvantages about complexity of application if the number of spare parts is high as for the optimization models proposed by other authors.

Chu *et al.* (2008) proposed a new inventory control approach called ABC fuzzy classification, which can handle variables with either nominal or non-nominal (i.e. quantitative) attribute. Besides, several other meta-heuristics are proposed in the scientific literature for the multi-criteria inventory classification, such as genetic algorithms (Guvenir and Erel, 1998; Marseguerra *et al.*, 2005), artificial neural networks (Partovi and Anandarajan, 2002) and particle swarm optimization (Tsai and Yeh, 2008). Still, these methods present a very low applicability to real industrial cases.

Another method with a multi-criteria perspective by its true nature is the analytical hierarchy process (AHP). AHP was first introduced by Saaty (1988). Partovi and Burton (1993) were the first ones to propose the AHP as a tool to classify maintenance items. The following year Gajpal and Ganesh (1994) analysed how to apply the methodology for classifying spare parts by proposing an application of AHP with VED. Along the years AHP established itself over the scientific research as a flexible tool implementable to integrate qualitative aspects together with quantitative ones, as well as to assign weights to different criteria when their importance is not the same. Then, Sharaf and Helmy (2001) proposed another AHP application for spare parts classification and Cakir and Canbolat (2008) referred to it as a useful tool combined with the fuzzy logic for multi-criteria inventory classification. The latter proposed the fuzzy logic as a tool which enables to capture the uncertainty regarding the criteria evaluations. They use a prioritization procedure which does not require to construct the comparison matrices and derives the priority values directly from the judgment set via fuzzy optimization. Zeng *et al.* (2012) also proposed an algorithm integrated of AHP, fuzzy comprehensive evaluation and grey relational analysis: the algorithm is utilized in order to convert the qualitative description to quantitative data for spare parts to confirm their criticality classes under highly uncertain environment with limited data. AHP is also an essential tool used in Braglia *et al.*'s (2004) model. In his work he proposes a multi attribute spare part tree analysis (MASTA) for spare parts management to define the best strategies of spare inventories classification. This represents the first paper which explicitly relates the classification of spare parts and the decision about management policies to be implemented for different kinds of spares, assuming an integrated perspective. The MASTA method is referred to in Danas *et al.* (2006), where it is applied to the healthcare industry. Other contributions on AHP for spare parts classification are given by Wong (2010) and Molenaers *et al.* (2012).

Table III highlights advantages and drawbacks for most of the methods emerged by the extensive literature review.

In conclusion the current research is focused on the proposal of methods for multi-perspective classification with the purpose to consider both quantitative and qualitative criteria for spare part criticality analysis. It is clear that a common issue of spare parts classification with a multi-criteria perspective is the identification of the relative importance of criteria: a part classification method should comprise an algorithm/model/method/approach for deciding the relative weights/importance of the criteria. The proposals from literature to this end are often too complicated in practice (e.g. when fuzzy logic is adopted) or limited due to computational efforts (e.g. in the case of adoption of a linear optimization model): these limits have to be considered when implementing the part classification in industry.

3.3 On the criticality criteria

An important aspect for multi-criteria parts classification methods is the identification of which criteria to base them on.

It is a fact that there is no accordance in the research literature about which are the most proper criteria to be considered. Moreover, as also stated by Zeng *et al.* (2012), there is no evidence that systematic and well-structured procedures exist for evaluating criticality classes of spare parts: even if there are several papers in this field, the lack of systematic procedures leads to a limited focus on the choice of the best criteria representative of criticality.

Model	References	Advantages	Drawbacks
Classical ABC analysis (Pareto)	Partovi and Burton (1993), Tanwari *et al.* (2000)	Easy to use and understand	Based on just one single classification criteria
VED classification	Mukhopadhyay *et al.* (2003)	The classification reflects the importance given to each item by who manage them	Qualitative, high exposure to subjectivity
Bi-criteria approach	Flores and Whybark (1985), Duchessi *et al.* (1988)	Introduction of more than one criteria	Too much computational complexity if more than 2 criteria are considered/ difficult real applicability
Weighted linear optimization method	Ramanathan (2006), Zhou and Fan (2007)(rivisitation)	It allows implementing a multi-criteria classification giving different weights to each criterion	The processing time can be very long when the number of items is large
ABC classification based on a single overall score per item by skipping optimization (Ng model)	Ng (2007)	Simple to implement (no optimizer is needed)	When the number of criteria is large, it is not an easy task for decision maker to rank all criteria as it is requires
Ng model revision	Hadi-Vencheh (2010), Celebi *et al.* (2008)	Introduction of a nonlinear programming model to determine a common set of weights for all the items	Only applicable for continuous criteria measures
DEA (Data envelopment Approach)	Liu (2006)	Optimization method in order to overcome problems connected with subjective judgments	If the number of spare parts to classify is high, the computational complexity gets too high
ABC-fuzzy classication	Chu *et al.* (2008)	It allows considering nominal and non-nominal attributes	Difficult practical applicability
AHP-Analytic Hierarchy Process	Saaty (1988), Partovi and Burton (1993), Gajpal and Ganesh (1994), Sharaf and Helmy (2001), Braglia *et al.* (2004), Wong (2010), Molenaers *et al.* (2012)	Multi-criteria decision supporting method for calculating an overall criticality index for spare parts	It requires judgments to be expressed by a person
AHP- fuzzy method	Cakir and Canbolat (2008), Zeng *et al.* (2012)	Try to overcome subjectivity of AHP judgments by defining comparison ratios as fuzzy number	Difficult practical applicability
Genetic algorithms/ artificial neural networks/particle swarm optimization	Guvenir and Erel (1998), Marseguerra *et al.* (2005), Partovi and Anandarajan, (2002), Tsai and Yeh (2008)	Try to introduce a supporting persuasive analytical tool to take decisions	Very low applicability to real industrial cases and limited to research scopes

Table III.
Advantages and drawbacks of different classification methods

In order to widen the focus, an extensive literature analysis has been implemented. The purpose was to identify which are the most quoted criteria that allow the peculiarities of spare parts being evident. Given the lack of a common accepted theory, publications on spare parts have been selected regardless of the industrial sector to which they are referred to. This helped the investigation to be the more generic as possible, as a baseline for future investigations aiming at further in-depth analysis on industry related criteria. Moreover, some analysed papers do propose the classification criteria as their main contribution (e.g. Flores and Whybark, 1985; Gajpal and Ganesh, 1994; Zeng *et al.*, 2012); for some others, instead, classification criteria are defined only within examples of application of the proposed classification method (e.g. Ramanathan, 2006; Ng, 2007; Zhou and Fan, 2007).

The frequency of citation of different criteria has been taken as an indicator of the importance given by the scientific literature to each criterion. A set of 18 papers has been considered and Table IV shows which criteria they address to.

The most popular criteria, respectively, appearing in 15 and 14 works, relate to the stock out cost and the replenishment lead time of the items. Other popular criteria are: unit price of the items, its specificity (respectively, appearing in 13 and nine publications) and the demand volume (nine publications). Other referred criteria are the usage value and the predictability of demand. Other criteria, proposed by fewer studies, concern the part obsolescence rate and its life cycle stage/expiration date, the number of potential suppliers and the failure probability of the items.

A summary of the coverage obtained from the sample of 18 selected publications is shown in Figure 1. The percentages assigned for each criterion represents the number of papers citing it, out of a total of 18.

3.4 Concluding remarks on literature analysis

Given the investigation presented in the previous two sections, it is possible to list some remarks providing a synthesis of the literature analysis.

Regarding spare parts classification methods, the wide variety of approaches proposed in literature so far showed that in recent years researchers assessed more frequently the necessity of applying multi-criteria methods to take into account the peculiarities that do characterize spare parts items. Nonetheless, most of them reveal important limitations for what concern the computational complexity in a real industrial problem. Amongst the methods, many publications refer to the AHP as an easy to apply and efficient method for approaching multi-attribute spare parts classification considering the relative importance of criteria. The number of research works that use it suggests the strength of the AHP to be applied in order to classify spare parts and get a strong control of it. Exposure to uncertainty – due to many reasons, such as a poor inventory data recordings in place – and subjectivity – of different experts involved for part classification – are still an open issue for the AHP method.

Concerning the classification criteria, an investigation has been implemented to identify which are the most cited criteria in literature that are considered able to allow the peculiarities of spare parts being evident so to proceed with a proper classification process. The results show that the most cited criteria are: stock out cost, price, lead time, demand volume and specificity. Nonetheless, it is worth underlining that literature has partially discussed the criteria driving the spare parts classification: the 18 papers herein selected and analysed (Table IV) are a good but still limited sample resulting from more than two decades of publications.

Table IV.
Citation of criteria for part classification in scientific publications

	Price	Stock-out cost	Lead Time	Demand volume	Usage Value	Prob. of failure	No. of potential suppliers	Demand Predictability	Specificity	Obsolescence	Lifecycle stage	Others
Molenaers *et al.* (2012)		X	X			X	X	X				
Duchessi *et al.* (1988)		X	X		X	X						
Flores and Whybark (1985)		X			X							
Ernst and Cohen (1990)	X	X	X					X				
Petrović and Petrović (1992)	X	X		X					X			X
Partovi and Burton (1993)	X	X	X	X					X	X		
Gajpal and Ganesh (1994)		X	X						X			
Huiskonen (2001)	X	X						X	X			
Sharaf and Helmy (2001)	X		X		X				X		X	
Braglia *et al.* (2004)	X	X	X	X	X			X	X	X		X
Ramanathan (2006)	X	X	X	X								
Zhou and Fan (2007)	X	X	X	X								
Ng (2007)	X		X	X								
Cavalieri *et al.* (2008)	X	X	X						X			
Cakir and Canbolat (2008)	X	X	X	X								
Celebi *et al.* (2008)	X	X	X	X	X			X				
Wong (2010)	X	X		X					X			
Zeng *et al.* (2012)			X			X	X	X	X		X	X
Total number of papers	13	15	14	9	5	3	2	6	9	2	2	3

4. Empirical evidence from industry

4.1 Introduction

Following the literature analysis, an on field survey has been developed to achieve a more concrete understanding from the industrial perspective. Indeed, the objective in this part of the work is to understand the importance given to the spare parts management process as well as to the criteria needed to get a proper multi-criteria classification and the barriers faced in industry. The empirical assessment has been implemented both with a survey and with two exploratory case studies in the Chilean copper mining sector.

4.2 Survey methodology

The implemented survey aimed at analysing how the spare parts classification is currently approached in industry. The objective was to understand which classification method was used, if it had multi-criteria perspective, and which were the most commonly used criteria for spare parts classification.

The survey population is represented by asset-intensive firms and the study population is given by companies operating in the copper mining industry in Chile. The sample frame has been created using the available mining companies enlisted in databases from Chilean industry. A sample of 12 companies has been generated by random sampling strategy, applied on a subset of companies pre-selected based on a minimum threshold of production volumes and revenues. The target units for the survey were maintenance managers of manufacturing plants. Finally, the survey's target to which a questionnaire has been distributed is a group of 52 maintenance managers working in different plants of the companies in the sample.

Regarding the survey's implementation strategy, the focus was put on the design of an appropriate set of questions able to capture qualitative/quantitative information. In fact, some core investigation areas (like, e.g. judgments about the relative importance of different criteria) lay on qualitative judgments. For this reason the effort has been to create a semi-structured form for most of questions, thus allowing rapid, close questions and to give qualitative questions a semi-structured shape. The interviewed maintenance managers were asked to fulfil the questionnaire after a training workshop they were attending about spare parts management. The questionnaires were directly collected the same day and consequently to this approach a 100 per cent response rate was reached.

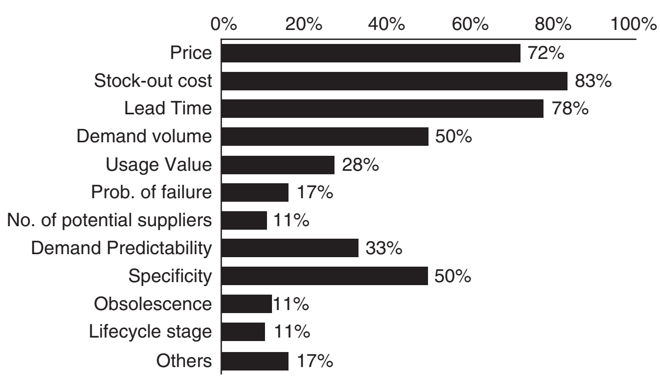

Figure 1.
Frequencies of citation of criteria for part classification in scientific publications

4.3 Survey results

The companies, to which the interviewed people belong to, are of big dimension with more than 1,500 spare parts items on stock. They all have a total or at least partial codification system for spare parts and in the 70 per cent of the cases also a classification method is used. Interestingly, according to the ones belonging to the rest 30 per cent, a classification process of spare parts would be convenient to get a better control of the inventory.

Referring to the above quoted 70 per cent of cases (companies that implement classification), only 17 per cent of them use a quantitative method based on two or more criteria while 31 per cent declares to use a quantitative ABC analysis based on a single criterion. The rest of the companies declared they use qualitative methods, either VED analysis or rules of thumb. Besides, it has to be specified that some of the companies using quantitative approach (ABC or multi-criteria) also declared they use qualitative approaches (VED, rules of thumb or both) jointly with it. On the whole, the VED analysis is adopted by 60 per cent of the cases in the sample and an empirical method following practical rules of thumb based on a kind of a priori knowledge of the expected behaviour of different types of items is adopted by 71 per cent. This result proves a gap between the scientific theory, which recognized the importance of multi-criteria classification methods, and the industrial practice: companies still lack a quantitative method to classify the spare parts inventories, and there is poor usage of multi-criteria classification methods. Figure 2 shows the obtained survey results.

The survey also inquired about the criticality criteria for spare parts classification. By restricting the analysis on those who answered that they have in their companies a multi-criteria method used even if partially (17 per cent out of 36 respondents), they were asked to specify which are the criteria currently used. The answers are shown in Figure 3: the percentages, shown for each criterion, express how many companies

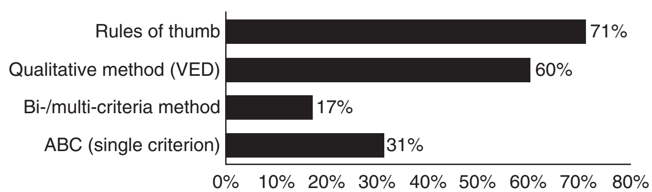

Figure 2.
Spare parts multi criteria classifications methods used in industry (survey's finding)

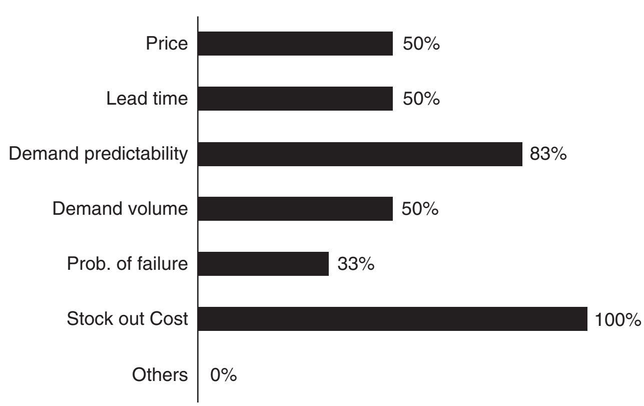

Figure 3.
Used criteria for spare parts classification in industry (survey's findings)

declared to use it. All in all, the practice provides an initial evidence on the most currently used criteria, which is aligned with literature analysis outcomes (Figure 1).

In addition all the interviewees were asked about their judgement of the relative importance of the wide set of criteria used. A ten-point scale was adopted to compare each criterion with respect to the others. The results have been summarized by taking the average of the votes given for each criterion, as provided by the base of respondents (see Figure 4).

Stock out cost and lead time are perceived as the criteria with the highest importance. This is well aligned with the evidences gained from literature analysis (Figure 1). We note that the price criterion has been rated lower despite the fact that the economic aspect is an obvious leading drivers in industry. It is possible that the respondents unconsciously took for granted the price of spare parts, thus not identifying it as an important criterion.

4.4 Exploratory case studies methodologies

Two exploratory case studies have been carried on with the purpose to obtain an assessment regarding spare parts classification practices as run in the industrial world, with a particular concern on the use of a multi-criteria perspective. The research questions for the case study analysis are focused on the way the multi-criteria method might be introduced in a company, hence they are so formulated: "which are the barriers that still exist in adopting a multi-criteria method for spare parts classification in industry? How can they be practically overcome?".

In order to answer to these questions the cases have been chosen to give an adequate coverage with respect to: the type of equipment for which the classification of its spare parts is needed and the level of experience in using a multi-criteria classification practice in the company. Given the context of production systems in the mining sector, case A involves the classification of spare parts for the trucks (i.e. dumpers) used for the transportation within the mine; on the contrary case B refers to fixed transport equipment in the plant of copper processing (i.e. a belt conveyor). No multi-criteria method is currently implemented in case A; instead, the usage of a multi-criteria method is already at some years of experience in case B.

In order to keep uniformity and comparability among the two cases, the same classification method has been used: the AHP has been chosen thanks to its flexibility of use. The aim is to try and implement the multi-criteria classification in each of

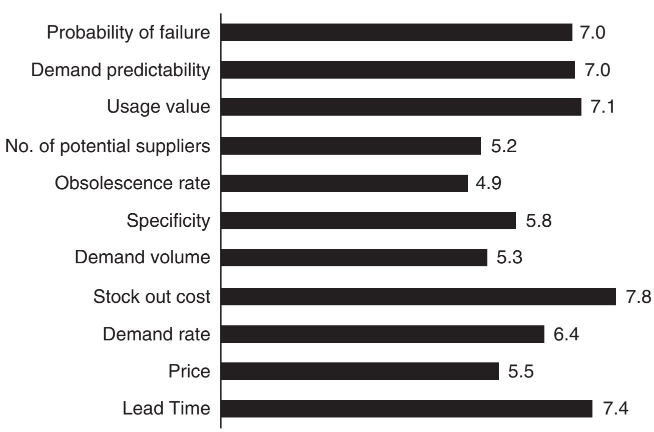

Figure 4.
Results of the industrial survey: scores measuring the importance given by practitioners to criteria for spare parts classification

the two cases keeping the perspective of bridging research and practice. For this reason, by comparing the results obtained by means of literature analysis and industrial survey (Figures 1 and 3), the following five criteria have been selected for both the two applications: lead time, price, turnover rate, stock out cost and specificity. The objective of the authors was to use the five selected criteria based on the comparative analysis made between the literature research results and the survey's results regarding classification criteria in both case studies. Hence, the feedbacks obtained from the case studies help deriving some issues concerning the implementation in industry of a spare parts classification method endowed with a multi-criteria perspective. To this end, the maintenance personnel, involved in carrying out the AHP classification method in the two cases, have been asked to answer few more questions in order to evaluate not only the results obtained after the AHP classification, but also the way the proposed method was applied. As a result, the main barriers which still exist have been depicted by considering two dimensions: efficiency and quality of the implementation referring to the data import process needed for each of the five criteria.

On the one hand, referring to the general meaning of the term "efficiency" the capability to produce the desired outcome (criteria evaluation) with a minimum quantity of unnecessary effort has been assessed. On the other hand, the "quality", as level of excellence of the implementation of the classification method, has also been assessed. The assessment was defined by asking opinions of each respondent involved in the cases development, based on a simple scale for "efficiency" and "quality" with three degrees, thus identifying which barrier exists between a "relevant", an "acceptable" or "no" barrier at all. The assessment is clearly dependent on the subjectivity of the respondents; nevertheless, their expertise in industrial environment (i.e. more than ten years of working age) and their independence of the previous phase of literature and industrial surveys can justify their feedbacks as valuables for the whole research.

4.5 Results of the exploratory case studies

In what follows the results of Cases A and B are presented separately.

Case A. Case A refers to a company whose business is dedicated to ore transport for different mining companies. The main activity of the company is the selling of equipment, maintenance and renewal (overhauls) of truck fleets; the case study refers to spare parts management in the context of maintenance and repair contracts (MARC[1]).

The analysis in the case study refers to the classification of the spare parts of a single equipment, a mechanical power-train haul truck specifically produced for high production mining. Its engine is a tandem unit consisting of two 12-cylinder engine blocks coupled in series to operate as a single engine for a total gross power of 3,400 hp. The focus of the study is on the components of its combustion system.

The main barriers have been identified so as it is indicated in Table V, classified according to the scale adopted for the assessment ("relevant" and "acceptable" barriers are indicated, while in the case of "no" barrier the table is left empty) and the judgement of the respondent.

Table V. Barriers found in the Quality and Efficiency dimensions – case study A

	Price	Lead Time	Turnover rate	Stock out cost	Specificity
Quality				Relevant	Acceptable
Efficiency	Relevant	Relevant	Relevant		

Quality and efficiency related problems, emerged during the case study, are discussed in the remainder.

Stock out cost is the criterion assessed with some relevant barriers preventing from reaching a high quality; specificity has also some barriers that can be better managed:

- A reliable estimate of the stock out cost, associated with running out of spare parts, has not been an easy task to solve, as the spares shortage may imply complex consequences in the whole production system, that are difficult to quantify in monetary terms. To overcome this barrier, the practical approach for the case study was to relate the stock out cost to a few degrees of consequences of the failure of the components over the production system and the difficulties connected to their reparability.
- The specificity of spare parts was also not an easy issue to quantify; nonetheless, it has been considered less complicated as a barrier to overcome basing on the experience of spare parts planner.

Efficiency is a relevant matter for other data, due to the time consumed for their management:

- Data regarding price, lead time and turnover rate came from different sources in the maintenance information system, as the SAP^{TM} plant maintenance of the company – for what concern the replenishment lead time and price of the spares – and the warehouse database, recorded in MS Excel^{TM} – for what concern the turnover rate.

On the whole, the most evident barrier to multi-criteria part classification is the fragmentation of information sources in different IT systems. MS Excel^{TM} is the current IT support tool for on field recordings, before transferring the information to the accounting management in SAP^{TM} plant maintenance. Such on field recordings are essentials, and the used IT system clearly represents a barrier: serving different client companies through MARC solutions requires quite relevant effort on information integration before applying spare parts classification.

Case B. Case B was developed in another mining company and in particular in its comminution plant located in Northern Chile. The analysis in this case study refers to the classification of the spare parts of a single equipment namely the belt conveyor used to transport, in a production line, the crushed mineral from the primary crushing process to the stock pile where the mineral is accumulated before moving it to other plants downstream. The critical components of a belt conveyor are: the belt (moving and supporting surface), the set of idles and pulleys, the drive and the structure. The maintainer, the planner and the work-team in charge of managing the suppliers were interviewed in order to evaluate the efficiency and quality of application of the multi-criteria perspective (all of them were involved in the implementation of the multi-criteria (AHP-based) analysis). As a result, the main barriers to quality and efficiency have been identified as indicated in Table VI and classified between "relevant" and "acceptable" barriers in a manner similar to the previous case.

	Price	Lead Time	Turnover rate	Stock out cost	Specificity
Quality		Acceptable			
Efficiency	Relevant		Relevant	Acceptable	Acceptable

Table VI. Barriers found in the Quality and Efficiency dimensions – case study B

Quality- and efficiency-related problems that emerged during the case study are discussed in the remainder.

Lead time is the criterion judged with barriers creating some difficulties for reaching a high quality:

- The correct estimation of the lead time has not been an easy issue, due to the highly variable demand of different mining companies competing on the components of the conveyor belt. An option to achieve lead time reduction is the flexibility of use of spares parts as components in more than one process: specifically for this case study, the main components under study can be actually used for different models of conveyor belts (i.e. installed in different production lines). A disadvantage of such flexibility is that a multiple demand source is present, which may cause a more complex demand variability to project. According to the data available from historical recordings, it could be estimated that sometimes the lead time is a few days while in other cases it lasts until about six months. Hence, using only the lead time on average was not acceptable. To solve this problem, it was necessary to split up the lead time criterion in two sub-criteria, the former measuring the lead team on average, the latter related to its coefficient of variation (CV) (i.e. in case $CV < 1$, it was considered a lead time with a low variability, otherwise, with $CV > 1$, a lead time with high variability). By using this simple computation, a higher quality of application of the multi-criteria method could be achieved.

The analysis of price, turnover rate, stock out cost and specificity of spare parts is considerably affected in terms of efficiency. In fact, the company of this case study has great experience with the application of a multi-criteria analysis, generally implemented in the identification of critical equipment and components hence, the analysis was not really seen as affected by quality problems. The problem instead is the loss of efficiency, occurring for two main reasons:

- First, the time spent in the analysis of many sources of information (i.e. SAP™ plant maintenance, MS™ Excel and Access database, plus some technical reports in other formats). Indeed, the integration, consistency and usability of all the information needed for applying AHP analysis implied a lot of time and resources also because of the need to pass through different functional units in the organization (i.e. maintenance, operations and planning units).
- Second, an organizational problem related to the outsourcing of maintenance activities, generally implemented as a global maintenance service, as an usual practice in this business. Normally, contracts primarily are focused on equipment, while they do not necessarily mind of maintaining relevant information on the spare parts; this is then missed, which leads to the risk of losing spare parts knowledge. The information is anyhow available, at a certain level of efficiency loss, when consulting more than one organizational unit, considering also the suppliers as information source to apply the multi-criteria method. The fact that two months were needed for data integration and analysis in this case study is symptomatic of the lost efficiency.

On the whole, the most evident barrier for the case study to multi-criteria part classification is still related, similarly to case A, to the fragmentation of information sources. However, case B is particularly helpful for underlining not only the technological barrier (i.e. different IT systems used to support the information) but also the organizational barrier: the main encountered problem while reaching the needed information seems related to the fact that it is dispersed through different functional units within the organization and across the organizational boundaries, because of the involvement of service providers to whom the maintenance activities are outsourced.

4.6 Concluding remarks on industrial evidences

Using the evidences of the two exploratory cases, no definitive conclusions can be achieved for what concern the barriers for the adoption of multi-criteria method in industry. Nonetheless, some interesting remarks emerge which may be further investigated in future works.

The first remark is that, even if the two cases refer to two different contexts, it has emerged from both of them that the adoption of an integrated information system is needed and this is still an existing barrier in industry for efficient classification. As remarked in case B, this can be even magnified due to the separation of information between the company owning the spare parts and thus needing to manage the criticality analysis, and the third parties providing services.

The second remark is that the experience levels reached in using a multi-criteria method might be a relevant factor influencing the perceived barriers and this could be due to different reasons. One reason may be that the quality problems are overcome with experienced persons, since they found adequate forms of representation of the criticality of the spare parts (see, for a comparison, the different perceptions on stock out cost and specificity in case A and case B, in Tables IV and V). Another reason may be related to the fact that, with experienced persons/companies, there is an improved perception of what is really critical in a given business context, as it happens in the case of the lead time perception of case B, which leads to more sensitivity to such a quality problem.

These remarks are assumptions that can be considered as research statements to be further verified through an extension of exploratory case studies in a first phase, and later on through a survey, when a number of remarks are ready for generalization.

5. Conclusions

This research aimed at depicting the current state of the art about spare parts classification methods and criteria. This was achieved by comparing the solutions already fostered by the scientific research, with the industrial companies' practices and their expectations. After the comparative analysis between theory and practice, developed with the support of a literature analysis, an industrial survey and two case studies, the following results have been achieved: first, five criteria have been identified as the ones with the highest potentials for spare parts classification, both for what concern their citations in scientific literature, as well as their understanding in industrial practice; second, an extensive review over the classification methods has allowed identifying pros and cons of various approaches proposed in literature or used in industry, revealing some concerns on their problems for industrial application, which can be summarized as computational complexity, exposure to uncertainty and to subjectivity when using qualitative data; and third, the existence of technological and organizational barriers causing non-efficient search for information fragmented in different IT sources and organizational units, both inside the company owning the plant and outside, in relation to an outsourcing strategy to maintenance service providers. On the whole, this work made evident that a distance between research and industry is still present. In particular, even if the important role of multi-criteria for part classification within the management process of spare parts clearly emerged, at least as a desired end in industry, existing limits are keeping quite distant research and industry.

Henceforth, there are two main efforts that should be focused on the research agenda for the next few years: first, the development of integration levers, considering both the perspective of IT systems as well as organizational roles, comprising also the suppliers in such integration, to enhance data usability for a multi-criteria classification. Second, the further study of criteria to achieve more common concepts, shared within the scientific context, as well as useful to really represent criticality as perceived by industrial personnel – the stock out cost is just an example of such criteria to be further studied. Once the part classification step is improved, it can also be envisioned that the criticality of spare parts classes may be better exploited to drive the next steps of the entire spare parts management process towards effective decisions. To this end, the research agenda may comprise also the development of: third, methods for the alignment of the stock management system with the criticality of the spare parts resulting from classification; fourth, methods for demand management/forecasting for different classes of spare parts; fifth, methods for performance improvement of focused, critical classes of spare parts. In general, a more holistic and multidisciplinary approach managing the supporting supply chains of spare parts is recommendable (Martin *et al.*, 2010; Huiskonen, 2001).

Last but not least, it is worth underlining the limits of the research. Indeed, the survey used for this study was related to the mining sector, hence its result presents some specificities depending on such context. In the next investigations, extensive surveys should be undertaken in order to study the interaction between contextual factors (e.g. the industrial sector) and spare parts management practices. Besides, the case studies of this paper may represent the first ones of a set of future cases to study the implementation approaches for robust multi-criteria classification methods. As such, they may be used as a reference example for further applications in contexts which present similar conditions to the mining sector or for an extension to other mining companies.

Note

1. Comprehensive maintenance and repair contract (MARC) solutions are frequently cited when referring to equipment dealers or Original Equipment Manufacturer (OEM) managing maintenance and repair contracts; the acronym is frequently found in the terminology of the mining industry.

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