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Criticality analysis of spare parts management: a multi-criteria classification regarding a cross-plant central warehouse strategy

J. Stoll · R. Kopf · J. Schneider · G. Lanza

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Abstract Today an efficient warehouse and inventory management of spare parts for production machinery is essential for service organizations. Optimal strategies in procurement, stocking and supply play an important role for serviceability in spare parts management. In this context, individual item criticality should be considered, which describes how crucial a spare part is. This paper presents a three-dimensional classification approach for spare parts regarding a cross-plant central warehouse strategy of a service network. The approach uses two dimensions to estimate value and predictability of spare parts with aid of an ABC and XYZ analysis. The third dimension VED analyses a multi-criteria criticality classification and six feasible criteria are identified to describe item criticality. The methodology of the analysis is based on a decision tree, which represents the defined criteria by nodes. In addition, the analytic hierarchy process is used to solve the multi-criteria decision problems at the different nodes of the decision tree. The approach is developed in a research project and evaluation of spare parts is performed based on real inventory and transaction data in cooperation with an industrial company. As a result 15,000 out of 50,000 items could be classified as suitable for central warehousing.

Keywords Spare parts management · Service networks · Central warehousing · Criticality · Multi-criteria classification · AHP

1 Introduction

Spare parts logistics play a crucial role when it comes to increasing the serviceability of service networks. On the one hand spare parts should be provided at low cost, on the other hand they should be highly available. While an unavailability of spare parts leads to production shutdowns, increased stocks of spare parts cause storage costs. These costs are ultimately aggregated in the serviceability and considered as cost per component that needs supervising, depending on the employment of staff and the number of components [1, 2]. Hence, optimal logistics strategies of spare parts make a substantial contribution to the efficiency and cost reduction of service processes.

However, up until now the unsatisfactory situation is that all spare parts are traditionally procured, stored and provided according to intuitive assessment, and therefore individual characteristics of spare parts cannot be taken into account. Therefore, especially classification analyses are applied in practice. Here, spare parts are classified according to criteria such as the value of the parts and the predictability of demand and based on those differentiated logistics strategies are derived [3]. Particularly the individual criticality of a spare part plays a major role in this context. The criticality evaluates a spare part, for example, according to the risk in procurement and storage, or consequences caused by machine failure, if the spare part is not available [3, 4].

The central theme of spare parts logistics is the stockage of spare parts. There is a risk of increased stocks and consequently excessive storage costs. Especially in a service network, a substantial rationalization potential results from merging decentralized storage sites to a central warehouse. Central warehousing is most suitable for stores of multiple locations that can be merged to form larger

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J. Stoll (✉) · R. Kopf · J. Schneider · G. Lanza
wbk – Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany
e-mail: Johannes.Stoll@kit.edu

storage units. Thereby, lower minimum stock levels in total are realized and demand fluctuations are compensated [3–6].

This is the starting point of this paper. Using a three-dimensional classification approach, multi-site warehouse and inventory strategies for individual classes of spare parts are derived and eventually spare parts that are suitable for a central warehouse are identified. The classification approach is based not only on the dimensions of the value of the parts and the predictability of demand, but also on the individual criticality of a spare part. In order to describe the criticality, which must always be derived from the individual context of the user, a multi-criteria classification is required. This paper develops a multi-criteria criticality analysis by using appropriate methods for the decision support.

The developed classification approach is exemplarily applied for a real range of spare parts in the industrial environment of a major German vehicle manufacturer.

2 Literature review

In literature and in practice, there is great interest in spare parts logistics, particularly in the areas of warehousing and inventory management. According to the current state of science, analyses are used to divide spare parts in individual classes by means of different criteria and based on this, warehouse and inventory strategies can be derived.

In industry, the ABC analysis for the monetary assessment of the value of the spare part is the most common. A great advantage of this analysis is its simple application: spare parts can be classified using only one criterion [7]. Syntetos et al. [8] apply the ABC analysis for the entire European spare parts logistics network of an electronics manufacturer. However, a successful implementation of the ABC analysis requires a spare part structure, which can be differentiated by only one criterion [9].

As an extension of the ABC analysis, an additional classification analysis can be applied, that is, spare parts are classified by using two criteria in the form of a matrix model. Especially in the context of inventory management, the inventory turnover plays an important role besides the value of the part. Gelders and Van Looy combine the ABC analysis with the FSN analysis (“fast moving”, “slow moving”, “no moving”) and implement this approach in a petrochemical company. Biedermann, Matyas and also Pawellek however, develop individual procurement and inventory strategies from a combined ABC–XYZ analysis. By using the prediction accuracy of the demand, which can be operationalized from the coefficient of variation as a measure of fluctuation, factors such as the safety stock or range can be set and storage strategies can be derived [3, 6, 10]. Flores and Whybark [11] expand the value of the parts by the criterion criticality and test their approach in practice. For the consideration of uncertainty, Chu et al. [12] develop the ABC–FC analysis (“fuzzy classification”), which is also a bi-criterial matrix consisting of ABC and fuzzy classification for deriving individual disposition policies.

Other authors expand the traditional ABC analysis by a variety of methods. In his approach, Ramanathan [13] uses weighted linear optimization for the classification; Partovi and Anandarajan [14] develop Artificial Neural Networks based on knowledge of neurobiology. In their Operations Related Groups method, Ernst and Cohen derive warehousing and inventory strategies by clustering spare parts with similar characteristics into groups. Compared to other methods, the major advantage of the cluster method lies in the variety of used criteria [15]. De Almeida [16] examines the competitiveness of an industrial system on the basis of utility functions. Petrovic and Petrovic [17] develop an expert system that uses the attention handling of individual steps for the classification and incorporates the uncertainty using the fuzzy logic. Although good results can be obtained by various methods for the multi-criteria classification, there is a great limitation in the selection criteria. The number of criteria is partially limited and on the other hand qualitative criteria cannot be taken into account to some extent [13, 14, 16].

Some authors use criticality as a fundamental criterion for classification. Huiskonen divides criticality in process and control criticality. Process criticality describes consequences in the process, whereas control criticality creates possibilities to control the situation [18]. Regarding the control criticality, Paaki et al. [19] investigate the external processes of procurement and the demand of a distribution center for spare parts. Even if the criticality is described in detail, there is no unified categorization [18, 19].

Dekker et al. [20] classify the demand for spare parts in the categories “critical” or “non-critical”, which can be categorized according to the safety stock of a spare part. If a demand cannot be covered by the inventory, it is categorized as “critical”. Another categorization of criticality is presented by Porras and Dekker and considers the number of machines in which the spare part is installed as a criticality criterion. A spare part is therefore especially critical when it is installed in a variety of machines, as a possible non-availability of the part affects a larger machine population. The criticality is differentiated in three categories: “high”, “medium” and “low” [21].

In addition to focusing and categorization of criticality, the criticality analysis is integrated into multi-dimensional classification approaches based on the current state of research. Botter and Fortuin use a two-dimensional classification approach consisting of the VED and FSN analysis to investigate a central warehouse problem. The VED analysis divides spare parts into the criticality classes "vital", "essential" and "desirable"; the FSN analysis evaluates the inventory turnover according to the categories "fast moving", "slow moving" and "no moving" [22]. Bošnjaković develops a three-dimensional approach for deriving storage strategies and uses the dimensions of the ABC, FSN and VED analysis. Due to the variety of criticality criteria, the VED analysis is methodologically based on a decision tree, which ends in one of the VED criticality categories. In total, twelve criticality criteria are selected and displayed using the decision tree [23].

Furthermore, several authors use the AHP as a decision supporting methodology for the VED analysis [7, 9, 24, 25]. The biggest advantage is that several criteria, both quantitative and qualitative, can be used to describe the criticality as a basis for the classification. By applying different weightings and the hierarchization of criteria, the AHP also leads to a realistic representation of the decision problem. However, a disadvantage is the high subjectivity that is included through pairwise comparisons by experts. Gajpal et al. [24] combine the AHP with the VED analysis at a major Indian producer; Sharaf and Helmy [25] use the AHP as a classification method for spare parts in a hospital. In an industrial project with BASF Antwerp, Molenaers et al. develop a criticality analysis that leads to inventory reductions. Due to the variety of criteria, a decision tree that ends in one of the VED categories and maps the criteria selected by nodes is developed as a methodology in addition to the AHP. Using the AHP, multi-criteria decision problems can be solved at the nodes of the decision tree. The combination of decision tree and AHP shows a better clarity and transparency of the classification [9]. Braglia et al. also present a transferable classification approach from the paper industry. By means of the AHP and a decision tree, spare parts can be mapped based on 17 criteria. Individual inventory strategies for all spare parts can be derived through the classification [7].

In this paper, a classification approach which ensures the transferability to a central warehouse strategy and an easy implementation for a wide range of spare parts should be developed. For this, the state of the art enables combined classification analyses such as the ABC–XYZ analysis, which operationalize the criteria value and predictability. However, in the context of spare parts logistics, an approach, which also includes criticality as a fundamental criterion should be developed. Here, the AHP should be used because it is a versatile method for the multi-criteria classification and is applied in practice. Regarding the criticality, the AHP in combination with a decision tree is a suitable methodology for the VED analysis. The publications of Braglia et al. [7] and Molenaers et al. [9] are the basis for developing the own approach. Based on the publications by Botter and Fortuin [22] as well as Bošnjaković [23], the critical dimension is integrated in a classification approach by further analyses.

3 Three-dimensional approach

The classification approach has been developed within the research project "Evaluation and optimization of the serviceability" and tested in cooperation with a German vehicle manufacturer. It integrates the dimensions of the value of the parts, predictability of the demand for spare parts as well as the individual criticality of spare parts.

The ABC analysis looks at the relative value of a spare part in relation to the relative amount. In this paper, the purchase price of parts is used as an evaluation criterion for the classification. The relative component price for any spare part is calculated in relation to the total component price of the spare part spectrum. The classification into ABC classes is based on the following system: quality A-parts take up 80 % of the total component price, average B-parts have a value share of 15 % and low C-parts represent a total component cost of 5 % [5].

In order to evaluate the predictability, the XYZ-analysis is applied. The prediction accuracy is determined by the coefficient of variation $\vartheta(x)$ operationalized, which, as a relative measure of variation, normalizes the standard deviation $\sigma(x)$ with the arithmetic mean $\bar{x}$. The following formula illustrates the calculation of the coefficient of variation [26].

$$\vartheta(x) = \frac{\sigma(x)}{\bar{x}} \tag{1}$$

The XYZ limits were determined in collaboration through an expert survey with dispatchers. By using a sample, spare parts were divided into one of three XYZ categories and the limits of the XYZ categories are determined by the corresponding coefficients of variation (cf. Table 1). For the purpose of verification, the XYZ limits were rechecked in a panel of experts.

To describe the criticality, a multi-criteria VED analysis was developed, which divides the spare parts into three criticality categories: "vital", "essential" and "desirable". The classification was based on the AHP methodology, taking the production and maintenance perspective into account. V-parts are especially critical and cause enormous

Table 1 XYZ-categories

Category	Description	Condition
X	Uniform, constant course of demand	$\vartheta(x) < 1{,}5$
Y	Average prediction accuracy	$1{,}5 \leq \vartheta(x) \leq 3$
Z	Random course of demand	$\vartheta(x) > 3$

consequences in the production process in case of unavailability. A prompt delivery of the spare part is desired, because a risk in the procurement and storage is not tolerated. E-parts are not necessarily critical, but are defined as rather important. If the needed part interrupts the production there are serious consequences, however, these can be corrected and controlled. There is an imputed risk in procurement and storage and hence the E-part should be delivered in a short time. D-parts, however, are quickly available on the market and pose no risk in the production process, as these can be substituted [9, 27]. In contrast to the ABC and XYZ analysis, the criticality is not described by only one indicator. The VED analysis uses several criteria to assess the criticality and hence multi-criteria decision problems in the classification of a spare part arise. The focus of this paper is thus the VED analysis, whose development is described separately in Sect. 4.

The three dimensions value, predictability and criticality can each be categorized by a threefold gradation in 27 quadrants (cf. Fig. 1). An individual warehouse and inventory strategy can eventually be derived for each quadrant. In the following, some quadrants or spare part classes will be exemplarily examined in more detail.

V-parts describe very critical spare parts and require a maximum level of service. For this reason, a decentralized storage is especially suitable, i.e. the storage at the machine site. Regardless of the VED classification, Z-parts, that is, parts with a poor predictability and therefore an irregular failure performance, should be stored on site in order to respond to a breakdown more quickly. Furthermore, a decentralized storage of inferior C-parts is also recommended as it is expected that the administrative effort of their central storage exceeds the low added value due to the possibly reduced capital commitment costs. In summary it can be concluded that especially C–Z–V-parts are not suitable for central warehousing.

The storage strategy “order on demand” (JIT order) particularly covers X-parts that are characterized by a high prediction accuracy of the case of need. In addition, it is recommended to request A-parts on demand to minimize the otherwise high capital commitment costs. D-parts should not be stored, as they pose only a very low risk in the production process and may be available on the market quickly. Consequently, A–X–D-parts are particularly suitable for JIT ordering.

Regarding the value of the part, especially B-parts are suitable for central warehousing, because this category is mainly comprised of carry-over parts and classical standard machine components, which can be used across different locations. It also recommended to centrally store E-parts. Although they require storage due to their criticality, E-parts are not critical enough to be mandatory stored on site. The same applies for the predictability. Regularly varying Y-parts are assigned to a central warehouse strategy. These parts are indeed suitable for storage due to the fluctuating demand, but because of their predominant constant demand, they are not suitable for decentralized warehousing. According to the presented logic, the central warehouse strategy is particularly suited for B–Y–E-parts (cf. Figs. 1, 2).

In addition to individual stock strategies, the presented approach differentiates the inventory strategies “no storage”, “one unit on stock” and “optimal order quantity”, whose assignment to quadrants is based on the publication of Bošnjaković (cf. Fig. 2) [23]. The storage of one unit is understood to be the amount of a spare part that is demanded in the case of need. The optimal order quantity calculation for central warehousing-appropriate spare parts can be realized by the EOQ formula, which calculates the economic order quantity Q based on the demand D, the order fixed costs C and variable storage costs h [23].

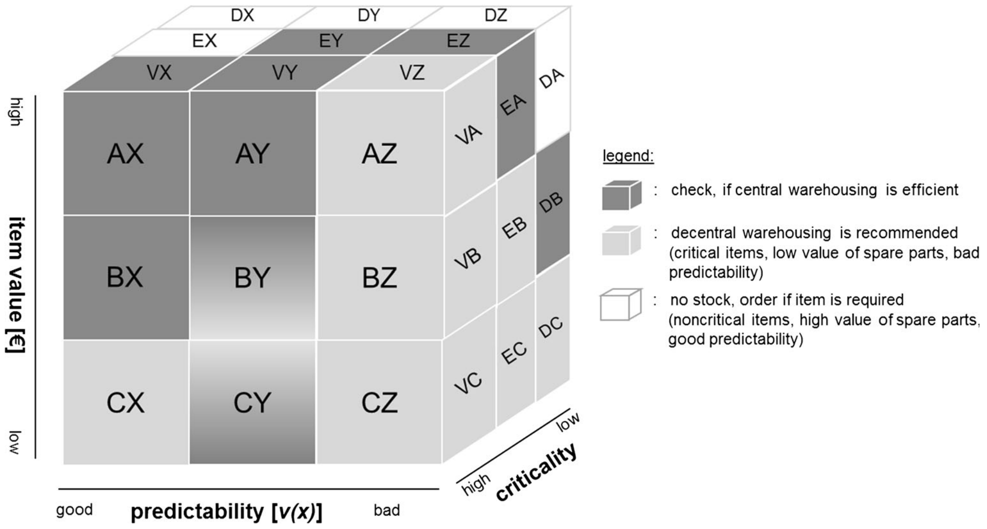


Fig. 1 Integrated classification approach

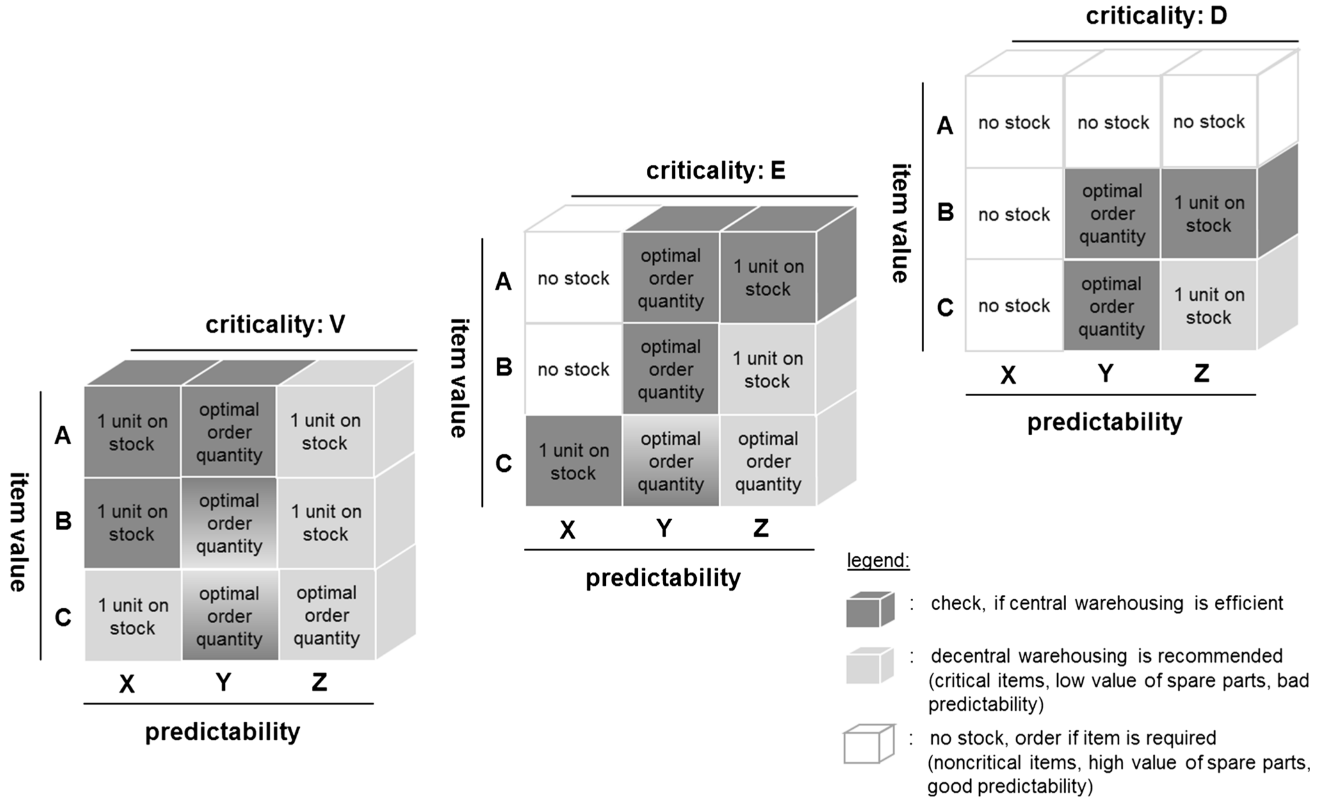


Fig. 2 Integrated classification approach—stocking stategies

$$Q = \sqrt{\frac{2 * C * D}{h}} \tag{2}$$

Hybrid quadrants were partly defined with the recommendation to decentrally store one unit as a safety stock, while the optimal order quantity is stored centrally (cf. Fig. 2).

4 Spare parts classification based on criticality

The proposed classification approach was exemplarily applied in an industrial context. The operationalization of the third criticality dimension was based on several criteria. As supporting methods for multi-criteria decision-making, a decision tree and the AHP were primarily used.

4.1 Criticality criteria

Through a workshop with experts from the vehicle manufacturer, 31 criteria for assessing the criticality of spare parts in the service network were initially collected. Here, it was important that the criteria cover various departments of the company. This requirement was supported by the participants of the workshop, who were experts from disposition, warehouse, maintenance and manufacturing.

After the criteria were selected, they were grouped as eight clusters (cf. Table 2). A cluster is the internal process time of the spare part, which can be summarized, for example, from an internal transport time, shift allocation of the warehouse or the availability of the purchase. The maintenance strategy was also defined as a criterion for the evaluation of the criticality, which includes the costs of the warehouse budget. A third overriding criterion is the supplier, who can be described for example by the geographical location or the availability of the spare part. An additional cluster is the failure frequency of an item that is influenced by the production method (electrical, mechanical), or by the existence of carry-over parts, i.e. the existence of spare parts that are installed in multiple machines. The fifth overriding criterion is the priority of the machine that was assigned to the spare part, which defines, among others, whether the machine is in a network or if an alternative production is possible at a machine breakdown. The definition of machine priority was already existing as an internal index to characterize machine performance. In addition to the created clusters, there are three further criteria that form isolated cluster. These include the installation time of a spare part as well as the shift plan of an allocated machine. The experts defined equipment availability as eighth cluster which is described by the target availability of a machine.

Table 2 Cluster of criticality criteria

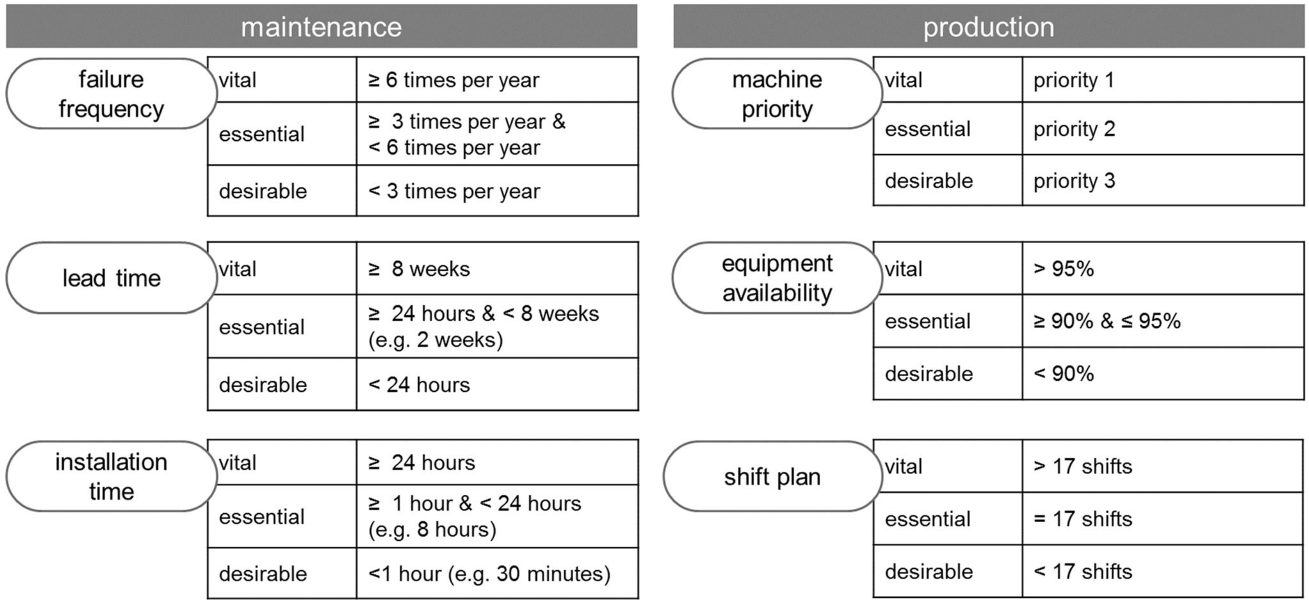
Cluster	Examples of criteria
Internal process time	Transport time, shift allocation, warehouse, availability of the purchase
Maintenance strategy	Costs of the warehouse budget
Supplier	Geographical location, availability of the spare part
Failure frequency	Production method (electrical, mechanical), existence of carry-over parts
Machine priority	Machine network, alternative production at a machine breakdown, bottleneck machines
Installation time	–
Equipment availability	Target availability for required throughput
Shift plan	–

In the next step, these clusters were assigned to the departments of production and maintenance. For reasons of practicality, those criteria that could be guaranteed for the automated data analysis were filtered (cf. Fig. 3). The evaluation of the internal process time as well as the criticality of the supplier proved to be criteria that are difficult to implement, since the necessary internal processing times were not recorded and the assessment of the supplier criticality was difficult to quantify. For this reason, both criteria were combined to the evaluable lead time because it is composed of the internal process time for the initiation of the order and the delivery time. Regarding the eighth criterion, maintenance strategy, a distinction between failure-based maintenance and service was made. Condition- or time-based maintenance did not exist in the considered application of the vehicle manufacturer. However, it does provide a theoretical third alternative. Justified by an impractical differentiation of maintenance strategies on a spare part basis, the criterion of the VED analysis was excluded. Finally, thresholds for the selected criteria were defined according to the VED categories (cf. Fig. 3).

4.2 Decision tree

The decision tree is a method for the decision support and can transparently and clearly illustrate a complex and multi-stage decision-making process. It is visualized by a graph that consists of nodes and edges. By using nodes, the criteria are shown, while edges represent the decision options for a VED categorization. After passing through the decision paths, the decision-making processes eventually end in a VED overall criticality category [28, 29].

The two areas of maintenance and production are presented by nodes, each integrating the criteria failure frequency, lead time and installation time or machine priority, equipment availability and shift plan as nodes of the sub-level. The department or the criterion with the highest weighting vector defines the first node. Edges that branch from each node ultimately form the decision path. The path for an individual spare part runs through all criteria and is dependent on each VED category. This means that the logic according to which a spare part is categorized is ultimately resolved by the AHP (cf. Chapter 4.3) at the corresponding nodes [28, 29]. The decision tree is shown in Fig. 4.



failure frequency		
	vital	≥ 6 times per year
	essential	≥ 3 times per year & < 6 times per year
	desirable	< 3 times per year

lead time		
	vital	≥ 8 weeks
	essential	≥ 24 hours & < 8 weeks (e.g. 2 weeks)
	desirable	< 24 hours

installation time		
	vital	≥ 24 hours
	essential	≥ 1 hour & < 24 hours (e.g. 8 hours)
	desirable	<1 hour (e.g. 30 minutes)

machine priority		
	vital	priority 1
	essential	priority 2
	desirable	priority 3

equipment availability		
	vital	> 95%
	essential	≥ 90% & ≤ 95%
	desirable	< 90%

shift plan		
	vital	> 17 shifts
	essential	= 17 shifts
	desirable	< 17 shifts

Fig. 3 Criticality criteria and VED classification

4.3 Analytic hierarchy process

Today, the AHP is a common methodology for multi-criteria decision making. In addition to the variety of criteria, both quantitative and qualitative criteria can be considered in the classification. The AHP can represent all aspects of a problem by using a hierarchical structure, and hence dissolve the complexity at individual levels [30–33]. The first level is the overall objective, that is, the evaluation of the overall criticality. The second level is represented by the areas of maintenance and production, which in turn are influenced by the criteria that were presented in Sect. 4.2. All six criteria can be classified in VED categories on the fourth level by thresholds. Figure 6 visualises the hierarchical structure of the described criticality criteria and VED categories.

By weighting through a pairwise comparison, a rational consideration of individual criteria at each level is achieved [30–32]. During the expert workshop, elements of the corresponding level were evaluated through a pairwise comparison in relation to the element of the next higher level to which they are related. In general, the evaluation was done by using a comparison matrix that shows through quantitative entries, how much an element affects the next higher level compared to another element. Figure 5 presents the pairwise comparisons that emerge from the expert workshop.

Based on the comparison matrices, weighting vectors for each element of the matrix were created, which can be calculated as normalized eigenvectors. The eigenvector indicates the amount to which each criterion or alternative influences the element at the next higher level. Figure 6 shows the weighting vectors for each criterion. Here, the lead time is the most important criterion for describing the criticality, whereas the criteria machine priority and equipment availability are the major contributors to production. Overall, the maintenance was weighted double, compared to the production. Although the expert panel originally saw the production as a more significant department in terms of the component criticality, the weighting had to be change afterwards based on the poor data quality of production criteria. Main reasons were the missing differentiation in shift plans and a differing definition of machine priority in the single plants. The poor data quality of production criteria combined with the double weight ended in a low differentiation of VED classification. Therefore, the vehicle manufacturer decided to change the initial weighting of total criticality.

Ultimately, the aggregated weighted criteria lead to an optimal decision-making in the last step of the AHP. A synthesis takes place, that is, the individual criteria weightings and VED categories are merged and combined to a whole. First, so-called global priorities of individual VED categories, which represent the importance of each category in the context of the overall hierarchy, were determined by a bottom-up process. The global priority $p_{h,i}^{global}$ of a category h in terms of a criterion i is calculated by multiplying the weighting of the VED category v^h with the criteria weighting v^i at the next higher level, as can be seen in the formula (cf. Fig. 4).

$$p_{h,i}^{global} = v^h * v^i \tag{3}$$

By summing up all global priorities $p_{h,i}^{global}$ of one level in the hierarchy, which consists of several criteria i, the overall priority of the category p_h^{total} ultimately arises, which is weighted with respect to the overall goal.

$$p_h^{total} = \sum_i p_{h,i}^{global} \tag{4}$$

This means that the overall priority of the department on the second level is obtained by the calculation of global priorities of the three criteria on the third level (cf. Fig. 6). The calculation is analogous for the overall criticality on the first level, which can be summed up from the global priorities of the departments.

5 Implementation of the approach

After the development of the classification approach in Sect. 3 and the criticality analysis in Sect. 4, they were applied to the spare part spectrum of the internal maintenance organization by the vehicle manufacturer. For this purpose, three plants with similar production units were observed and the resulting similar spare part ranges were checked for their central warehouse suitability. A total of 115,000 spare parts could be identified, which served as an input to the classification. When applying the ABC and XYZ analysis, almost all parts were classifiable because the needed information on the price per part and the demand for parts could be provided. The VED analysis identified only about 50,000 classifiable spare parts, due to the complexity of the amount of data required for evaluating the criteria failure frequency, lead time, installation time, machine priority, equipment availability and shift plan.

For the derivation of storage strategies, the three dimensions value, predictability and criticality were considered in an integrated way (cf. Sect. 3) and approximately 50,000 spare parts could be evaluated in all plants. Of these, about 15,000 spare parts were suitable for central warehousing, whereas for just under 5,000 spare parts an order as needed was recommended (JIT delivery). The largest amount of spare parts should be stored decentrally on site. This strategy applies for more than 30,000 spare

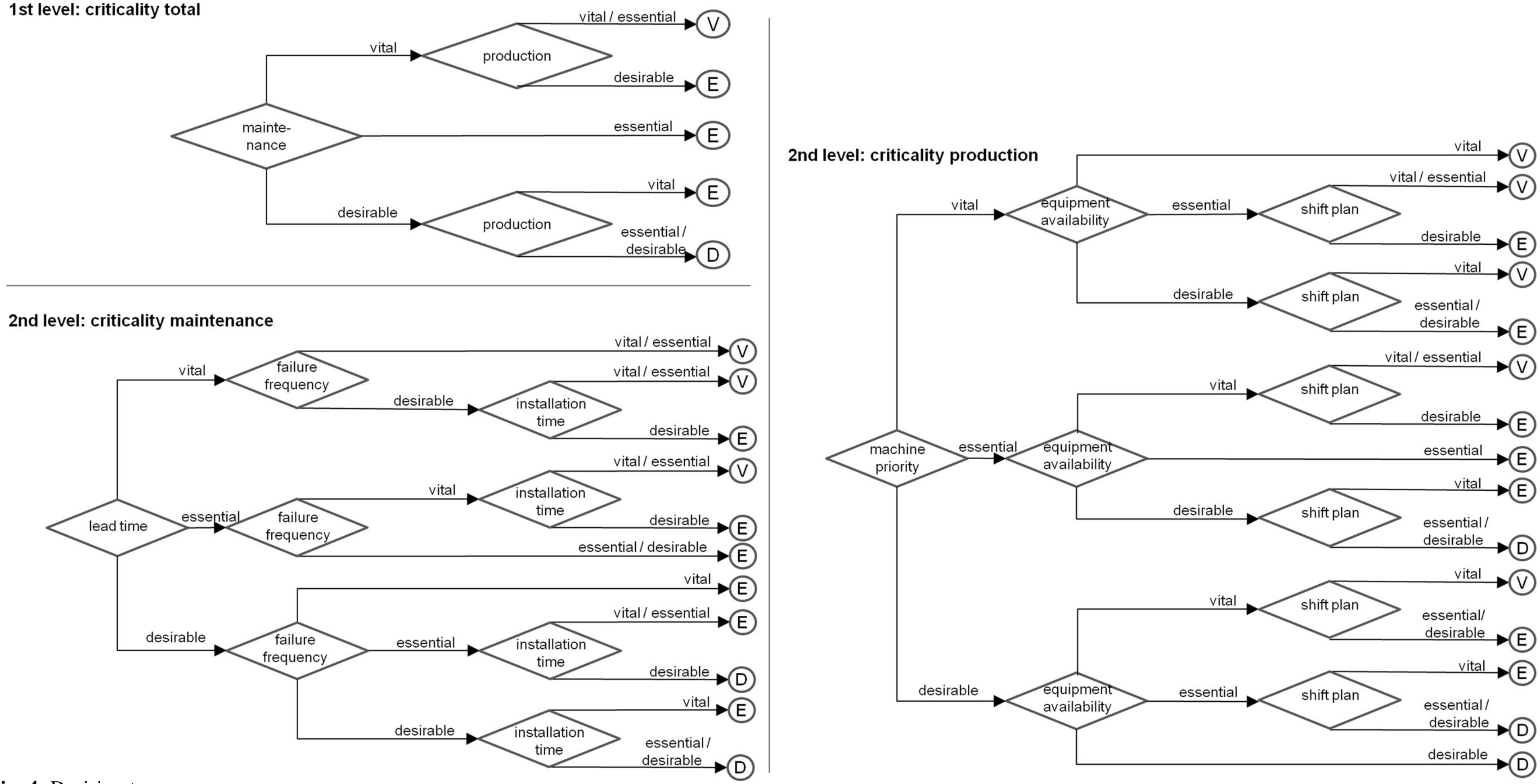


Fig. 4 Decision tree

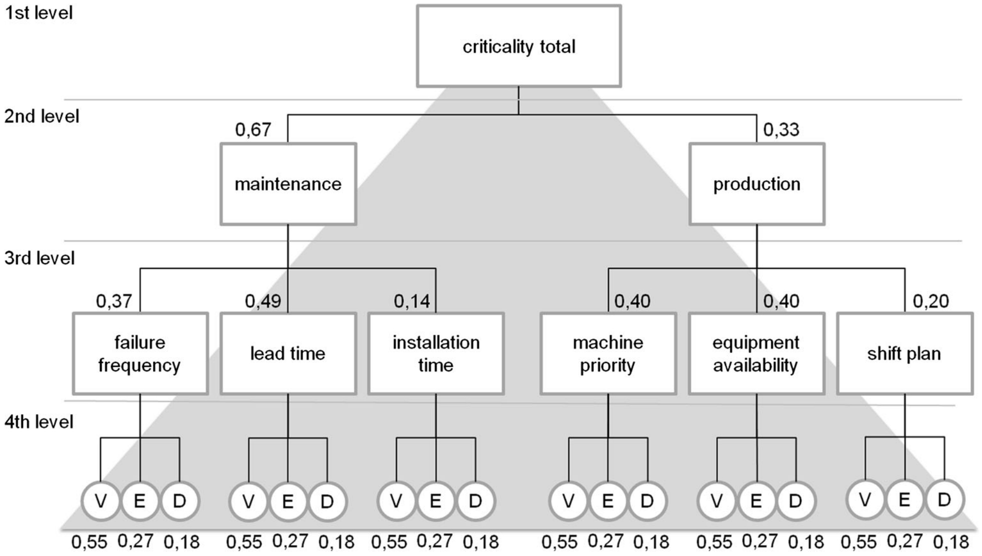
maintenance	failure frequency	lead time	installation time
failure frequency	1	1/2	3
lead time	2	1	3
installation time	1/3	1/3	1

production	machine priority	equipment availability	shift plan
machine priority	1	1	2
equipment availability	1	1	2
shift plan	1/2	1/2	1

criticality total	maintenance	production
maintenance	1	2
production	1/2	1

Fig. 5 Pairwise comparisons

Fig. 6 Hierarchy and weights



parts. A similar allocation of the storage strategies could be ascertained for the distribution over the three plants.

The development of the classification approach showed weaknesses that should be mentioned. First, the greatest disadvantage of the AHP is the high subjectivity, which is included in the VED analysis through pairwise comparisons by experts. Furthermore, the methodology of the AHP reaches its limits in terms of subsequent changes. Regresses during the development are only partially possible or associated with a high modification effort [30–32].

Despite weaknesses in the development, the positive aspects of the approach prevail. The biggest advantage of the AHP is that it uses several criteria to describe criticality as a basis for classification. In addition to the full selection of criteria, the level of detail of the decision problem is a further advantage of the AHP. By applying different weightings and the hierarchization of criteria, the AHP leads to a realistic illustration of the decision problem. Furthermore, the methodology of the AHP ensures an automated data analysis of each criterion, which is of great importance due to the complex range of spare parts of the vehicle manufacturer [30–32].

In summary it can be concluded that the classification is applicable in an industrial environment and derives a satisfactory result for the central warehouse suitability for 15,000 spare parts which is about 30 per cent.

6 Conclusion

As part of the research project “Assessment and optimization of serviceability”, which is supported by the German Research Foundation (DFG), a classification approach to identify spare parts that are suitable for central warehousing was developed and tested on the internal service network of a maintenance unit at an industrial company. Based on the given requirements, especially the transferability to a cross-plant central warehouse strategy and the applicability on the range of spare parts of the vehicle manufacturer, three analyses were chosen for this approach. In addition to the dimensions value of the parts (ABC analysis) and predictability of the demand (XYZ analysis), the approach considered the individual criticality (VED analysis) of a spare part.

The VED analysis for the description of the criticality was developed with experts from the industry partner and the spare parts were divided into the categories "vital", "essential" or "desirable". In order to evaluate the individual criticality of a spare part as accurately as possible, the VED analysis was operationalized based on six criteria: failure frequency of the spare part, lead time, installation time, machine priority (alternate manufacturing, output relevance and concatenation in the network), equipment availability and shift plan.

Based on a literature review, analyses and methods were evaluated for the classification of multi-criteria criticality and the AHP was identified as a suitable method for the VED analysis. In addition, a decision tree was developed that illustrates the selected criteria by nodes and solves the multi-criteria decision problems at the various nodes of the decision tree by means of the AHP. Every spare part thus passes through a path and ultimately ends in a VED category.

Through the structured procedure of the classification approach and the results of the data analysis, this paper is an analytical and practice-oriented approach that can be used successfully in the context of the research project.

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