MULTI CRITERIA CLASSIFICATION FOR SPARE PARTS INVENTORY

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ABSTRACT

Maintenance operations directly influence the performances of railway vehicles and play a crucial role in railway services to provide uninterrupted and high quality service to passengers. With the exception of preventive activities, the demand of spare parts for maintenance tasks is usually random; hence, the fast and secure management of the spare parts inventory is an important factor for the successful execution of the maintenance process. The purpose of this research is to extend the classical ABC analysis by developing a multi-criteria inventory classification approach for supporting the planning and designing of a maintenance system. Relevant classification criteria and control characteristics of maintenance spare parts are identified and selected and discussed in terms of their effects on maintenance operations, purchasing characteristics, positioning of materials, responsibility of control, and control principles.

KEYWORDS

ABC Classification, Spare Parts Inventory Management

1 INTRODUCTION

The most important aspect of railway services are availability and reliability which both depend on the maintenance operations. The function of spare parts inventories is to assist the maintenance operations in keeping vehicles in operating condition. Providing an adequate yet efficient supply of spare parts, in support of maintenance activities in railway service is challenging management problem.

For successful execution of the maintenance process, keeping a certain amount of spare part inventories that is balanced with the demand for spare parts is required. Different inventory control practices are needed for two fundamental types of maintenance; namely scheduled or preventive maintenance, and unplanned repair. For scheduled maintenance, the demand for spare parts is predictable and it may be possible to order parts to arrive just in time for use, and it may not be necessary to stock spare parts at all. However for unplanned repair, the consequences of stock-outs often cause interruptions in maintenance operations, and some kind of safety stock policy is necessary.

In developing a good spare parts plan, there are two conflicting objectives. In order to minimize the likelihood of a service failure, as well as to minimize the cost of transporting parts, parts should be kept in a wide variety of locations and in significant quantities. Conversely, inventory and warehousing costs are minimized by consolidating small numbers of parts in a limited number of locations. The stochastic nature of spare part demand and the large number of distinct parts add to the complexity of the planning process.

The use of classification schemes as a spare parts management tool represents a popular approach in industrial world. ABC-classification according to the Pareto's principle is the most well known and used classification scheme to manage the inventories. However, spare parts inventories used for maintenance operations differ from other manufacturing inventories in several ways. For example, rather than customer usage, maintenance policies dictate the need for spare parts inventories. Work in process or final inventories can be increased or decreased by changing production rates and schedules, improving quality, reducing lead times, etc. Spare parts inventory levels, however, are largely a function of how equipment is used and how it is maintained. Maintenance which requires a given kind of part can sometimes be postponed or avoided, and the choice of a maintenance action can have an immediate impact upon the relevant spare parts inventories (Braglia et al., 2004). More importantly, the costs of being out of a part generally include quality as well as service lost, and these costs are difficult to quantify. Increased risk of failure may also be a factor, and costs associated with such risks are not easy to calculate. For some spare part items being out of stock implies a very high cost and in this case, extra importance is required.

2 CLASSICAL ABC CLASSIFICATION

Potentially, thousands of items may be held in inventory for maintenance operations, but only a small portion of them deserve management's close attention and accurate control (Braglia et al., 2004). ABC inventory classification is a widely used inventory planning and control method that is designed to achieve an appropriate discrimination of items according to the level of attention needed for control of their inventories.

ABC-classification according to the Pareto principle suggests that there are a few items which contribute most of the inventory costs and a large number of items whose costs are relatively low. This is also known as the 80 : 20 rule, as approximately 20% of items contribute 80% of the costs and the remaining 80% of items account for only 20%. Obviously, it is important to maintain tight controls on the 20% and moderate control on the rest (Waters, 1992). Therefore, ABC analysis classify inventory items according to the importance of their contribution to the annual cost of the entire system inventory. The inventory of a small number of items which accounts for a large share of the cost-volume are labeled as A items. Similarly, B items constitute an intermediate category of moderate cost-volume items and C items include a large number of low cost usage items.

Empirical evidence shows that once the analysis is performed and the categories determined, concentrating the attention on the A items to maximize managerial effectiveness is a reasonable rule for allocating scarce resource-management time (Flores and Whybark, 1985).

Classical ABC analysis is easy to use, and serves well the inventory management of materials that are fairly homogenous in nature and differ from each other mainly by unit price and demand volume. Therefore, ABC-analysis has retained its popularity among the practitioners in directing the control efforts and choosing the sufficient-enough control parameters without the need of item-specific analysis. 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 the traditional ABC analysis may not be able to provide a good classification of inventory items in practice (Guvenir and Erel, 1998; Partovi and Anandarajan, 2002).

3 MULTI-CRITERIA ABC CLASSIFICATION

Multi-criteria inventory classification has been addressed by some studies in the literature. Flores and Whybark (1985) suggested that ABC classification considering multiple criteria, such as lead time, criticality, commonality, obsolescence and substitutability can provide a more comprehensive managerial control. They proposed a bi-criteria approach which uses standard ABC classification of each of two criteria, and then combine the two single-criterion grouping by a joint-criteria matrix. The resulting matrix requires the development of nine different policies, and for more than two criteria it becomes impractical to use the procedure.

Botter and Fortuin (2000) presented a case study for developing a strategy for spare parts inventory and use a multi-criteria classification of items. They defined a distinction between vital, essential and desirable service parts through the criteria of criticality of the function to be performed by a system that has become defective, response time, consumption, price, delivery time, repairability and life-cycle phase of the service part. Gajpal et al. (1994) elaborated the criticality analysis of spare parts by using the analytic hierarchy process (AHP) for classifying the spare parts.

Petrovic and Petrovic (1992) designed an expert system model for advising on spare part inventory control where the decision rules were based on several operational characteristics of spare parts: availability of required system, essentiality, price, weight, and volume of the part, availability of spares in the market, and efficiency of repair.

Ramanathan (2006) proposed a weighted linear optimization model for multi-criteria ABC inventory classification. The model first converts all criteria measures into a scalar score which is a weighted sum of measures under individual criteria. Then the weights are generated by a linear optimization and the classification is performed by grouping the items based on the scores generated. An extended scheme was presented by Zhou and Fan (2007). Liu and Huang (2006) followed the same approach to address ABC inventory classification. They used unit cost, procurement/downtime, demand, and lead time as evaluation criteria and employed simulation example to verify the efficiency of the model.

Chu et al. (2008) recently proposed a new inventory control approach called ABCfuzzy classification, which can handle variables with either nominal or non-nominal attribute. Several meta-heuristics are also proposed for the multi-criteria inventory classification, such as genetic algorithms (Guvenir and Erel, 1998), artificial neural networks (Partovi and Anandarajan, 2002), and particle swarm optimization (Tsai and Yeh, 2008).

This paper presents new a spare parts inventory classification scheme based on the following steps:

1. A criticality analysis of the spare parts is conducted through three sub-criteria which are *penalty costs*, *substitutability*, and *commonality*. Criticality degree of each item is obtained through this analysis and used in the further step of determining the overall importance of that item.

2. A multi criteria ABC analysis is carried out to classify the different items into three classes of criticality: (a) very important (A-class); (b) important (B-class); and (c) less important (C-class).

3. Finally, according to demand patterns, A-class items are reclassified for an accurate redefinition of the stock control systems for the different spare parts.

4 CRITICALITY ANALYSIS

The criticality analysis of the components represents a fundamental aspect of this study. When it comes to spare parts inventory management, determining the importance of a part by classical annual cost usage model becomes insufficient. The impact of a shortage of a critical part may be a multiple of its commercial value. An item with a need of immediate action in case of stock out has high criticality, while some lead time is allowed to correct the failure caused by an item of medium criticality (Huiskonen, 2001). The parts of lower criticality, that are having no specific time restrictions for corrective operations in case of failure, don't require any specific attention, but can be controlled by standard logistics methods.

There is a substantive amount of subjective criteria used in assessing the criticality of parts in practice (Cohen et al., 1997). Mainly it is related to the consequences of a failure and shortage and the possibilities to control the situation. We analyze the criticality of an item based on the three sub criteria, stock-out penalty, substitutability, and commonality which covers the essentials of railway maintenance system.

1. **Stock-out Penalty:** This factor is closely related to the idea of stock-out costs. The criticality of a spare part item is related to the consequences caused by the lack of the item when it is required. Theoretically, it can be evaluated by the downtime costs of the system related to the failure to be corrected by the use of the part. However it is often very difficult to determine in practice, so instead, it might be sufficient to determine a few degrees of criticality for practical purposes.

   One practical approach is to relate the criticality to the time in which the failure has to be corrected. For example, three degrees of criticality in regard of consequences might be determined on the following basis (Huiskonen, 2001):

   (a) **High:** The failure has to be corrected and the spares should be supplied immediately,

   (b) **Moderate:** The failure can be tolerated with temporary arrangements for a short period of time, during which the spare can be supplied,

   (c) **Low:** The failure is not critical for the process, and can be corrected and spares can be supplied after a longer period of time. Quantification of the given criticality degrees is done through assigning a penalty index (α_n) for each item n and setting it to 1 for a high level item, to 0.01 for a low level and to 0.50 for a moderately critical item.

2. **Commonality:** Another important aspect of criticality is commonality which is a measure of how many uses there are for a spare part item. If the item is used in many different vehicles or maintenance types, it might be important to devote extra attention to it and for management purposes it could be classified in group of A items. Using common parts can be beneficial in terms of risk sharing and substantial savings up to can be achieved by use shared stocks compared to using separate stocks (Kranenburg and Van Houtum, 2007). Furthermore, when the same spare part item can be used with several maintenance types or vehicles, the system allows the possibility of economies of scale since a common component can be supplied in larger volumes [Stake01]. On the other hand, a stock out occasion of common components will have an higher impact on the maintenance system that the maintenance schedules that have a use of shared component will be delayed or changed.

   Measuring commonality, however, might not be quite that simple. Although various types of commonality indexes can be found in literature (Lyly-Yrjanainen et al., 2004), a simple and useful measure is the number of different maintenance types that the use of the item is needed. A normalizing function might be useful to make all criteria data for each item between $[0, 1]$.

   $$\beta_i = 1 - \frac{m_{max} - m_i}{m_{max} - m_{min}} \qquad (1)$$

   The commonality index, β_i, given in (1), has a positive impact on the importance of the item i where m_i represents the number of different maintenance types that part i has a use regardless of the frequency of the maintenance schedule. Here, m_{max} goes for the maximum number of types sharing one particular item, while m_{min} is the minimum number which is most of the time equal to 1.

3. **Substitutability:** Another aspect of spare part items is substitutability. The substitution potential provides flexibility in response to problems, reducing the importance of the item relative to less substitutable items in the spare parts inventory. If the item has a close substitute, more flexibility and reduced response time is possible, both of which reduce the criticality of the part.

   Substitutability has a direct impact on the purchasing decisions which can affect both efficiency and effectiveness of maintenance operations. One dimension of substitutability is technical. Technical similarities between spare part items might permit mutual substitution without loss of function or suitability. Higher level of substitutability might provide to lower levels of stock out risks that when there is a stock-out of one type of item, it can substituted for the interchangeable item. However, even where another item may technically be suitable as an alternative for the item in question, its cost may be so much higher that it becomes a poor substitute in a practical sense.

Other dimension of substitutability is related to the availability of different suppliers who can provide the same product with very little or zero quality and cost differences. Among the wide spectrum of maintenance spare parts there are typically both standard parts, which are widely used by many users and hence also readily available from several suppliers, and a certain amount of parts specifically tailored for and used by a particular user only. For standard parts the availability is usually good, there are stocks of these parts at different levels of the supply chain, and the suppliers are willing to cooperate with the users, as the volumes are high and offer economies of scale. For the user-specific parts quite the opposite is true: suppliers are unwilling to stock the special, low volume parts and the responsibility of availability and control remains with the user himself.

Similar to *penalty index*, a substitutability index might be a method of determining the substitution availability of an item. A substitutability index of $\gamma_i = 1$ implies that item i is fully differentiated and $\gamma_i = 0$ implies that it has perfectly substitutable products.

4.1 Criticality Model

To evaluate item criticality we use a modified input-oriented Data Envelopment Analysis (DEA) model with single input and multi output. The model takes the values of three sub-criteria as outputs and tries to maximize the criticality value against the single unit input. The criticality level for each item is obtained using the following model:

$$\begin{aligned} & max \quad c_i, \\ & u_1\alpha_n + u_2\beta_n + u_3\gamma_n \leq 1 \qquad n = 1, 2, ..N \\ & c_i - u_\alpha\alpha_i - u_\beta\beta_i - u_\gamma\gamma_i = 0 \\ & u_\alpha, u_\beta, u_\gamma \geq 0 \end{aligned} \tag{2}$$

In this model, c_i is the criticality value of item i. Variables u_α, u_β, and u_γ represent the weights assigned to criteria of penalty cost, commonality, and substitutability respectively. Similarly $\alpha_n, \beta_n,$, and γ_n represent the performance of item n on relevant criterion where N is the total number of items in the spare part catalog.

The maximization objective function implies that all the sub-criteria are assumed to be positively related to the importance level of an item. When the model is solved repeatedly for each item, the value of the objective functions give the optimal criticality scores which is then used in the classification of the inventory items presented in next section.

5 MULTI-CRITERIA ABC ANALYSIS

The classical ABC-analysis does not make it possible to discriminate all the potential control parameters of different types of items. To overcome this limitation, new multi-attribute classification models have been developed which are able to manage multiple factors which conflict with each other and heterogeneous units.

Some of the criteria considered in the literature include inventory cost, part criticality, lead time, commonality, obsolescence, substitutability, number of requests for the item in a year, scarcity, repairability, order size requirement, stockability, demand distribution, and stock-out penalty cost (Flores and Whybark, 1985; Gajpal et al., 1994; Guvenir and Erel, 1998; Ramanathan, 2006; Zhou and Fan, 2007).

Of above, commonality, substitutability, repairability, obsolescence, scarcity, and stockout penalties can be taken as factors which have impact on criticality of an item, thus are included in criticality aspect. Our criticality analysis model though, undertakes only three of them; penalty-costs, substitutability, and commonality since there are no repairable items in railway maintenance operations and obsolescence is not considered. As presented in Figure 1, in addition to criticality, value-usage, lead times, and unit cost are found to be relevant characteristics to be included in the model.

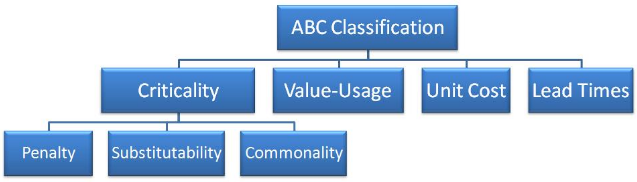

Figure 1: ABC Classification Criteria

5.1 Value-Usage

Similar to classical ABC classification, we chose annual value usage as one of our criterion, where items are evaluated through their annual monetary usage values which are the products of annual usage quantities and the average unit prices of the items. The value of a part is a common control characteristic to items, and stocking large amounts of high value items preferably avoided. In general, a high value of a part favors controlling the inventories of that item more carefully. As a result, this criterion is positively related to the importance of the item since items with the highest annual monetary value receives the most attention where low-monetary value items are controlled routinely.

5.2 Lead Times

Among several factors that can influence the management of the inventory, lead times of spare parts play an important role. Lead time of an item refers to the time between placing an order at the supplier of an item and the moment it is available for use. Both the length of the lead time and its variability could be important in maintaining an adequate supply of an item without excessive costs (Flores and Whybark, 1985). The length of the lead time is important since it directly determines the stock levels of items with unknown demand and dictates the response time to a crisis. The variability also affects the amount of safety stock required to provide the level of service desired. For example items with long lead times may incur financial losses as a result of possible interruption of maintenance operations and/or huge inventory levels.

Even though it excludes the variability dimension, using time as a measure of lead times criterion constitutes a common basis for all items in the product catalog. It also provides both the user and the supplier with a common means for setting the objectives and for controlling the performance of operations.

5.3 Unit Cost

Control of items on strategic and tactical level also differs according to unit costs. High value items requires decisions like setting up the incentives, developing the cooperation with suppliers, and building opportunities for increasing the negotiation power. On the other hand, with low price items, the replenishment arrangements have to be efficient so that the administrative costs do not increase unreasonably in proportion to the value of the items themselves.

5.4 Criticality

A criticality value of each item is determined by solving (2). The resulting index, c_i, of item i gives a continuous value of criticality level of range $[0, 1]$ where $c_i = 0$ level implies very little or no criticality and $c_i = 1$ means item is highly critical.

5.5 ABC Analysis Model

The greater the number of criteria that are viewed as important, the more complex the task of developing the classification becomes (Flores and Whybark, 1985). Since all criteria mentioned in above are important and need to be incorporated in the analysis, the weights of these criteria are generated by a DEA-like linear optimization to avoid the subjectivity on the weight assignments.

The DEA model used is a simple input-oriented, single input, multi output model which is very similar to model developed by Ramanathan (2006). The model takes lead time, criticality, value-usage, and unit price as outputs and tries to maximize the their values against the single unit input. The importance level for each item is obtained using the following model:

$$
\begin{aligned}
max \quad & I_i, \\
& \textstyle\sum_{j=1}^{4} v_j x_{jn} \leq 1 \qquad n = 1, 2, ..N \\
& I_i - \textstyle\sum_{j=1}^{4} v_j x_{ji} = 0 \\
& v_1, v_2, v_3, v_4 \geq 0
\end{aligned} \tag{3}
$$

As model shows, all the criteria are assumed to be positively related to the importance level of an item where I_i is the importance level of item i. v_j represent the weights assigned to criteria j and variable x_{jn} represents the performance of item n on relevant criterion where N is the total number of items in the spare part catalog.

When the model is solved repeatedly for each item, the value of the objective functions give the optimal inventory scores which can then be used to classify the inventory items.

Once the ranking has been determined, the cutoffs for each of the classes A, B and C must be set. The final decision, of course, depends on the management tradeoffs on the number of items classified in group A. Setting a large number of A items will demand more management attention, and therefore will defeat the purpose of the classification in the first place.

A items constitutes approximately roughly the top 15 percent of the items, B items approximately the next 30 percent, and C items approximately the last 65 percent. Due to nonparametric nature of DEA, solution of the model will assign values to weights which are most favorable for the item in question. As a result, it avoids the subjectiveness in determining weights and provides an objective way for multi-criteria ABC inventory classification. If an item has a value dominating other items in terms of a certain criterion, this item would always obtain a high aggregated performance score which is primarily aimed by ABC classification. However, such a case also may lead to the situation where an item with a high value in an unimportant criterion but with low values in other important criteria is inappropriately classified as class A, which may not reflect the real position of this inventory item (Zhou and Fan, 2007). One method to prevent such a situation is using the weight restrictions inclusion. Weight restrictions allow for the integration of managerial preferences in terms of relative importance levels of various criteria.

6 DEMAND PATTERN

After ABC analysis in order to find the best control strategy for A class items, we developed a further classification scheme according to the following criteria:

1. **Demand Predictability:** First grouping is done through the randomness of the demand structure. Items which mostly takes place in preventive maintenance are likely to have a known demand structure where spare parts of repair maintenance depends on the frequency of the failures which is the source of randomness.

2. **Volume:** We classify items in to two groups as low-demand, and high-demand. By low demand, we mean that the probability of more than one failure of that particular part system wide within the replenishment lead time is sufficiently small. In other words, should one installation of that part fail, it is highly unlikely that a second failure of the same part will occur anywhere within the system before the first repair part is replenished. Given that a repair part satisfies this definition of low demand, there is no longer need to consider how many of this part to stock, but simply where to stock it.

3. **Variability:** We consider four main demand variability structures. *Steady* demand refers to the items with demand which is constant from one period to next. *Trend* demand indicates that the demand is increasing or decreasing with a constant rate of change. Items with a variable demand structure but with a repeating pattern are grouped under *seasonal* demand. Finally, items with discontinuous and nonuniform demand structures, with frequent periods of zero demand are grouped under *lumpy* category.

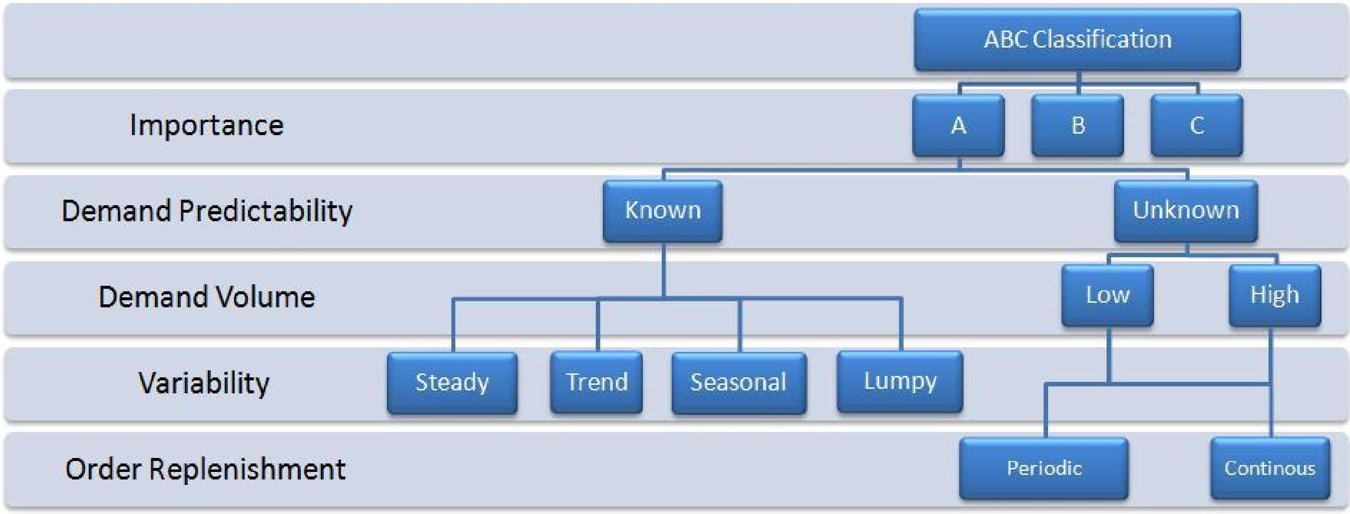

Figure 2: Hierarchical Representation of Demand Classification Factors

4. **Inventory Review:** For control of items with random demand there are two main control structures: continuous review and periodic review.

Figure 2 graphically represents the hierarchical structure of demand classification factors. A classification by these factors creates 10 different particular groups of service parts, each with its own inventory control technique.

7 CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Management of spare part inventories is very important for successful execution of the maintenance processes. In this paper, we extended the classical ABC analysis of spare part inventories by developing a three level, multi-criteria classification approach for supporting the planning and designing of a maintenance system. The first level of proposed approach is criticality analysis, followed by an ABC analysis based on the criteria of criticality, lead times, value-usage, and unit cost of items. We presented a mathematical model for evaluating importance level of each item. Finally, according to demand patterns, A-class items are reclassified for an accurate re-definition of the stock control systems.

The next step of this study is to present a numerical example and investigate the validity of the proposed approach by a case study application in İstanbul Metropolitan Municipality Light rail system. Then we plan to extend this study through some future research directions which can address some of the limitations.

As mentioned in section 5.5, model(3) allows for unrestricted weight flexibility in determining the importance scores of inventory items. This allows units to achieve relatively high efficiency scores by indulging in inappropriate input and output factor weights. Weight restrictions allow for the integration of managerial preferences in terms of relative importance levels of various inputs and outputs. One extension of this study might be incorporating weight restrictions by using one of the methods that have been suggested by several researchers. Included in this stream of research are works by Dyson and Thannassoulis (1988); Charnes et al. (1990); B. and Beasley (1990); W. et al. (1999); S. and G. (2004).

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