Master's degree thesis

LOG950 Logistics

Inventory management of slow moving spare parts in National Electricity Power Plant of China

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Number of pages including this page: 57

Molde, June 2013

Molde University College

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Preface

This Master Thesis is the last assignment of the Master of Science in Logistics program at Molde University College. I want to express my gratitude to the people who guided me through this wonderful journey.

First of all I want to highly appreciate my supervisor Arild Hoff for his guidance and feedback during the writing process.

Furthermore, I want to thank the managers in the National Electricity Power Plant, who gave me an opportunity to gain further insight into the situation of inventory management in the power plant.

Last but not least I want to thank all my friends and my family for their support during the last two years.

Abstract

Slow-moving spare parts are common in manufacturing, in contract to fast-moving spare parts, slow-moving spare parts are more expensive, more critical, and more difficult to forecast. Therefore, the inventory management of them is more complicated. Efficient inventory management of slow-moving is vital in reducing logistic costs and improving capital utilization. At present, lack of wide attention from researchers and infeasibility of traditional approaches makes research on inventory management of slow-moving spare parts is significant.

Concentrating on the inventory management of NEPP power plant's slow-moving spare parts, the disadvantage of traditional ABC classification is presented, an improved ABC classification model involving equipment criticality is forwarded based on two-stage method. Considering the difficulty of inventory control of slow-moving spare parts, and using the results of two-stage classification, an inventory model is provided. The optimal order size and reorder point can be found with the model, and effectiveness of this model is presented by using different real cases. The results indicate that the model is effective and has good performance for most of cases.

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1 Introduction

1.1 Backgrounds

National Electricity Power Plant (NEPP) is one of the biggest five electricity generating companies in China. In 2000, it successfully separated from the State Grid Corporation of China and completed transition from state-owned to private. At the end of 2011, NEPP has 37 branch plants, 1.530 million employees and 533,950 km of transmission lines. Every year it will generate around 1.672 billion kVA of electricity to cover most area of central and west of China. Now its major business is engaging in electricity power production, sales, investment, construction, operation and management, and other relevant electric business service including coal, power generation facilities, new energy and environmental protection industry.

After the transition, the top managers were confronted with lot of challenges. One of them is the inventory management control of spare parts. Different from other manufacturing enterprises, spare parts is the major concern in inventory system for power plant, instead of work-in-process items and finished productions.

Spare parts or replacement parts are the interchangeable parts that are kept in an inventory and used for the repair or replacement of failed parts. There are approximately 103 different kinds of spare parts with total number of 3,400 storing in in each branch power plant[1]. They are common and playing an important role in the daily production of NEPP.

If sorted by purpose, spare parts can be divided into two groups:

- Mechanical parts, these spare parts are special mechanical components for one certain type of machine, such as gear, screw, bearing, crankshaft, connecting rod.
- Supporting parts, these are standardized, common to all kinds of equipment which are produced by the professional manufacturers, such as the rolling bearing, hydraulic components, electrical components and seals [2].

If sorted by source, spare parts can be divided into the following groups:

- Self-made spare parts. They are produced by their own design, mapping, and basically belongs to the category of mechanical parts.
- Outsourcing spare parts. These are purchased by orders from other manufacturers; generally supporting parts are the outsourcing spare parts. Due to the self-capacity of enterprises and economic requirements, mechanical parts such as high-precision gears, main spindle of machine tool, friction plates are also purchased [2].

If sorted by use frequency, spare parts can be divided into another two groups:

- Spare parts with high use frequency. They are always cheap and required to maintain a certain inventory. Such as large consumption of supporting parts, key equipment insurance reserve parts.
- Spare parts with low use frequency. They are the spare parts with the low frequency of use and high value, such as rotator of electricity generator [2].

If sorted by maintainability, spare parts can be divided into following groups:

- Repairable spare parts. A repairable part is one can be sent to a repair facility that when failure occurs. After that it is returned to an operational state [3].
- Non-repairable parts. These spare parts are uneconomical or physically impossible to repair and have to be abandoned once it fails [3].

In the power plant, the spare part could also be called as the component. The difference is that the spare part is kept in the warehouse, while component is the same part that has been installed in a running machine.

1.2 Logistics Problems

Compared with the fast-moving spare parts, slow-moving items are usually more critical, more expensive and more difficult to forecast. So this master thesis is focused on the inventory management research about the slow-moving spare parts which is based on the real situation in one of branch power plants. The power plant now has 4 generator units with capacity of 400 MW (million watts). In 2003, these four units merged into northeast regional grid. Besides the main business of electricity generation, the power plant is also responsible for providing hot water for heating the local people`s houses in winter.

Traditional ABC classification method [4] is used for managing the 86 different kinds of spare parts in this power plant. All the different kinds of these spare parts are divided into three categories according to their purchasing value. For example, items costing more than 100,000 dollars are belonging to class A, where 1 dollar equals to 6.2 RMB.

Although the spare parts are divided into three categories, the inventory control policy is almost the same one that is purchasing the certain number of items once the stock reaches a fixed stock level (reorder point).

Actually, managers of power plant have been conscious of doing something to reduce logistics cost. For the slow-moving spare parts with high value, long-term storing makes the lots of money is occupied and total holding cost quite large. For example, in 2011, the inventory holding cost is 620,000 dollars for spare parts, which accounted for about 76% of total logistics cost. At the end of 2010, 400 days of average annual inventory turnover is much higher than general level of other stocks such as finished goods and raw materials. Long-term storing of spare parts also leads to being discarded without using. For example, as a part of valve, gasket which is made of rubber is very easy to deteriorate. What is more, lots of unused slow-moving spare parts are wasted because of technology and equipment updating, which also causes inefficiency.

1.3 Research Questions and Objectives

These logistics problems show that the traditional classification method is not suitable for the spare parts and the power plant lacks good inventory control for slow-moving spare parts.

Therefore, the main objective of this thesis is to address these issues by focusing on a continuous review inventory management system of slow-moving spare parts, leading to the following research questions:

- What is the best classification method for spare parts in power plant?
- What is lead time?
- How many slow-moving spare parts are needed during the lead time?
- When is the best time for placing the order?

- How many units to order when an order is placed?
- Whether the new inventory management system is better than current policy?
- What is the disadvantage of the new system?

The purpose of implementing inventory management of spare parts is to keep the balance between minimum cost and continuous production. On the premise of safe production, how to reduce inventory cost and holding time is significant to using the capital efficiently and increasing the productivity. Therefore the performance of inventory management of slow-moving spare parts is bound up with the development of company. At present, in China, there is less research on slow moving spare parts, especially in inventory control[5]. Because of special characters, the traditional inventory control method is not suitable for the slow-moving spare parts, so the research on inventory control of these items is significant and practical.

1.4 Structure of the Thesis

The remaining of the paper is organized as follows. Section 2 provides a literature review of studies addressing inventory management, spare parts classification, demand forecasting, and inventory control models.

An improved ABC classification method based on equipment criticality is introduced in section 3. This new method is much more suitable for managing the spare-parts and used to define the slow-moving spare parts for the real case.

In the fourth section, best inventory control policy for slow-moving spare parts will be calculated by mathematic models and the new solution will be compared with the current inventory policy to find out whether the new one is better. In the last section, the conclusion of this paper is presented.

2 Literature Review

2.1 Inventory Management

Inventory management is defined as “the continuing process of planning, organizing and controlling inventory that aims at minimizing the investment in inventory while balancing supply and demand”[6]. Specifically, the process is a supervision of supply, storage and accessibility of items in order to ensure an adequate supply without excessive oversupply.

Since the mid-1990s, there has been a large increase in annual number of inventory management articles[7]. Researchers conduct such relevant research in several respects. First, most of publications in logistics journals are about traditional inventory control models. These papers evaluate traditional inventory control models under particular conditions or incorporate additional considerations into established models[7]. Another popular theme is about developing approaches to reduce the quantity of inventory that a warehouse must have, which refers to reducing the safety stock by centralization of warehouse locations[7].

From both operational and financial viewpoints, inventory management plays an important role in daily production. On one hand, the gross and net profit of a company will be increased by reducing carrying costs, procurement costs and associated operational expenses after conducting effective management of inventory. What is more, cash flow will be improved through saving on purchasing and storing the goods, which can be used to invest in other services. On the other hand, efficient inventory management guarantees meeting the demands of customers and daily production.

2.1.1 Factors affecting inventory management of spare parts

To develop a complete inventory management system of slow-moving spare parts inventories, the following factors that make them different from work-in-process or finished product inventories need to be considered.

- Maintenance policies, decide the demand for spare parts. Whether to use regular repair policy is the first decision that should be made. Some critical equipment parts are repaired according to a time schedule and opposite decision is to repair the machines when they shut down. Then next decision is whether to repair or replace, which means maintenance can be postponed. For example, one way to restore the functionality of a machine is to repair the part and another one is replace the failure parts [8].

- Transportation cost should be considered during the repair period. For some special machines, they need to be removed and repaired in the repairing center [9].
- Obsolescence may be a problem. Besides the spare parts, the machines also have service life and can be obsolete. It is difficult to determine how many units of spare parts to stock for an obsolescent machine [10].
- Part failures can be dependent. Dependence relation is generally not available [8].

2.1.2 Evaluation of inventory management

Inventory management performance indicators are used to measure how an inventory control system is used to manage the inventory. The most practical approach is calculating the inventory turnover rate (ITOR) [6] which is a method of measuring how effectively inventories are being used. The ITOR is calculated as how many times a company's inventory has been replaced (turned over) during a period of time, which equals the cost of goods replaced divided by the average level of inventory on hand. Higher ITOR values indicate good management of inventory which was quickly produced, sold or replaced within a specific time interval.

Another important indicator is service level which is used to control the amount of inventory needed for satisfying customers' demand. Two service level measures are frequently used in inventory control according to literatures [11]. P_1 is often denoted as the probability of no stock-out during replenishment lead time, and P_2 is denoted as the fraction of demand satisfied directly from the shelf (also called fill rate).

There are also some other indicators such as average inventory-holding cost showing what percentage of average cost of holding inventory accounts for average inventory value and incremental ordering cost which equals to the average incremental cost of placing each order [12].

2.1.3 Inventory-associated costs

Inventory costs are basically categorized into three headings: ordering cost, carrying cost and stock-out cost. Ordering costs are the costs involved with purchasing the products, which includes placing and receiving orders, stocking and paying the invoices [6].

Carrying cost refers to costs associated with product storage and cost of capital. Stock-out cost, also known as shortage costs are the costs of not having the product on the hand when needed [6].

2.2 Slow-moving Spare Parts Inventories

The function of spare parts inventories is defined as “to assist a maintenance staff in keeping equipment in operating condition” [8]. Spare parts inventory levels can be expressed as a function of how equipment is used and how it is maintained. The maintenance policy has a direct impact upon the relevant spare parts inventories. In the production activities, the maintenance of equipment can be postponed or avoided, and one way to restore the functionality of a machine which has a broken part is to repair the failed part. Or the part can be replaced. So that, maintenance policy has a direct impact on the relevant spare parts inventories.

Slow-moving spare parts is one particular type of spare parts that have low demand in terms of both order size and number of orders placed per period [13]. At present, there is no strict definition to make a distinction between slow-moving and fast-moving spare parts. The frequency of demand for these items is less than 12 units per period [13]. The "item" is defined as a stock keeping unit (SKU), while the "unit" is defined as one piece of a specific type of item held in inventory.

Although quantitative criteria have not been defined to distinguish the slow-moving spare parts from the fast-moving ones, the qualitative description of slow-moving ones is shown below: (BTO is short for build to order, and it is a production approach where products are not built until a confirmed order for products is received. BTS is short for build to stock, and it is a build-ahead production approach in which production plans may be based upon sales forecasts or historical demand).

Table 2-1 The comparison between slow-moving and fast-moving spare parts

	Criticality	Commonality	Demand	Price	Forecast	Supply mode
Slow-moving	high	low	low	high	hard	BTO
Fast-moving	low	high	high	low	easy	BTS

2.3 Classification method

In order to treat more complicated and more practical circumstances, modern production planning and inventory control has been developed regarding the appropriate level of inventory [14]. However, in practice, firms usually have hundreds of different kinds of products, materials and spare parts, and all inventories cannot be treated with equal attention. So that, for many asset-intensive industrial plants, classification of the total assortment was put forward as the solution for matching appropriate stocking policies to different classes of inventories, which has become a crucial task in order to control the wide and highly varied assortment [15].

The most traditional and widely used method that warehouse managers use for classifying inventory items for planning and control purpose in organizations is the annual-dollar-usage ranking approach (ABC classification) [16]. ABC classification method is described in the one of logistics literature "allows an organization to separate stock keeping units into three groups: A-very important, B-important and C-least important. The amount of time, effort, and resources spent on inventory control should be in the relative importance of each item" [17].

Due to high service requirement and finance resources involved, it is obvious that classification is an important part of spare parts inventory research, and a classification of spare parts is helpful to determine service requirement for different spare parts classes, and for forecasting and stock control decisions [18]. It is obvious that the classical ABC-method is easy to understand and implement, but the limitation of the ABC control system is that the classification of items into these three groups has generally been based on one criterion.

In the context of industrial spare parts, the assortment is so heterogeneous that ABC classification based on one parameter is not considered as the most suitable method [19]. For example, Teunter et al. [20] showed in their research that cost inefficient solutions could be caused by using single ranking criteria, such as demand value or demand volume when conducting inventory management. This leads researchers to extend classical ABC-classification to a multi-criteria ABC-analysis including other parameters like demand pattern, critical factor, lead time, substitutability, repairability, commonality [21]. Depending on the nature of items and industry, these criteria have different weights and it is subjective to prioritize the weights of criteria [22]. At last, Flores et al. [16] suggested that the number of categories under any system of classification can be more than three.

2.3.1 Analytic hierarchy process (AHP)

The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions. Based on mathematics and psychology, it was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then [23].

Gajpal et al. and Braglia et al. adopted the AHP for spare parts classification based on item criticality [24, 25]. The main reason AHP being chosen is that it is involved with the process of pair-wise comparisons regarding both qualitative and quantitative criteria. Another advantage of the AHP approach is assigning weights to the different parameters, which guides the analyst towards the best criticality class of a spare part.

2.4 Demand Forecast

During the past 50 years, forecasting and planning for inventory management has received considerable attention due to its implication for decision making [26]. A crucial issue for the successful inventory organization is the accurate demand forecasting, since the demand distribution during the lead time is used to determine the replenishment order quantity and reorder points [27].

Under most of general conditions, an appropriate forecasting method is exponential smoothing and moving average [28]. Forecasting lead time demand is complicated for slow-moving items. Firstly, demand of spare parts is often intermittent, which means that a random demand has a large proportion of zero values [29]. Secondly, historical data of spare parts demand are usually limited due to high turnover rate [30].

In 1972, Croston firstly found that traditional forecasting methods such as moving average and exponential smoothing can lead to sub-optimal stocking decisions which demonstrated that these methods may be inappropriate for slow-moving items, and he proposed another traditional forecasting method called single Croston method (CR) [31] that takes account of both demand size and inter-arrival time between demands. The CR method has been estimated by several authors since 1972 and most researchers made the conclusion that the CR method is more suitable for intermittent demand than traditional methods [32].

2.5 Inventory control models

As an important part of inventory management, inventory control models aim to determine how much of each item should be kept, when items should be replenished, and how many items should be ordered or made when replenishment is needed.

The Economic Order Quantity (EOQ) model is one of the oldest traditional production scheduling models, which was developed by Ford W. Harris in 1913 and it can be used to figure out the optimal order quantity that minimizes total inventory holding costs and ordering costs. EOQ applies only when demand for a product is constant over the year and each new order is delivered in full when inventory reaches zero.

Harris also introduced a basic (Q, r) inventory model which goes beyond a simple assumption of EOQ inventory control model. Orders of size Q is allowed in this model, whenever its inventory position reaches a re-order point (r) where the order quantity is the deterministic demand during the lead time [7]. Meanwhile, researchers has extended the (Q, r) approach in several respects, such as transportation factors buyer and seller relationship, emergency conditions, short lead time.

Another widely used inventory control approach is the periodic review (S, T) control system.

The (S, T) model which is described by Hadley an Whitin in 1963 controls inventory through ordering on pre-set review intervals (T). When reaching a review interval, an order is placed such that inventory position is brought to the up-to-level (S) [7]. Logistics literature also integrates different logistics considerations into established basic models to solve more and more practical logistics issues.

2.6 Vendor managed inventory (VMI)

Vendor managed inventory is a retailer-vendor relationship that the vendor decides on the appropriate inventory levels within bounds that are agreed by contract with the retailer. The replenishment is placed at the vendor who is then allowed to determine the timing and size of deliveries [33]. VMI is a pull replenishing system that is built to allow a Quick Response (QR) from the supplier to actual demand. Due to high level of partnership of vendors and suppliers, both partners could benefit from the implement of VMI.

2.7 Jointly managed inventory（JMI）

Inventory includes three main elements, namely warehouse location, inventory keeper, and inventory owner [34]. For most of manufacturing enterprises, inventory keepers and inventory owners are working together where the inventory is kept. This is a typical centralized inventory management model. The ideal of JIM (Jointly Managed Inventory) model is to separate those three elements.

3 Judgment of slow-moving spare parts

3.1 Disadvantage of using traditional ABC classification

Although advanced theoretical inventory classification approaches such as weighted linear optimization [19] and fuzzy AHP-DEA approach [22] are proposed in literature, real case applications are limited. For most industrial companies like NEPP, implementations seem to fall behind the theoretical models since the most popular spare part classification method is still the traditional ABC approach. Actually, the power plant had incorporated ABC classifications into the management of their spare parts inventory.

- The annual purchasing cost of each item is used as the criteria when conducting the ABC classification. It is known that total purchasing cost is equal to annual demand multiplying by unit cost. For the different items with the same total purchasing cost, some of them are cheap but high consuming while some are slow-moving but expensive. So that it is not reasonable to treat these spare parts equally based on this single criteria.

- Due to the special characteristics of spare parts, some parameters are not considered when applying ABC analysis. Some spare parts which are critical to the equipment running should be paid more attention. However, criticality has not any connection with the criteria of dollar usage. On the other hand, obsolescence is another parameter needed to be taken into account [10]. Some spare parts such as rubber items will be deteriorated and out-of-date due to long-term stock. Some spare parts might become obsolete stocks because of generation upgrades.

3.2 Improved traditional inventory ABC classification

Owing to limitations of traditional ABC classification, several improved methods have been developed for inventory classification, especially multi-criteria inventory classification (MCIC) that account for other important criteria leading to more logical results in practice. Obviously, inventory management in NEPP can be conducted as MCIC problem.

Complex computational tools are needed while applying multi-criteria ABC classification. Flores and Whybark proposed a matrix-based methodology, wherein a joint-criteria matrix is combined with two criteria [21, 35]. However this approach cannot be used when considering three or more criteria and also weights of all criteria taken into account equal. Some heuristic approaches, such as genetic algorithms [36] and artificial neural network (ANN) [37], have also been used to address the MCIC problem. It is apparent that learning the heuristics approach is difficult for inventory managers and in addition, qualitative criteria cannot be used into the model. Another famous methodology is analytic hierarchy process (AHP) [38] which has been employed in many MCIC studies [19]. The general idea of using AHP is to get a single scalar measure of criticality of inventory items by subjective judgment. Subjectivity has become the most important issue involved in the AHP-based analysis.

3.3 Two-stage spare parts classification model

3.3.1 Model introduction

Spare parts criticality has been recognized as an important criterion in many researches for spare parts classification [3, 15, 20, 24, 35], but equipment criticality is always ignored. For example, one certain spare part belong to crucial item for equipment A and B, which means those machines will be forced to shut down when spare part is out of stock. However, the importance of equipment A and B for keeping safe production is different. When A is vital equipment and B belongs to auxiliary ones, effect of spare parts shortage on the production will be different. If just considering item criticality but equipment criticality when doing ABC classification analysis, one faces the problem of assigning critical spare part belonging to auxiliary equipment B to class A. Therefore, regarding the special characteristics Ding Liuming [39] developed a two-stage classification model for spare parts inventory.

First stage of the model is equipment classification based on equipment criticality. Dekker, et al. [40] defined equipment criticality as “the importance of equipment for sustaining production in a safe and efficient way” and “a function of the use of equipment, rather than of equipment itself”. The equipment can be distinguished between vital, essential and auxiliary one based on its functionality [15]. After that, all the spare parts belonging to auxiliary equipment can be categorized directly to class C.

Second stage is doing ABC classification of spare parts in vital and essential equipment. ABC classification does not need to be done for spare parts of auxiliary equipment, which leads to significant reduction of classification work. Once the analysis is completed and the categories determined, much more managerial attention should be concentrated on the critical spare parts of crucial equipment which can also be called class A items.

Generally speaking, the basic idea of two-stage improved method is to split the criticality classification of spare parts up into two procedures, namely equipment classification and spare parts classification which all based on item criticality. It is easier and more efficient for enterprises to carry out this two-stage ABC classification method to manage their spare parts inventory. The process of the model is shown below:

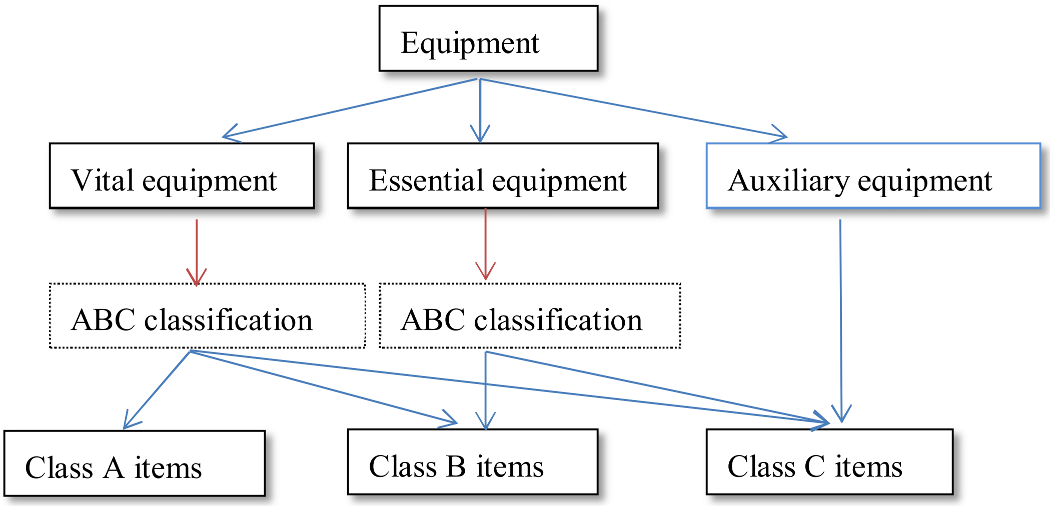


Figure 3-1 Two-stage ABC classification model based on equipment criticality

3.3.2 Judgment of item criticality

The ruling criterion of classification method for equipment and spare parts is item criticality. Evaluating the criticality of items is not an easy task because different parameters can have an impact on the degree of criticality. In order to defectively solve this multi-criteria problem, multi-attribute technique AHP is proposed. The choice for AHP lies in the fact that it is suitable and flexible for modeling qualitative criteria and assigning weights to different criteria. Detailed information of AHP can be found in the literature [22].

3.4 Judgment of slow-moving spare parts

Slow-moving spare part is one kind of special items of category A. In order to achieve efficient inventory management for this kind of spare parts, the two-stage classification model can be used to separate the slow-moving ones from hundreds of spare parts quickly.

Due to the limitation of time, the final judgment of slow-moving spare parts is based on current classification results. Three parameters can be used as criterion to distinguish slow-moving spare parts from class A, which are supply mode, annual consumption and unit value.

The threshold value for annual consumption and unit value is 50 and 10,000 dollars separately, which means that spare parts with larger unit value or smaller consumption can be considered as slow-moving spare parts. Judgment model is shown below:

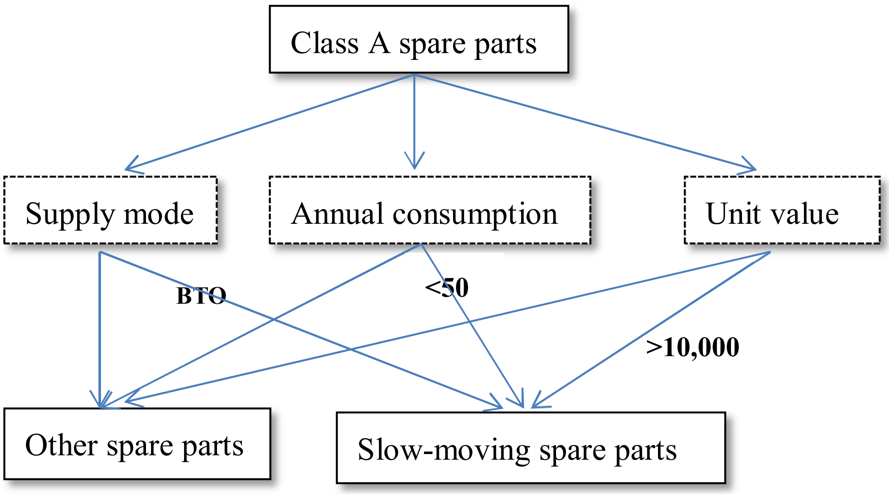


Figure 3-2 Judgment model for slow-moving spare parts

The result of judgment of slow-moving spare parts can be found in table 3-1.

Table 3-1 Judgment of slowing-moving spare parts

Item	Description	Class	Supply mode	Consumption	Value	Judgment
3215	Diesel generator	A	BTO	15	25,000	S
3426	Generator transformer	A	BTO	9	39,000	S
3211	Generator PT cubicle	A	BTO	11	30,500	S
4325	Socket box	A	BTS	269	1,240	N
3454	6kv station section	A	BTO	23	14,000	S
3880	Unit auxiliary transformer	A	BTO	7	45,700	S
5423	Support insulator	A	BTS	1267	238	N
6421	Copper busbar	A	BTS	987	260	N
4589	Main generator	A	BTO	4	60,000	S
7684	Fan Coil Unit	A	BTS	230	1010	N
8311	Switch blade box	A	BTS	451	440	N
2432	Change over cubicle	A	BTO	35	5400	S
3256	Forced draft fan	A	BTS	33	3200	S
1254	Pressure governor	B	BTO	0.49	45,000	S
1394	Main axle	B	BTO	0.59	11,200	S

Note : S is slowing–moving spare part; N is others

4 Inventory control model

The judgment of slow-moving spare parts is based on data coming from maintenance reports of 2012. Some slow-moving spare parts are selected as examples to show how to make an optimal inventory control policy.

4.1 Model introduction

4.1.1 Basic assumption

- The number of components whose corresponding spare parts are slow-moving items in one kind of equipment is single.
- There is no difference in performance between the components and their spare parts.
- For a slow-moving spare part, lifetime is larger than procurement lead time.
- The inventory control model is based on continuous-review, order point and order quantity system (s,Q).
- The demand in the lead time is assumed to be Poisson distributed.
- The inventory control policy with service levels which are more than 98% can be accepted.

4.1.2 Parameter definition

B_1: Total stock-out costs which is caused by no supply of stock after failure of component.

H: Inventory holding costs per unit time for single spare parts.

r: Internal interest rate.

V: Unit value.

D: Expected annual demand of spare parts.

L: Lead time.

s: Reorder point.

μ_L: Average demand in lead time.

A: Ordering costs for placing an order.

SS: Safety stock.

ES: Expected number of stock-outs in a cycle.

P: Probability.

Q: Order size.

Q*: Optimal order size.

σ: Standard deviation of annual demand distribution function.

P_1: Service level which is the probability of not having a stock-out.

P_2: Service level which is the fraction of demand to be satisfied routinely from shelf.

TRC: Expected annual total relevant cost.

4.1.3 Mathematic model

The mathematic model is based on expensive and slow-moving items [4].

Theorem 1: when demand is so small, we use discrete distribution like Poisson distribution to simulate the demand in the lead time. In the Poisson distribution [41], mean and variance are considered to be equal. $\sigma_L = \sqrt{\mu_L}$.

Probability of an outcome of x when expected demand in lead time is variance:

$$\mathrm{P}(\mathrm{x}|\mu_L) = \frac{{\mu_L}^x}{x!} \times e^{-\mu_L}, \mathrm{x} \in \{0,1,2,3,4\ldots\}$$

Theorem 2: indifference between reorder points (s) and (s+1) when Q>1:

$$\frac{P(s+1|\mu_L)}{P_{\leq}(s|\mu_L)} = \frac{QVr}{DB_1}$$

Where,

$P(s+1|\mu_L) =$ probability that a Poisson variable with mean μ_L takes on the value $s+1$.

$P_{\leq}(s|\mu_L) =$ probability that a Poisson variable with mean μ_L takes on the value less than or equal to s.

In an inventory control model using (s, Q) system, the safety stock is the average level of net stock when a new order arrives, and it is kept to reduce the risk of a stock-out.

According to the relationship between order size, reorder point and safety stock, we can see that: $s = \mu_L + ss$.

Figure 4-1 shows how the inventory level changes over time involving with order size, reorder point and safety stock.

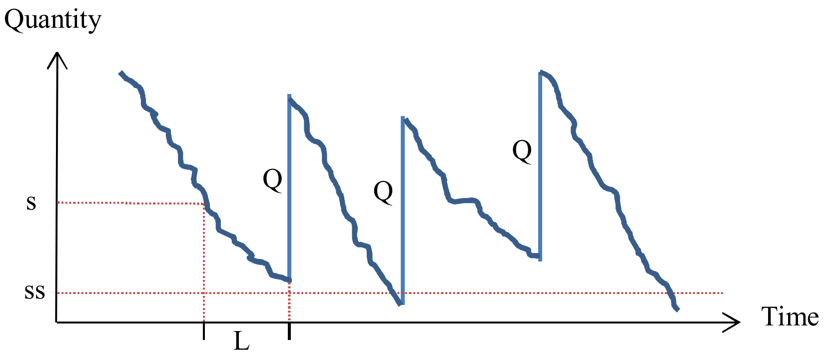


Figure 4-1 Representation of order size, reorder point and safety stock

According to theorem 3, for a given item, values of Q, V, r, D and B_l are used to evaluate the critical ratio $CR = \frac{QVr}{DB_1}$. The reorder point s corresponding to this critical ratio is the best value to use.

In an inventory control model with uncertain demand, safety stock equals to remaining stock for outcomes multiplied by corresponding demand probability. Therefore, safety stock is: $ss = \sum_0^s (s - x) \times P(x|\mu_L)$, and inventory holding cost for safety stock is $V \times r \times ss = 365 \times H \times ss$. Expected number of stock-outs in a cycle is $ES = \sum_s^\infty (x - s) \times P(x|\mu_L)$. If potential reorder point is more than determined reorder point there will be out of stock. Probability of having stock-out is $P_>(x = s|\mu_L) = \sum_{x=s}^\infty P(x|\mu_L)$ and stock-out cost is $\frac{D}{Q} \times B_1 \times P_>(s|\mu_L)$. Service level P_1 is $1 - P_>(s|\mu_L)$, and service level P_2 is $1 - \frac{ES}{Q}$. If order size is Q for each time, we need to make $\frac{D}{Q}$ orders in one year. The ordering costs is $\frac{D}{Q} \times A$ and cyclical inventory holding cost is $\frac{1}{2} \times 365 \times H \times Q$. The annual total relevant cost is :

$$TRC(Q, s) = \frac{D}{Q} \times A + \frac{1}{2} \times 365 \times H \times Q + 365 \times H \times ss + \frac{D}{Q} \times B_1 \times P_>(s|\mu_L)$$

4.1.4 Model application

We will take one kind of slow-moving spare parts which is called generator transformer as an example to show the improvement of the proposed control inventory policy which is determined by mathematical model. The general information is shown in table 4-2.

Table 4-2 General information of generator transformer

Unit value	**39,000 dollars**
Lead time	36 days
Stock-out costs	**35,000 dollars each time**
Holding costs	10 dollars per day for each unit
Ordering costs	**850 dollars each time**
Annual demand in 2011	9
Demand in each production line	**1**
Valid period in warehouse	450 days

There are four main production lines and two relevant assistant machines in the power plant. Each production line can be independently completed all the work required for electricity generation. The assistant equipment is used to deal with extra steam with high temperature and high pressure. Some treated steam goes back to the combustion system and some hot water will be an important heating source for houses. Each machine is designed to serve two production lines at the same time.

Each production line and assistant equipment keeps a separate stock. Annual demand in 2011 for all the production lines and assistant equipment is 9. No matter which one is broken, if there is no spare part there will be production losses.

The current inventory control policy is to replace the broken component with the corresponding spare part and send orders to the suppliers immediately once the failure component is replaced.

Inventory control activities in one of production lines are shown in figure 4-1.

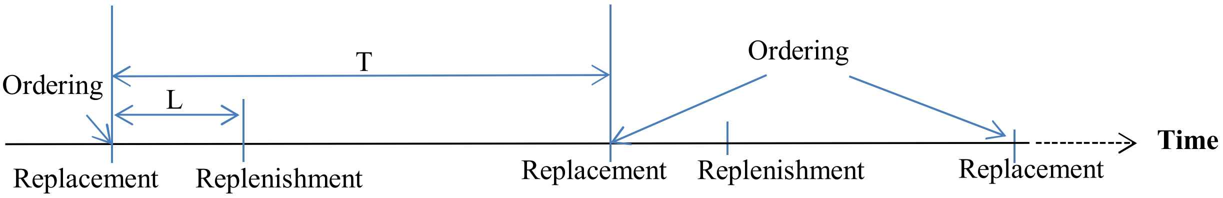


Figure 4-1 Representation of inventory control activities

Generally speaking, the probability of components failure during the lead time under current policy is quite low because that the lifetime of spare part is much larger than lead time. Managers in our case kept one extra item for each production line and assistant equipment as safety stock in order to avoid emergency case, such as non-standard installation, which could lead to much shorter lifetime than usual.

Under current policy, figure 4-2 shows the change of inventory level for one of production lines.

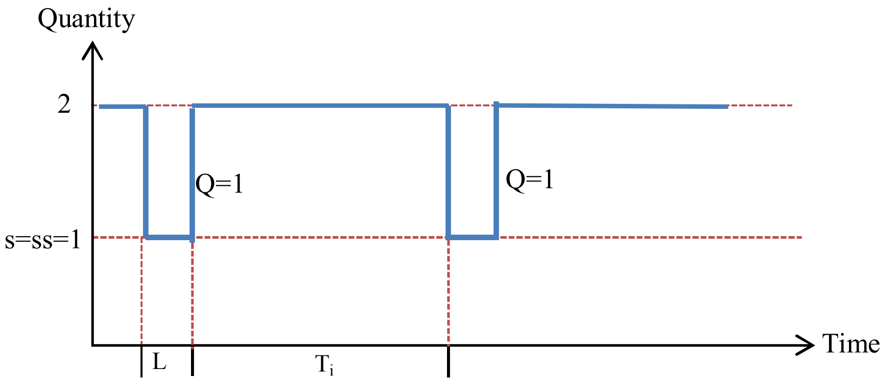
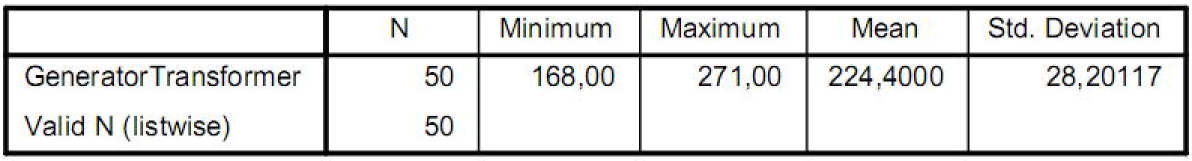


Figure 4-2 change of inventory level under current policy

We use SPSS software to make a descriptive statistics of 50 samples and find the average lifetime of generator transformer. The result is shown below:

Table 4-1 Descriptive statistics of generator transformer samples



	N	Minimum	Maximum	Mean	Std. Deviation
GeneratorTransformer	50	168,00	271,00	224,4000	28,20117
Valid N (listwise)	50				

The average lifetime of generator transformers is 224.4 days, which means that annual demand of each production line and assistant equipment is 1.63. Cyclic inventory cost is the average size of the cyclic stock multiplied by the unit value. Since the lead time is 36 days and lifetime is 224.4 days. The stock consists of two items in a much longer period than one item, and the ratio of average stock will then be closer to 1 than 0.5. Thus, instead of multiplying with 0.5, the annual inventory holding costs for cyclic inventory under current policy should be $6 \times \left(\frac{T-L}{T} \times \mathrm{Q} \times \mathrm{H} \times 365\right) = 18396$, and annual inventory holding costs for safety stock is $6 \times \mathrm{ss} \times \mathrm{H} \times 365 = 21900$. An annual ordering cost is $6 \times (\frac{D}{Q} \times A) = 6 \times 1.63 \times 850 = 8313$. The service level here is so close to 100% that we do not consider stock-out costs.

The annual total relevant cost is:

$$\mathrm{TRC} = 18396 + 21900 + 8313 = 48609 \text{ dollars}$$

We can see that each production line or equipment has their own independent inventory control system in current inventory control policy. Actually, using same component means that we can take all the production lines and equipment involving with same component in as a whole system. Orders from different production lines can be coordinated which lead to reduction of ordering costs, and inventory holding cost can also be declined due to stock centralization. The following graph shows the representation of production lines and spare parts.

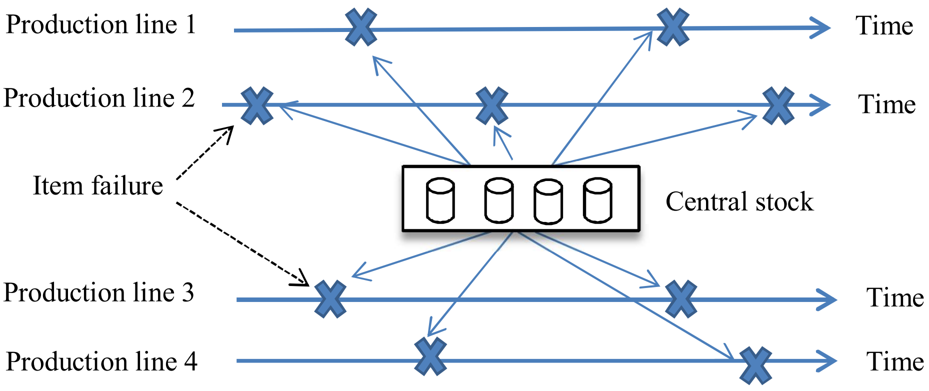


Figure 4-3 Representation of production lines and spare parts

We can use probability function from theorem 3 to find out the indifference between reorder points (s) and (s+1), where average demand in lead time is: $\mu_L = \frac{1.63\times 6}{365}\times 36 = 0.96$.

Table 4-2 Indifference between reorder point (s) and (s+1)

s	P(s)	$P_{\leqslant}(s)$	P(s+1)/ $P_{\leqslant}(s)$
0	0.381887	0.381887	0.962630
1	0.367616	0.749503	0.236075
2	0.176939	0.926442	0.061284
3	0.056776	0.983218	0.013897
4	0.013663	0.996882	0.002639
5	0.002631	0.999512	0.000422
6	0.000422	0.999934	0.000058
7	0.000058	0.999992	0.000007
8	0.000007	0.999999	0.000001

In order to find optimal order size Q, we can enumerate all possible Q and find corresponding annual total relevant cost:

$$\mathrm{TRC(Q,s)} = \frac{D}{Q}\times A + \frac{T-L}{T}\times 365\times H\times Q + 365\times \mathrm{H}\times \mathrm{ss} + \frac{D}{Q}\times B_1\times P_{>}(s)$$

If take Q=2 as an example, $\mathrm{CR} = \frac{QVr}{DB_1}$ =0.0213 which is smaller than 0.061284 and bigger than 0.013897. 0.061284 is indifference between 2 and 3, and 0.013897 is indifference between 3 and 4. Therefore reorder point should be 3 when Q=2.

Calculation results by enumeration are shown in table 4-3:

Table 4-3 List of enumeration results

Q	CR	s	TRC	P_1	P_2
1	0.0107	4	23548	99.69%	99.63%
2	0.0213	3	20684	98.31%	98.97%
3	0.0320	3	21401	98.31%	99.31%
4	0.0427	3	23292	98.31%	99.48%
5	0.0533	3	25654	98.31%	99.59%
6	0.0640	2	28122	92.61%	98.42%
7	0.0746	2	30388	92.61%	98.65%
8	0.0853	2	32854	92.61%	98.82%

When Q=2, annual total relevant cost equals to 20684 which is minimum. Therefore, the best solution is making an order of two items each time when only three left in inventory.

4.1.5 Comparison analysis

We use total relevant cost and service level to estimate the performance of suggested inventory control policy. Comparison in total relevant cost between current and suggested policy is shown in figure 4-4. Compared with current policy, total relevant cost will be reduced by 57% if using suggested policy.

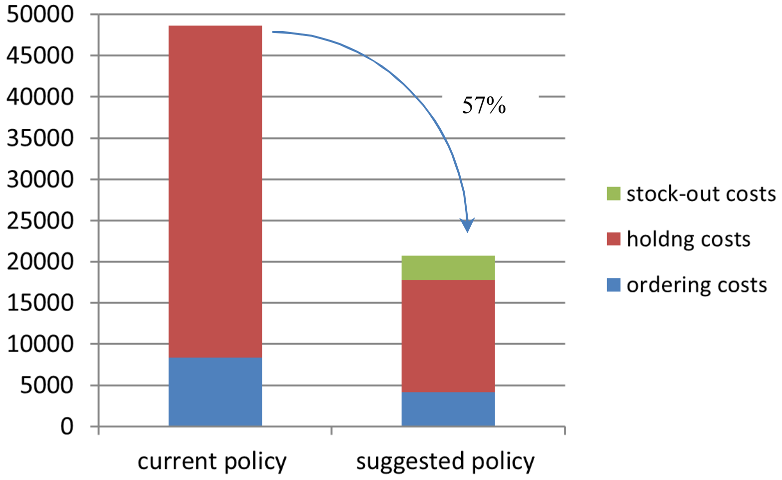


Figure 4-4 Comparison in annual total relevant cost

The figure 4-5 shows that the comparison in service level. We can see that although the suggested solution could not guarantee the safety in production for one hundred percent, 98.3% of P1 service level and 98.97% of P2 service level is acceptable for managers in our case.

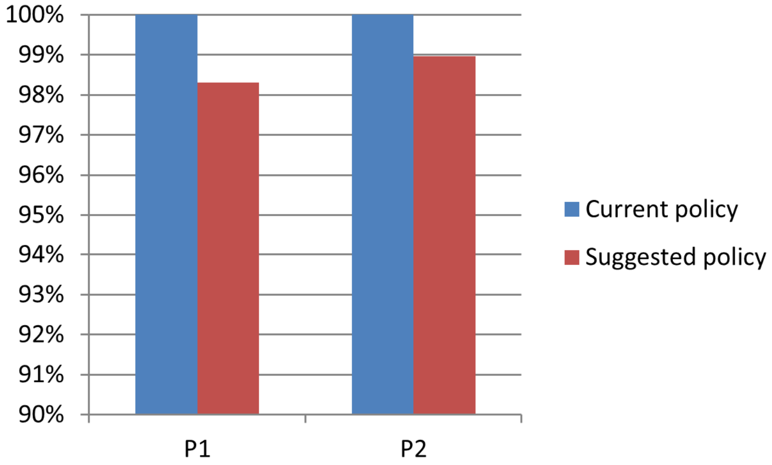


Figure 4-5 Comparison in service level

4.2 Extended application of model

In slow-moving spare parts inventory systems the situation may occur that identical parts can only be installed in one kind of equipment. For example, a spare part called pressure governor is only designed for the main transformer. We will take pressure governor as an example to find out whether the proposed inventory control model is available for some slow-moving spare parts with much longer lifetime and higher value.

4.2.1 Basic assumption

- The inventory control policy with service levels which are more than 99% can be accepted.

- Other assumptions are the same as previous ones.

4.2.2 Current policy introduction

In our case, there is only one main transformer which is shared by four main production lines. The current inventory control policy for pressure governor is the same as other usual slow-moving spare parts, namely ordering one new component once failure happens and keeping one item as safety stock.

Table 4-4 General information of pressure governor

Unit value	**45,000 dollars**
Lead time	55 days
Stock-out costs	**140,000 dollars each time**
Holding costs	11.5 dollars per day for each unit
Ordering costs	**900 dollars each time**

The average lifetime of pressure governor is 750 days, which means that annual demand equals to 0.4878. Because of low annual demand total relevant cost for ten years will be concentrated on in this case analysis. Under current policy, annual inventory holding costs is $\frac{T-L}{T} \times 365 \times H \times Q + 365 \times \mathrm{H} \times \mathrm{ss}$ =8101, and annual ordering costs is $\frac{D}{Q} \times A = 439$. Total relevant cost for ten years is $10 \times (8101 + 439) = 85400$. Meanwhile, P_1 and P_2 service level here could be considered as 100%.

4.2.3 Suggested model application

Average ten-year demand of the pressure governor (D_{10}) is 4.878. Indifferences between reorder point s and (s+1) for a demand of 0.735 in the lead time are given in table 4-5.

Table 4-5 Indifference between reorder point (s) and (s+1)

s	P(s)	$P_{\leqslant}(s)$	$P(s+1)/P_{\leqslant}(s)$
0	0.929132	0.929132	0.073504
1	0.068295	0.997427	0.002516
2	0.002510	0.999937	0.000062
3	0.000061	0.999999	0.000001

We will enumerate all possible Q and find its corresponding annual total relevant cost in table 4-6.

Table 4-6 List of enumeration results

Q	CR	s	TRC	P_1	P_2
1	0.0615	1	84184	99.74%	99.74%
2	0.1229	0	104467	93.00%	96.31%
3	0.1844	0	134706	93.00%	97.55%
4	0.2459	0	169344	93.00%	98.16%
5	0.3073	0	205741	93.00%	98.53%

The best inventory control policy is ordering item each time when inventor level reaches to reorder point s=1. Total relevant cost for ten years equals to 84184, 0.929 items are left as safety stock. We also can find P_1 and P_2 service level is 99.74%.

4.2.4 Comparison analysis

In figure 4-4, we can see that there is not too much difference between current and suggested policy in ten-year total relevant cost. Compared with current policy, 2% of reduction in total relevant cost means that the improvement is not obvious if using suggested policy.

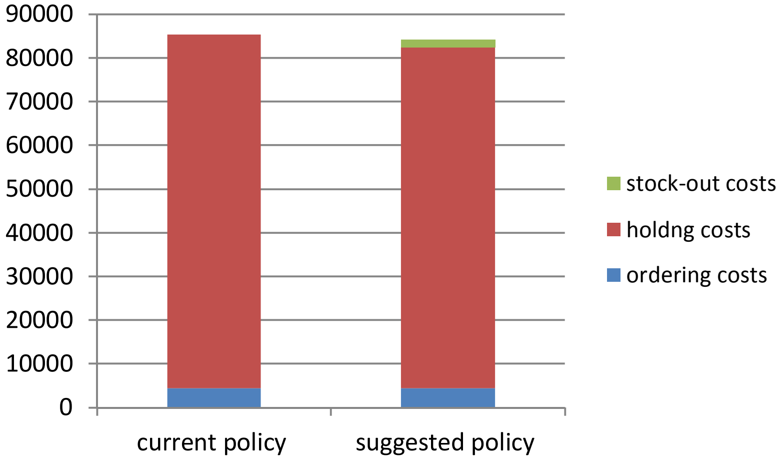


Figure 4-6 Comparison in total relevant cost for ten years

Figure 4-5 shows the comparison in service level between two policies. Although there is a little reduction in service level after using suggested policy, 99.74% of P_1 is also acceptable for the managers in power plant.

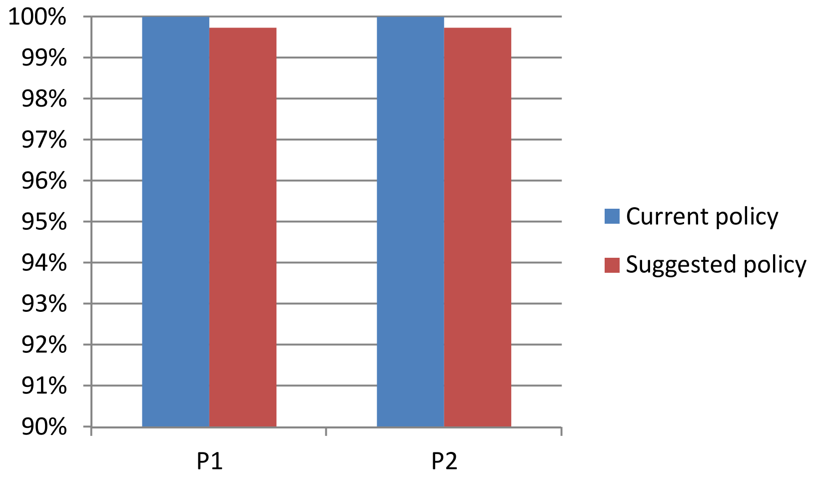


Figure 4-7 Comparison in service level

Actually the current policy and suggested policy could be considered as the same policy if calculation error is disregard.

4.3 Inventory control policy for repairable components

In many applications, components can be returned to an operational state by repair other than just replacement, that is, they are repairable. If components can be repairable, their corresponding spare parts are also repairable. In our case, repairable spare parts with high value and low commonality are one kind of common slow-moving spare parts.

Louit et al. [3] presented an optimization model for repairable spare parts inventories based on an assumption that repair is perfect, which means that the broken component is returned to the central stock in a new state after it is repaired, and that components can always be repaired. In our practical case, the expected number of repairs for the same component over its lifetime is limited. For example, main axle can only be repaired for around 4 times and after that it will be abandoned. We describe models under an opposite assumption, namely limited repair capacity, that there is limit on the number of repairs that can be performed simultaneously at the workstation.

4.3.1 Basic assumption

- Limited repair capacity and each repair is not perfect.
- Repair time is much shorter than lead time and its effect can be disregarded.
- The inventory control policy with service levels which are more than 99% can be accepted.
- Other assumptions are the same as previous ones.

4.3.2 Parameter definition

m: Besides the parameters which have been introduced, the number of repair times should also be considered. Because that the actual lifetime of repairable component is determined by how many times it will be repaired. The more times the component is repaired, the longer lifetime it will have, and lower annual demand there will be.

pc: Purchasing cost. As one important part of total relevant logistics costs, it is ignored in previous model application because of fixed annual demand. However, annual demand could be changed for repairable spare parts, and purchasing cost should be considered in this case.

R: Repair costs.

4.3.3 Current policy introduction

Main axle of suction fan, as one typical repairable component, is used to show the current inventory control situation. For repairable components, whenever a component fails or is preventively removed from operation it is replaced by a spare part, and the removed component is sent to a repair workstation for repair or maintenance. Once repair has been completed, the component is sent to the stock where it waits until it is needed for next operation. The representation of repairable spare parts is shown in figure 4-8.

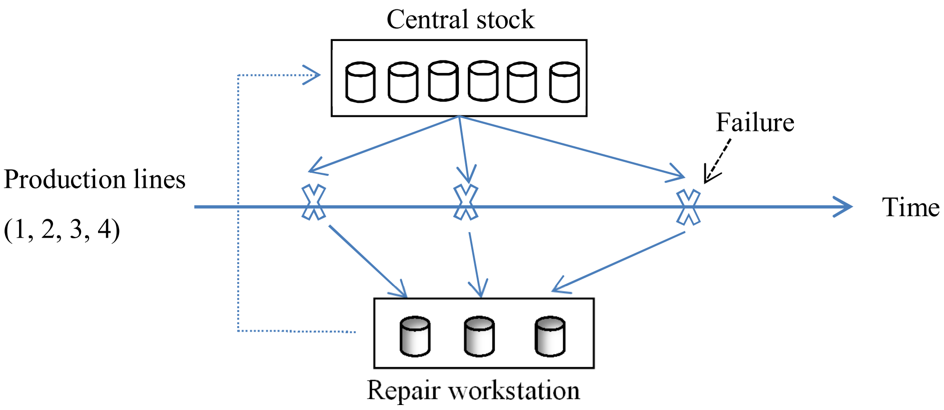


Figure 4-8 Representation of repairable spare parts

In the power plant, each production line needs only one such component. There are always four spare parts available kept in the central stock. Managers usually place an order for one new main axle only when one of the components is scrapped. Under current policy, figure 4-9 shows the change of inventory level in the central stock.

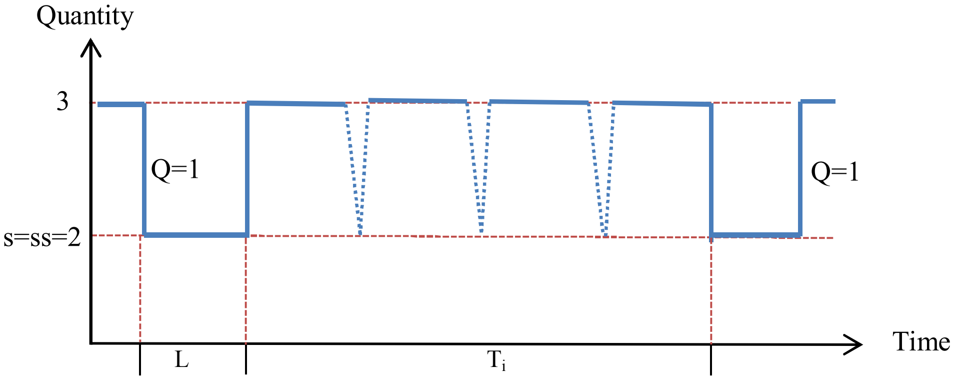


Figure 4-9 Change of inventory level for repairable components

Service time of the repairable component usually decreases gradually with the increase in the number of maintenance. The decreases in service time are not obvious for the first few times, but apparent reduction will happen after that. Take one of main axles as an example, the service time for the first three-time repairs is 141 days, 135 days, and 113 days respectively. Even though the component can be continued to be repaired, after multiple repairs it could only be working for no more than 30 days. The average lifetime according to the number of repairs based on 20 samples is shown below:

Table 4-7 Average lifetime according to the number of repairs

No. of repairs	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Lifetime (days)	151	292	427	540	572	594	604	615	620

The other general information of main axle is shown below:

Table 4-8 General information of main axle

Unit value	**11200 dollars**
Lead time	30 days
Stock-out costs	**35000 dollars each time**
Holding costs	3 dollars per day for each unit
Ordering costs	**320 dollars**
Repairing costs	2200 dollars each time per unit

In the power plant, the repairable components are repaired for as many times as possible. Therefore, the average lifetime of main axle for current policy is 620 days. The annual demand is less than one, and we need to focus on the ten-year total relevant costs.

The ten-year demand (D_{10}) is 5.89 items. For each item, it needs to be repaired for 8 times. Therefore, total repair cost for ten years is $\mathrm{m} \times \mathrm{R} \times D_{10} = 8 \times 2200 \times 5.89 = 103664$. Ten-year purchasing cost is $D_{10} \times \mathrm{V} = 5.89 \times 11200 = 65968$. Total ten-year ordering cost is $\frac{D_{10}}{Q} \times A = \frac{5.89}{1} \times 320 = 1884.8$. Inventory holding costs for safety stock is $\mathrm{ss} \times \mathrm{H} \times 3650 = 2 \times 3 \times 3650 = 21900$. Inventory holding costs for cyclic stock is $(\frac{620-30}{620} \times Q \times H \times 3650 = 0.95 \times 1 \times 3 \times 3650 = 10420$. The service level here is so close to 100% that we do not consider stock-out costs.

Total ten-year relevant cost is:

$$103664 + 65968 + 1884.8 + 21900 + 10420 = 203837$$

4.3.4 Model application

Although repairable component is different from usual component, the suggested inventory control model is also available in making the decisions.

The function of total ten-year relevant cost is determined by three variables, namely number of repairs, order size and reorder point. In order to find out the best inventory control policy, we should firstly enumerate all possible number of repairs, and get an optimal solution by using suggested inventory control when number of repairs is confirmed. The maximum number of repairs is eight in this case which means there will be eight possible optimal solutions. Then compare these candidates to make sure which the best solution is. Specific calculation processes are shown below.

When m=0, the repairable spare parts can be considered as unrepairable ones. Thus, there is no repair cost for the ten years. The average lifetime is 151 days and ten-year demand is 24.2. Purchasing cost is $D_{10} * V = 24.2 * 11200 = 271040$. Indifferences between reorder point s and (s+1) for a demand of 0.1989 in the lead time are given in table 4-9.

Table 4-9 Indifference between reorder point (s) and (s+1) when m=0

s	P(s)	$P_{\leqslant}(s)$	P(s+1)/ $P_{\leqslant}(s)$
0	0.819628	0.819628	0.198904
1	0.163027	0.982656	0.016500
2	0.016213	0.998869	0.001076
3	0.001075	0.999944	0.000053
4	0.000053	0.999998	0.000002
5	0.000002	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-10 Enumeration results when m=0

Q	CR	s	TRC	P_1	P_2
1	0.0129	2	309879	99.89%	99.88%
2	0.0259	1	312037	98.27%	99.07%
3	0.0388	1	318700	98.27%	99.38%
4	0.0517	1	327233	98.27%	99.54%
5	0.0646	1	336514	98.27%	99.63%

We can find that the minimum total relevant cost is 309879 and Q=1, s=2 is the best inventory control policy.

When m=1, the components will be abandoned after only one-time repair. The average lifetime is 292 days and ten-year annual demand is 12.5. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 27500$ and purchasing cost is $D_{10} * V = 12.5 * 11200 = 140000$. Indifferences between reorder point s and (s+1) for a demand of 0.1027 in the lead time are given in table 4-11.

Table 4-11 Indifference between reorder point (s) and (s+1) when m=1

s	P(s)	$P_{\leqslant}(s)$	$P(s+1)/ P_{\leqslant}(s)$
0	0.902362	0.902362	0.102740
1	0.092708	0.995070	0.004786
2	0.004762	0.999833	0.000163
3	0.000163	0.999996	0.000004
4	0.000004	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-12 Enumeration results when m=1

Q	CR	s	TRC	P_1	P_2
1	0.0250	1	193940	99.51%	99.49%
2	0.0501	1	201264	99.51%	99.74%
3	0.0751	1	210641	99.51%	99.83%
4	0.1001	1	220530	99.51%	99.87%
5	0.1251	0	228856	90.24%	97.95%

We can find that the minimum total relevant cost is 193940 and Q=1, s=1 is the best inventory control policy.

When m=2, the components will be abandoned after two-time repairs. The average lifetime is 427 days and ten-year annual demand is 8.55. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 37620$ and purchasing cost is $D_{10} * V = 8.55 * 11200 = 95760$. Indifferences between reorder point s and (s+1) for a demand of 0.07 in the lead time are given in table 4-13.

Table 4-13 Indifference between reorder point (s) and (s+1) when m=2

s	P(s)	$P_{\leqslant}(s)$	$P(s+1)/ P_{\leqslant}(s)$
0	0.932138	0.932138	0.070274
1	0.065505	0.997643	0.002307
2	0.002302	0.999945	0.000054
3	0.000054	0.999999	0.000001
4	0.000001	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-14 Enumeration results when m=2

Q	CR	s	TRC	P_1	P_2
1	0.0366	1	157431	99.76%	99.76%
2	0.0732	0	165707	93.21%	96.49%
3	0.1098	0	172269	93.21%	97.66%
4	0.1464	0	180751	93.21%	98.24%
5	0.1830	0	190001	93.21%	98.59%

We can find that the minimum total relevant cost is 157431 and Q=1, s=1 is the best inventory control policy.

When m=3, the components will be abandoned after three-time repairs. The average lifetime is 540 days and ten-year annual demand is 6.76. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 44616$ and purchasing cost is $D_{10} * V = 6.76 * 11200 = 75712$. Indifferences between reorder point s and (s+1) for a demand of 0.055 in the lead time are given in table 4-15.

Table 4-15 Indifference between reorder point (s) and (s+1) when m=3

s	P(s)	$P_{\leqslant}(s)$	$P(s+1)/P_{\leqslant}(s)$
0	0.945954	0.945954	0.055562
1	0.052559	0.998512	0.001462
2	0.001460	0.999973	0.000027
3	0.000027	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-16 Enumeration results when m=3

Q	CR	s	TRC	P_1	P_2
1	0.0463	1	143604	99.85%	99.85%
2	0.0926	0	148608	94.60%	97.22%
3	0.1388	0	156519	94.60%	98.15%
4	0.1851	0	165676	94.60%	98.61%
5	0.2314	0	175331	94.60%	98.89%

We can find that the minimum total relevant cost is 143604 and Q=1, s=1 is the best inventory control policy.

When m=4, the components will be abandoned after four-time repairs. The average lifetime is 572 days and ten-year annual demand is 6.38. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 56144$ and purchasing cost is $D_{10} * V = 6.38 * 11200 = 71456$. Indifferences between reorder point s and (s+1) for a demand of 0.052 in the lead time are given in table 4-17.

Table 4-17 Indifference between reorder point (s) and (s+1) when m=4

s	P(s)	$P_{\leqslant}(s)$	$P(s+1)/\ P_{\leqslant}(s)$
0	0.948913	0.948913	0.052438
1	0.049759	0.998672	0.001306
2	0.001305	0.999977	0.000023
3	0.000023	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-18 Enumeration results when m=4

Q	CR	s	TRC	P_1	P_2
1	0.0490	1	150731	99.87%	99.86%
2	0.0981	0	155130	94.89%	97.38%
3	0.1471	0	163291	94.89%	98.25%
4	0.1961	0	172572	94.89%	98.69%
5	0.2452	0	182302	94.89%	98.95%

We can find that the minimum total relevant cost is 150731 and Q=1, s=1 is the best inventory control policy.

When m=5, the components will be abandoned after five-time repairs. The average lifetime is 594 days and ten-year annual demand is 6.14. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 67540$ and purchasing cost is $D_{10} * V = 6.14 * 11200 = 68768$. Indifferences between reorder point s and (s+1) for a demand of 0.05 in the lead time are given in table 4-19.

Table 4-19 Indifference between reorder point (s) and (s+1) when m=5

s	P(s)	$P_{\leqslant}(s)$	$P(s+1)/ P_{\leqslant}(s)$
0	0.950786	0.950786	0.050466
1	0.047982	0.998769	0.001212
2	0.001211	0.999979	0.000020
3	0.000020	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-20 **Enumeration results when m=5**

Q	CR	s	TRC	P_1	P_2
1	0.0510	0	159251	95.08%	94.95%
2	0.1019	0	163883	95.08%	97.48%
3	0.1529	0	171696	95.08%	98.32%
4	0.2038	0	181053	95.08%	98.74%
5	0.2548	0	190827	95.08%	98.99%

We can find that the minimum total relevant cost is 159251 and Q=1, s=1 is the best inventory control policy.

When m=6, the components will be abandoned after six-time repairs. The average lifetime is 604 days and ten-year annual demand is 6.04. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 79728$ and purchasing cost is $D_{10} * V = 6.04 * 11200 = 67648$. Indifferences between reorder point s and (s+1) for a demand of 0.0496 in the lead time are given in table 4-21.

Table 4-21 **Indifference between reorder point (s) and (s+1) when m=6**

s	P(s)	$P_{\leqslant}(s)$	$P(s+1)/P_{\leqslant}(s)$
0	0.951568	0.951568	0.049644
1	0.047239	0.998808	0.001174
2	0.001173	0.999980	0.000019
3	0.000019	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-22 Enumeration results when m=6

Q	CR	s	TRC	P1	P2
1	0.0518	0	169950	95.16%	95.04%
2	0.1036	0	174267	95.16%	97.52%
3	0.1554	0	182641	95.16%	98.35%
4	0.2072	0	192029	95.16%	98.76%
5	0.2590	0	201823	95.16%	99.01%

We can find that the minimum total relevant cost is 169950 and Q=1, s=1 is the best inventory control policy.

When m=7, the components will be abandoned after seven-time repairs. The average lifetime is 615 days and ten-year annual demand is 5.93. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 91322$ and purchasing cost is $D_{10} * V = 5.93 * 11200 = 66416$. Indifferences between reorder point s and (s+1) for a demand of 0.0487 in the lead time are given in table 4-23.

Table 4-23 Indifference between reorder point (s) and (s+1) when m=7

s	P(s)	P≤(s)	P(s+1)/ P≤(s)
0	0.952429	0.952429	0.048740
1	0.046421	0.998850	0.001133
2	0.001131	0.999981	0.000018
3	0.000018	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-24 Enumeration results when m=7

Q	**CR**	**s**	**TRC**	**P_1**	**P_2**
1	0.0528	0	179911	95.24%	95.13%
2	0.1055	0	184428	95.24%	97.56%
3	0.1583	0	192896	95.24%	98.38%
4	0.2110	0	192869	95.24%	98.38%
5	0.2638	0	212105	95.24%	99.03%

We can find that the minimum total relevant cost is 179911 and Q=1, s=1 is the best inventory control policy.

When m=8, the components will be used until it cannot be repaired anymore. The average lifetime is 620 days and ten-year annual demand is 5.887. The repair cost for ten year is $\mathrm{m} * \mathrm{R} * D_{10} = 103611$ and purchasing cost is $D_{10} * V = 5.887 * 11200 = 65934$. Indifferences between reorder point s and (s+1) for a demand of 0.0487 in the lead time are given in table 4-25.

Table 4-25 Indifference between reorder point (s) and (s+1) when m=8

s	**P(s)**	**$P_{\leqslant}$(s)**	**P(s+1)/ $P_{\leqslant}$(s)**
0	0.952766	0.952766	0.048386
1	0.046101	0.998866	0.001117
2	0.001115	0.999982	0.000018
3	0.000018	1.000000	0.000000

We enumerate the possible order size and find corresponding reorder point and total ten-year relevant cost.

Table 4-26 Enumeration results when m=8

Q	CR	s	TRC	P_1	P_2
1	0.0531	0	191564	95.28%	95.16%
2	0.1063	0	196159	95.28%	97.58%
3	0.1594	0	204625	95.28%	98.39%
4	0.2126	0	214060	95.28%	98.79%
5	0.2657	0	223881	95.28%	99.03%

We can find that the minimum total relevant cost is 191564 and Q=1, s=1 is the best inventory control policy.

All the above results are summarized in table 4-27.

Table 4-27 Summary of calculation results for repairable spare parts

m	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Q	1	1	1	1	1	1	1	1	1
s	2	1	1	1	1	0	0	0	0
TRC	309879	193940	157431	143604	150731	159251	169950	179911	191564
P_1	99.89%	99.51%	99.76%	99.85%	99.87%	95.08%	95.16%	95.24%	95.28%
P_2	99.88%	99.49%	99.765	99.85%	99.86%	94.95%	95.04%	95.13%	95.16%

According to the table 4-27, we can easily find that the minimum TRC whose corresponding inventory control policy is order size Q=1, reorder point s=1, and number of repairs for each component m=3. Meanwhile, the service level is $P_1 = P_2$=99.85%.

4.3.5 Comparison analysis

Different cost elements of two policies are presented in table 4-28.

Table 4-28 Comparison in cost elements

	Ordering cost	Holding cost	Purchase cost	Stock-out cost	Repair cost	TRC
Current	1885	32320	65968	0	103664	203837
Suggested	2163	20761	75712	352	44616	143604

Compared with current inventory control policy, there is an apparent decrease in ten-year total relevant cost of suggested inventory control policy.

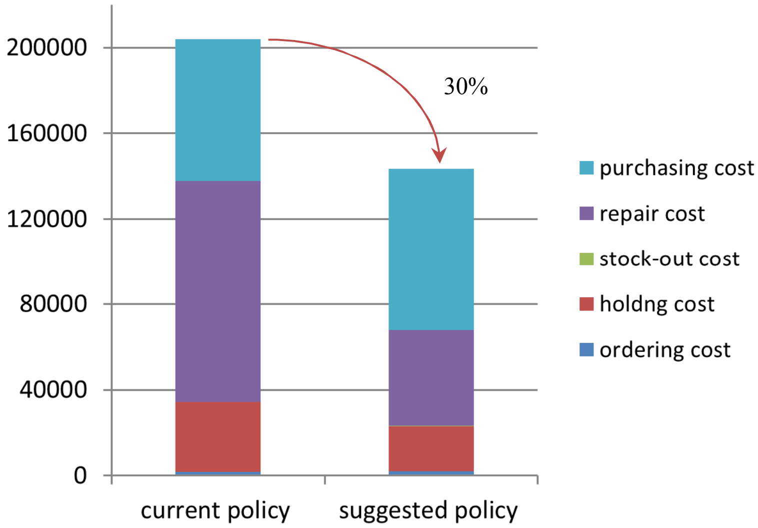


Figure 4-10 Comparison in ten-year total relevant cost

Figure 4-11 shows the comparison in service level between two policies. 99.85% of P_1 and P_2 are also acceptable for the managers in power plant.

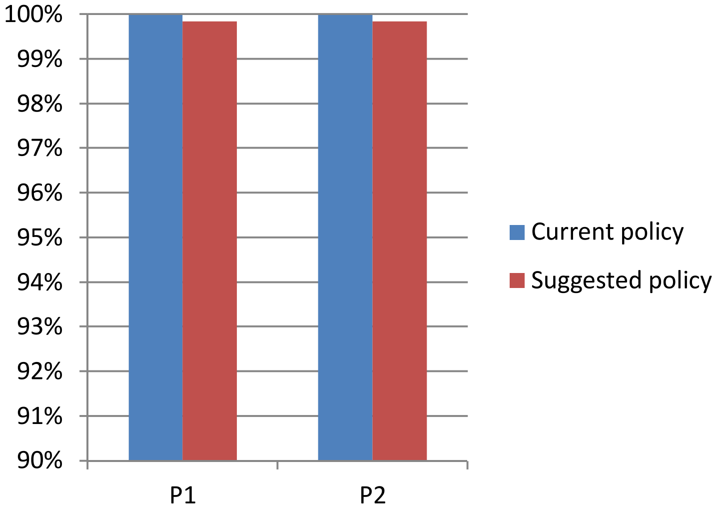


Figure 4-11 Comparison in service level

4.3.6 Other slow-moving spare parts' fits into the model

Some slow-moving spare parts are chosen from table 3-1 to show how these parts' fits into the model. Like the generator transformer, they are all ordinary and non-repairable. From the table 4-29, we can see that the reduction in annual TRC is obvious and the service levels are lower than 98%, which means that they are acceptable for managers.

Table 4-29 Model application to other slow-moving spare parts

Item	Current policy					Suggested policy					Costs saving
	Q	s	TRC	P_1 %	P_2 %	Q	s	TRC	P_1 %	P_2 %	
Diesel generator	4	8	24470	99.97	99.99	2	7	19636	99.80	99.92	4834
6 kv Station section	6	12	24312	99.99	100	3	9	17836	99.95	100	6476
Forced draft fan	15	10	10060	99.99	100	10	6	8200	99.73	99.97	1860
Unit auxiliary transformer	5	6	45629	99.99	100	2	4	27381	99.70	99.82	18248

For some spare parts we cannot cover in this paper, it is possible that the annual or ten-year total relevant cost of suggested policy can be reduced, while its service levels are not acceptable. When this optimal policy cannot be used, we can also use the model to find minimum total cost under acceptable service levels by adjusting the reorder point and order size.

4.4 Summary for model application

The table 4-30 shows the details of new suggested strategy for each of the parts we are treating in this thesis, such as service levels, order size, reorder point, annual total relevant costs and total cost savings.

This paper concentrates on total seven kinds of slow-moving spare parts. Besides these seven cases which have been introduced, there are still many different cases worth to be analyzed in the future.

Table 4-30 Summary for different cases

Item	Q	s	m	TRC	P_1 %	P_2 %	Costs saving
Generator transformer	2	3	0	20684	98.31	98.97	27925
Pressure governor	1	1	0	8418.4	99.74	99.74	0
Main axle	1	1	3	14360	99.85	99.85	6023
Diesel generator	2	7	0	19636	99.80	99.92	4834
6 kv Station section	3	9	0	17836	99.95	100	6476
Forced draft fan	10	6	0	8200	99.73	99.97	1860
Unit auxiliary transformer	2	4	0	27381	99.70	99.82	18248

5 Conclusion

Conclusively, a description of the slow-moving spare parts inventory management in the NEPP power plant has been presented. A two-stage spare parts classification approach is developed for category management of spare parts. To assist the managers in reducing total relevant costs of inventory management, a mathematical model has been introduced for developing a better inventory control policy than the current one. The model determines the optimal order size and reorder point which result in the minimum total relevant costs.

Conclusions can be summarized as follows：

- Compared with the traditional ABC classification method, a two-stage spare parts classification is more efficient in identifying the slow-moving items among all the spare parts.

- For unrepairable slow-moving spare parts, like a generator transformer, the suggested inventory control model can provide a better control policy with an acceptable service level than the current one.

- For some slow-moving spare parts, like a pressure governor which has much longer lifetime compared to the other parts, the suggested policy turns out to be the same as current one. Even though there is no improvement, our inventory control model is also effective to confirm that the current policy is optimal.

- For repairable slow-moving spare parts, like a main axle, the suggested inventory control model is also available. As a new parameter, the number of repairs is added to the inventory control policy. The results show that we can use the suggested model to find a better policy than the current one and still maintain a service level which is acceptable for the managers of the power plant.

5.1 Research limitation

Besides the three main cases which have been introduced, we apply the inventory control model to some other slow-moving spare parts. The results in table 4-29 show the effectiveness of the model in these slow-moving spare parts. However, we cannot find the optimal inventory control policy for all the slow-moving spare parts taking account into the limited time and resources in this paper.

5.2 Further study issue

As we know about the power plant, the actual situation is more complex than the description of the model. For some parts there are some special requirements that needs to be considered. For example, corrosion of rubber due to long-term stock will lead to invalidation of spare parts, and huge body size of some spare parts may be out of the warehouse capacity. Therefore, our inventory control model can be modified and extended by adding some parameters to deal with those special cases, such as spare parts with period of validity and warehouse space.

Meanwhile, efficient inventory management of slow-moving spare parts can also be achieved by external cooperation.

For faster-moving spare parts, they can be provided by many different suppliers. Some modern management approaches, such as JIT (Just in Time) and VMI (Vendor Manage Inventory) can be applied. However the slow-moving spare parts can only be purchased from one or two suppliers. Due to high value and low demand of slow-moving items, the suppliers often produce the spare parts according to orders and will not keep the inventory themselves. The huge pressure from the inventory of slow-moving spare parts is handled only by the purchasers who want to use them. For inventory management of spare parts, JIM (Jointly Managed Inventory) approach is suitable for slow-moving items with high value, low demand, and strong specialty. For example, some plants which are located closely and have the same equipment could manage their inventory jointly. On the basis of internal inventory management, the inventory level could be reduced further by sharing the inventory between external partners. Therefore, it is significant to build an inventory management system based on both JIM and internal inventory control policy.

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