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Research on Preventive Maintenance Strategy of Elevator Equipment

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Abstract

The real estate industry is booming with the accelerating process of urbanization. The elevator is widely used as an important part of the building and its sales volume and usage have continued to grow. The frequent occurrence of elevator accidents aroused people's attention in real life. Therefore, it is very important to strengthen the elevator maintenance process. This paper studies the optimal maintenance strategy of elevators within finite life from the perspective of preventive maintenance to reduce the failure rate of elevators. The number of elevator preventative maintenance and the time interval were found by establishing a target programming optimization model. Finally, the validity of the model is verified by numerical example.

Keywords

Elevator Equipment, Preventive Maintenance, Mixed Adjustment Factor, Optimal Maintenance Strategy

1. Introduction

Nowadays, the elevator has become an indispensable tool in people's daily life with the development of economy and urbanization. Although elevators bring convenience to people in life, the safety problems of elevators have aroused the attention of all parties due to frequent swallowing or fall incident in elevators, as shown in Table 1. Therefore, the elevator needs regular maintenance in order to ensure that the elevators can operate stably, efficiently and safely. However, there are many problems in the actual maintenance of elevator equipment which make it difficult to guarantee the safe operation of the elevator, such as improper maintenance methods, improper updating of elevator equipment, high maintenance costs and so on. So, it is the primary problem for the safe operation

Table 1. The number of elevator accidents (occurred in China).

year	2009	2010	2011	2012	2013	2014	2015	2016
number	45	44	57	36	70	48	58	49

of the elevator to take which scientific management approach to reduce the equipment failure rate.

There are many scholars to study the preventive maintenance of equipment. Lim *et al.* constructed a periodic preventive maintenance plan model for the equipment by setting the number of preventive maintenance times as the optimization variable [1]. Zhuo *et al.* considered the equipment maintenance costs, equipment age, learning effects and other factors into the improvement factor model and established a periodic preventive maintenance model of reliability limit device [2]. Qin *et al.* introduced the service age decline factor and the inefficiencies increment factor for the recession system, established a single equipment prevention and repair non-new model, and optimized the dynamic sequential maintenance plan based on reliability [3]. Dohi sets the expected cost of per unit time as the threshold of the restricted maintenance costs strategy. If the equipment maintenance cost is less than the set threshold, the equipment only needs to be maintained and the equipment must be replaced when this threshold is reached [4]. Based on previous studies [5] [6] [7] [8] [9], this paper attempts to establish a model that satisfies certain reliability and minimizes the average maintenance cost. Finally, the optimal preventive maintenance number and preventive maintenance interval of the elevator can be obtained by solving this model.

2. Problem Description

Elevator equipment will inevitably fail because of the accumulation of running time and service age. Preventive maintenance can reduce the occurrence of equipment failure. However, this maintenance process requires a certain cost (such as labor costs, spare parts costs, outage costs). The cost of the entire system will increase if the equipment is frequently maintained (causing over-maintenance). If preventive maintenance activities are not enough, the frequency of equipment failure will be greatly increased and post-maintenance costs and downtime costs of the entire system have also increased. This paper explores the elevator equipment optimal maintenance strategy to minimize the average maintenance cost. This strategy is mainly based on the effect of preventive maintenance, which is “repair non-new”.

The problems of elevator equipment can be described as follows: there are three maintenance methods of preventive maintenance, minor repairs and equipment replacement under this preventive maintenance. The equipment is maintained by preventive maintenance in the whole life cycle, assuming that the optimal preventive maintenance cycle of the equipment is N. When the equipment system reliability in the N-th preventive maintenance reaches the threshold

R set in advance, the device will be replaced; In other N − 1 times preventive maintenance cycle, the equipment fails and cannot run, unplanned maintenance is taken (minor repairs) to restore equipment to function, but minor repairs cannot change equipment failure rate and reliability.

3. Establishment of Preventive Maintenance Model for Elevator Equipment

3.1. Model Assumptions

In order to analyze conveniently, this paper makes the following assumptions:

The model satisfies the following assumptions:

1) The initial state of the equipment is completely new;

2) The state of the equipment can be monitored and diagnosed in real time, and the occurrence of equipment failure is random;

3) Minor repairs (non-planned maintenance) are taken, when the equipment fails during preventive maintenance;

4) During the limited service life of the equipment, the maintenance mode of the equipment is only preventive maintenance and non-planned maintenance, without equipment replacement;

5) The failure of the system can be described by mathematical function, and the distribution of weibull is adopted in this paper;

6) The system has sufficient maintenance resources and the failure can be maintained in time.

3.2. Symbols Description

Firstly, the paper defines the symbols to be used in the modeling, as shown in Table 2.

3.3. Model Establishment

1) The determination of the failure rate function

Table 2. Symbols and its meanings.

Symbols	Meanings	Symbols	Meanings
i	The i-th preventive maintenance cycle	c_o	Unit downtime costs
N	The optimal number of preventative maintenance	C_{pm}	Total cost of preventive maintenance
t_i	Time interval between i-1th and i-th preventive maintenance cycle	C_r	Cost of equipment replacement
$R_{\min}$	Reliability threshold	C_d	Maintenance downtime costs
$h_i(i)$	The failure rate function of the equipment during the i-th preventative maintenance cycle	α_i	The scale parameters of the weibull distribution
t_p	Time of single prevention maintenance	β_i	The shape parameters of weibull distribution
t_f	Time of single unplanned maintenance	a_i	Service age decreasing factor
c_P	Costs of single preventive maintenance	b_i	Failure rate increasing factor
c_f	Costs of single unplanned maintenance	γ_i	Improvement factor

As the equipment age and the number of maintenance increases, the possibility of a device failure also increases. In other words, the equipment failure rate gradually increases. However, equipment maintenance work does not make it as a new unit.

This paper introduces the mixed adjustment factor based on service age decreasing factor and failure rate increasing factor and gets the failure rate function before and after the elevator equipment preventive optimization, which is shown below [10] [11] [12]:

$$h_{(i+1)}(t) = b_i h_i(t + a_i t_i), t \in (0, t_{(i+1)}) \tag{1}$$

The approximate function of failure rate is

$$h_i(t) = b_i \lambda_o(t + i a_i t_i), t \in (0, t_{(i+1)}) \tag{2}$$

Among them, a_i and b_i are judged or estimated by expert experience, which is generally the result of historical data analysis of elevator equipment operation.

2) Optimization of non-planned maintenance cost

The improvement factor is introduced to describe the improvement degree of the equipment after preventive maintenance, which reflects the functional relationship between the equipment unplanned maintenance cost and the maintenance effect. The improvement factor is set as follows [13]:

$$\gamma_i = \left(u \frac{C_{pm}}{C_r} \right)^{vi * i^w} \tag{3}$$

Among them, C_{pm} is preventive maintenance cost, C_r is replacement cost, and “$0 < C_{pm} < C_r$”, u is cost regulation coefficient, v is time adjustment coefficient, w is learning effect adjustment coefficient, $w = \ln\theta / \ln 2$, θ is percentage of empirical curves, which is according to the experience judgment or estimation.

Therefore, the numbers of failure of the equipment in the i-th and i-1th preventive maintenance cycles can be obtained:

$$m(t_i) = \int_{\gamma_{i-1}}^{\gamma_{i-1}+t_i} h(t)\,\mathrm{d}t \tag{4}$$

The cost of non-planned maintenance of equipment between the i-th and i-1th preventive maintenance cycle is:

$$C_f(i) = c_f m(t_i) = c_f \int_{\gamma_{i-1}}^{\gamma_{i-1}+t_i} h(t)\,\mathrm{d}t \tag{5}$$

3) Shutdown cost

The maintenance of the elevator equipment is bound to affect the continuous operation of the equipment, resulting in the loss of downtime. According to the above parameter, the cost of shutdown of equipment maintenance during the i-1th and i-th preventive maintenance cycles is obtained as below:

$$C_d(i) = (t_p + t_f * \gamma_i) * c_o \tag{6}$$

where, t_p is a single preventive maintenance time, t_f is a single unscheduled maintenance time, and γ_i is the improvement factor in the i-1th and i-th preventive maintenance cycles, c_o is the unit time downtime loss.

When $i = N$, at this time

$$C_d(N) = t_f * \gamma_i * c_o \tag{7}$$

4) Objective function construction

According to the above analysis, preventive maintenance cost C_{pm}, total unplanned maintenance cost C_{fm} and shutdown cost C_d constitute the total maintenance cost of the whole service life period.

When $0 < i < N$, the total maintenance cost of the *i*-th preventive maintenance cycle is

$$C_T(i) = c_f \int_{\gamma_{i-1}}^{\gamma_{i-1}+t_i} h(t)\mathrm{d}t + c_p + (t_p + t_f * \gamma_i) * c_o \tag{8}$$

When $i = N$, the total maintenance cost is:

$$C_T(N) = c_f \int_0^{t_N} h(t)\mathrm{d}t + C + C_d(N) \tag{9}$$

Combine formula (2-6) and (2-7), the equipment maintenance cost rate in the whole life is obtained:

$$E_C = \frac{1}{\sum_{i=1}^{N} t_i}\left[\sum_{i=1}^{N-1} C_T(i) + C_T(N)\right] \tag{10}$$

$$C_p = \sum_{i=1}^{N} c_p * i$$

5) Restrictions

To ensure the reliability of the elevator equipment is a prerequisite for preventive maintenance. It is assumed that the failure rate function of elevator equipment obeys Weibull distribution, that is $\lambda_i(t) = \frac{\alpha_i}{\beta_i}\left(\frac{t}{\beta_i}\right)^{\alpha_{i-1}}$. According to the failure rate, we define $\lambda(t) = \frac{f_i(t)}{R_i(t)}$, $f_i(t) = \frac{\mathrm{d}F_i(t)}{\mathrm{d}t}$, where $F(t)$ represents the failure distribution function, and $R_i(t)$ is the reliability of the elevator equipment. The unreliability of the elevator equipment is its failure situation, $R_i(t) = 1 - F_i(t)$, so, we can deduce the relationship between the failure rate of elevator equipment and its reliability, $\ln R_i(t) = 1 - \int_0^{T_{ij}} \lambda_{ij}(t)\mathrm{d}t$.

The paper supposes that the upper limit of the number of maintenance cycles is N^*, and the lower limit of reliability is 0.7, so the constraint is:

$$s.t.\begin{cases} 0.7 < R \le 1 \\ 0 < N < N^* \\ 0 < i \le N \end{cases} \tag{11}$$

So, the objective function is:

$$\begin{aligned} \min E_c &= \frac{1}{\sum_{i=1}^{N} t_i}\left[\sum_{i=1}^{N-1} C_T(i) + C_T(N)\right] \\ &= c_f \int_{\gamma_{i-1}}^{\gamma_{i-1}+t_i} h(t)\mathrm{d}t + c_p + (t_p + t_f * \gamma_i) * c_o + c_f \int_0^{t_N} h(t)\mathrm{d}t + C + C_d(N) \end{aligned} \tag{12}$$

4. Case Study

This paper takes the elevator traction machine as an example and assumes that the equipment failure rate of the system obeys the weibull distribution with shape parameter $\beta = 3.2$ and scale parameter $\alpha = 120$. Assume that the initial state of the device is completely new, that is, the initial service age of the device is 0, and the minimum reliability is $R_{\min} = 0.7$, and all values of parameters are shown in Table 3.

Therefore, the failure function is

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} = \frac{3.2}{120}\left(\frac{t}{120}\right)^{2.2} \tag{13}$$

The run-time of the equipment is 3000, a single preventive maintenance costs $c_p = 50$, a single preventive maintenance time $t_p = 10$; a single unplanned minor repair cost $c_f = 100$, a single unplanned minor repair time $t_f = 20$; unit downtime cost of loss $c_o = 30$.

For the improvement factor $\gamma_i = \left(u\frac{C_{pm}}{C_r}\right)^{vi*i^w}$, among them, the equipment preventive maintenance cost $C_{pm} = 100$, the equipment replacement cost $C_r = 40000$, the cost adjustment parameter $u = 1$, the time adjustment parameter $v = 0.005$, the empirical curve parameter percentage $\theta = 0.8$, learning effect adjustment parameters $w = -0.322$, so

$$\gamma_i = \left(\frac{100}{40000}\right)^{0.005i*i^{-0.322}} \tag{14}$$

Figure 1 shows the relationship between learning effect and improvement factors. From the graph, we can see that considering learning effect the

Table 3. List of parameter values.

Parameter meanings	Parameter symbols	Parameter values
Shape parameters	β	3.2
Scale parameters	α	120
Time of single preventive maintenance	t_p	20
Time of single minor repair	t_f	10
Cost of unit downtime	c_o	30
Cost of single preventive maintenance	c_p	100
Cost of single minor repair	c_f	50
Cost adjustment factor	u	1
Cost of equipment replacement	C_r	40,000
Time adjustment parameter	v	0.005
Learning effect adjustment parameter	w	0.8
Equipment running time	T	3000
Lowest reliability threshold	$R_{\min}$	0.7

improvement factor is more than it when without considering learning effect at the same number of maintenance. That is said the improvement factor is decreased without considering the learning effect.

The optimal solution is (0.83, 7) by using genetic algorithm to solve based on Matlab, which means that when the traction machine for the seventh preventive maintenance, the reliability threshold is 0.83, the lowest maintenance cost of the equipment is 279.3710, the optimal number of maintenance N is 7, and this time is to replace the traction machine. Table 4 shows the (R, N) combinations of the partial maintenance strategies and the average maintenance costs EC under the combination.

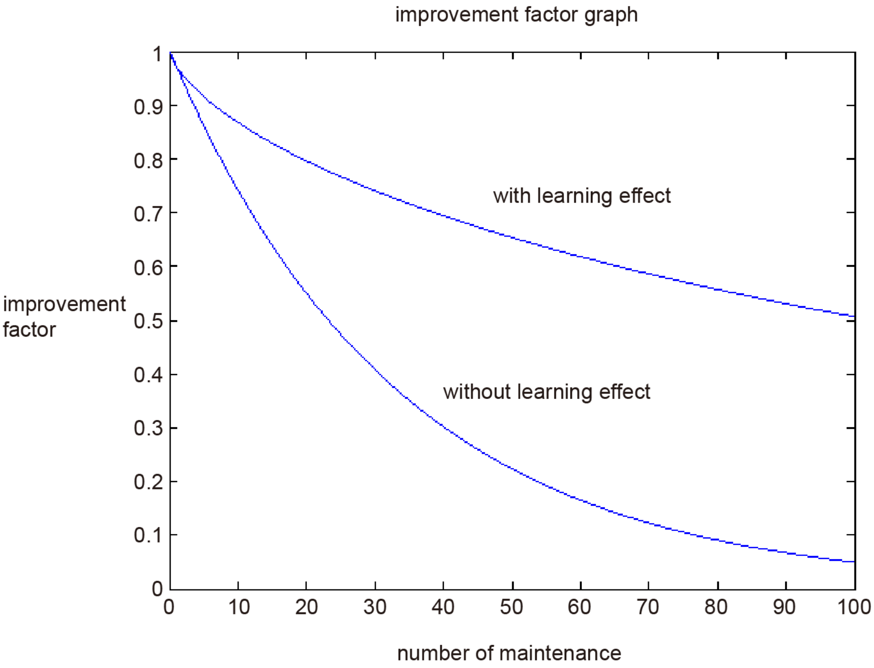

Figure 1. Comparison of improvement factors with or without learning effect.

Table 4. E_C values for some maintenance strategies (R, N).

R	0.76	0.82	0.83	0.84	0.90	0.94
N = 1	420.2597	431.6322	438.5527	457.9085	468.2121	482.1182
N = 2	373.8962	381.2114	383.3432	386.1132	395.7603	409.0522
N = 3	354.2891	358.7924	360.3051	364.9466	369.1164	372.2639
N = 4	336.8621	342.3226	344.9734	346.2639	349.1796	355.3397
N = 5	304.8090	305.3432	307.8987	310.3159	312.9153	337.1135
N = 6	297.9085	299.2114	301.8621	304.7672	310.5573	326.2121
N = 7	283.1148	280.8962	279.3710	281.9153	285.0121	293.3226
N = 8	284.2891	282.8090	280.0113	279.9972	284.1369	290.5694
N = 9	292.2597	288.7603	290.0375	292.4753	288.9153	290.0212
N = 10	314.8063	308.6561	306.3710	298.5305	288.4733	287.6783
N = 11	366.2891	357.0873	351.3051	346.7507	339.7718	309.6783

The optimization results are shown in Figure 2:

As can be seen from Figure 2, the average maintenance cost decreases first and then increases with the improvement of reliability, and the average maintenance cost is the smallest when the number of maintenance is seven times. In addition, as the system reliability requirements increase, the optimal number of preventive maintenance cycles also increases, which is in line with the actual maintenance of the elevator traction machine.

When the optimal number of maintenance N is 7, preventive maintenance intervals is shown in Table 5.

From Table 5, it can be seen that the preventive maintenance intervals of the traction machine are decreasing under the optimal maintenance strategy (0.83, 7), which accords with the degradation characteristics of the equipment itself. In other words, as the running time of the traction machine increases, it needs to be carried out more frequent maintenance; the results are consistent with the actual situation, which reflects the validity and practicality of the model.

5. Conclusion

Firstly, this paper presents a mathematical description of the maintenance of elevator equipment, and then the system failure rate function is optimized by introducing the age-dependent decrement factor and failure rate increment factor. This paper introduces improvement factors in order to break the traditional

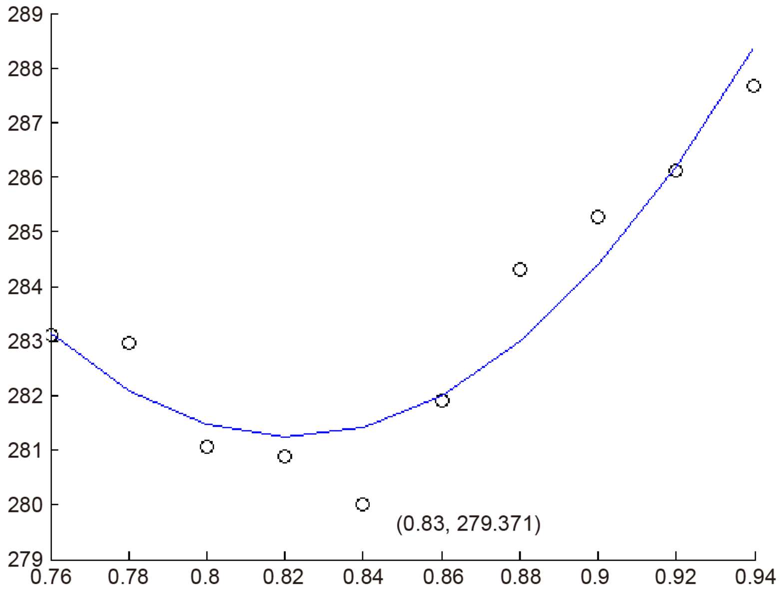

Figure 2. The relationship between average maintenance costs and system reliability.

Table 5. Optimal maintenance intervals under the optimal preventive maintenance intervals.

T_1	T_2	T_3	T_4	T_5	T_6	T_7
99.99	88.51	80.65	72.42	65.82	60.89	57.23

assumption of periodic maintenance strategy, which is expressed as "repair as new". The equipment condition maintenance model is constructed on the basis of reconsidering the repair costs and downtime losses of the elevator equipment. Finally, the model combined with a numerical example is solved by genetic algorithm with the aim of minimizing the average maintenance cost. The optimal equipment maintenance strategy is found and the practicality and validity of the model are verified. However, the relationship between one equipment and another is not discussed in this article, which needs to be studied in the future.

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