

CASE 89

Design of Preventive Maintenance of a Bucket Elevator through Simultaneous Use of Periodic Maintenance and Checkup

Abstract: To solve the problem of apparent failure on a casting machine, we studied three different types of preventive maintenance using on-line quality engineering. We discuss one of them, for which an optimal maintenance method was attempted.

1. Introduction

Preventive maintenance is a scheduled maintenance method to prevent failures during use of an item and to maintain availability of the item. A key issue on a practical basis is how to conduct optimal maintenance.

When operating a casting machine (Figure 1), we suffered considerable damage because of an “apparent” failure caused when a roller of a chain (Figure 2b), used for a bucket elevator (Figure 2a), was worn out and suddenly tore apart. Like a tray elevator, a bucket elevator transports a work by hanging it on a chain. An *apparent failure* is defined as a case where a machine stops when an automated measurement system fails.

To prevent the same failures from occurring again, referring to the history of repairs in the maintenance record book, we designed an optimal maintenance method in accordance with the following procedures:

1. We understand the current situation correctly.
2. Using on-line quality engineering, we analyze preventive maintenance from the viewpoint of the following three types and select one optimal maintenance method (Figure 3):
 - a. Periodic checking
 - b. Periodic maintenance
 - c. Simultaneous use of periodic checking and maintenance

3. Using the loss function, we study how much the optimal maintenance method can improve the current and determine the final optimal method.

2. Current Maintenance of Bucket Elevator

To determine the optimal maintenance method, we began by examining the current maintenance method.

Mean Time between Failures

For the current maintenance of chains, we checked the wear and fracture in a roller once a month, and with these data we predicted machinery failures and planned a maintenance schedule. To understand the failure modes that have occurred, using recent repair records for the bucket elevator, we rearranged 19 consecutive failure data (Table 1) and estimated the mean time between failures:

mean time between failures

$$\begin{aligned} &= \frac{\text{total of operational days}}{\text{number of stops}} \\ &= \frac{(3.5)(2) + (5.3)(5) + \cdots + (11.0)(3)}{19} = \frac{130.4}{19} \\ &= 6.9 \text{ months} \end{aligned} \quad (1)$$

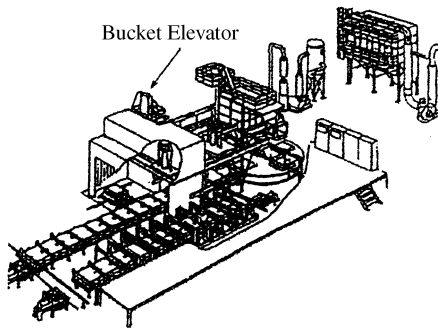


Figure 1
Vpro casting machine

As a result, we came up with approximately seven months, or 147 days, as the total number of operational days in a month is 21.

Arrangement of Parameters

The following are necessary parameters for the design of a preventive maintenance method.

- Mean time between failures: $\bar{u} = 147$
- Loss due to stoppage when a machine goes out of order: $A = 3,600,000$ yen
- Checkup cost: $B = 500$ yen
- Current maintenance cost: $C = 870,000$ yen
- Periodic maintenance cost: $C' = 670,000$ yen
- Functional limit: $\Delta_0 = 90\%$

□ Current checkup interval: $n_0 = 21$ days

□ Current maintainable limit: $D_0 = 80\%$

D_0 and Δ_0 indicate the amount of roller wear. A usable limit (functional limit Δ_0) that a manufacturer defines is the time when "a roller has a hole or cracks due to wear and tear" or "a bush has a hole due to wear and tear." Wear and tear occurs because of wear between each link plate and interference between the side of a roller and the inner surface of a link plate (Figure 4). If the amount of wear exceeds one-third of the thickness of a link plate, the possibility of insufficient chain strength needs to be assessed. In our experience, we set as Δ_0 90% of a period until a hole appears due to wear and defined D_0 as a point in time slightly before the functional limit. (We did not set up a control for the case where wear exceeds one-third of the regular thickness.)

We considered the difference between the current maintenance cost, C , and the periodic maintenance cost, C' . When implementing periodic maintenance, we need only C' . However, when the current checking method is used, because we need to check the machinery due to possible abrupt failures, a loss attributed to extra labor is required, in addition to the periodical maintenance cost, C' .

The checkup cost was estimated to be 500 yen, which is much lower than other costs. The reason is that only 5 minutes is required for this checkup because it requires only a visual examination of dimensional wear of representative rollers once a month.

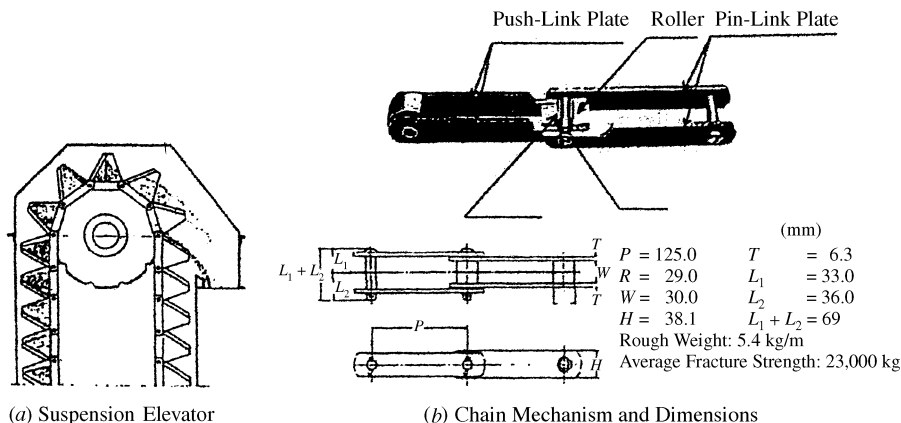


Figure 2
Vertical bucket elevator

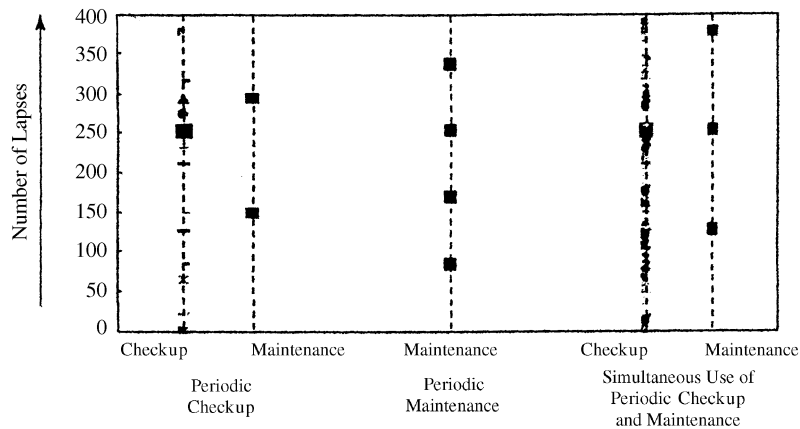


Figure 3
Types of preventive maintenance

Additionally, this casting machine recycles and reuses casting sand. After taking out a cast product, the remaining cast sand is transported by a bucket elevator and put into a sand hopper after it is cooled down. The operational time of this bucket elevator is generally constant, so we estimated not per product but per day.

Current Evaluation

The current management method is based on an ex post facto process in which a part is replaced by a new part when it has broken. In this case, no diagnosis is attempted. Using the idea of operations management, we calculated the loss function, L_0 . The maintenance cost, C , was computed as

repair cost,

$$\begin{aligned} C &= (\text{loss by machinery stoppage}) \\ &\quad + (\text{current maintenance cost}) \\ &= 3,600,000 + 870,000 = 4,470,000 \text{ yen} \end{aligned} \quad (2)$$

$$\begin{aligned} L_0 &= (\text{checkup cost}) \\ &\quad + (\text{loss by machinery stoppage}) \\ &\quad + (\text{repair cost}) + (\text{time lag loss}) \\ &= \frac{B}{n_0} + \frac{n_0 + 1}{2} \frac{A}{u} + \frac{C}{u} + \frac{lA}{u} \\ &= 0 + 0 + \frac{4,470,000}{147} + 0 \\ &= 30,408.2 \text{ yen/days} \end{aligned} \quad (3)$$

Therefore, the annual total of losses amounts to 7.66 million yen/year. [The symbol l in equation (3) indicates the time lag.]

Table 1

Maintenance data for bucket elevator ($n = 19$)

Months until Next Replacement	Cumulative Frequency	Cumulative Percentage
3.5	2	10.5
5.3	7	36.8
6.0	10	52.6
7.1	13	68.4
8.2	16	84.2
11.0	19	100.0

3. Optimal Preventive Maintenance Method

To choose an optimal maintenance method, we used the loss function to analyze the following three types of preventive maintenance methods.

Using Only Periodic Checkups

We calculated an optimal periodic checkup interval, n , and maintenance limit, D , that minimize equa-

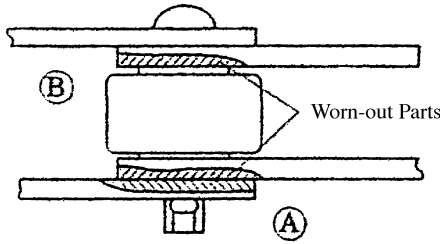


Figure 4
Wear and tear of link plate

tion (3). The optimal periodic checkup interval n is computed as

$$n = \sqrt{\frac{2B}{A}} \bar{u} = \sqrt{\frac{(2)(500)}{3,600,000}} (147) = 2.45 \quad (4)$$

Next, we calculated an optimal maintenance limit, D . Assuming the time to reach the functional limit, Δ_0 , is proportional to the square of the limit, the average maintenance interval, u , for a certain maintenance limit, D , is calculated by

$$u = u_0 \frac{D^2}{D_0^2} \quad (5)$$

Setting a mean time between failures with no maintenance to \bar{u} , we can predict a failure rate according to equation (5):

$$\bar{u} = u_0 \frac{\Delta_0^2}{D_0^2} \quad (6)$$

Then the optimal maintainable limit, D , is

$$D = \left(\frac{3C}{A} \frac{\bar{u}}{u_0} D_0^2 \Delta_0^2 \right)^{1/4} \quad (7)$$

Substituting equation (6) into (7), we have

$$D = \left(\frac{3C}{A} \right)^{1/4} \Delta_0 \quad (8)$$

The optimal maintainable limit D is computed as follows:

$$\begin{aligned} D &= \left(\frac{3C}{A} \right)^{1/4} \Delta_0 \\ &= \left[\frac{(3)(870,000)}{3,600,000} \right]^{1/4} (90) = 83.04\% \quad (9) \end{aligned}$$

Therefore, we can see that a periodic checkup

every three days and a maintainable limit of 83% are optimal. As a next step, we calculated the loss function L_1 under optimal conditions:

$$\begin{aligned} L_1 &= (\text{checkup cost}) + (\text{maintenance cost}) + (\text{loss by machinery stoppage due to maintainable limit}) + (\text{loss by machinery stoppage due to periodical checkup}) \\ &= \frac{B}{n} + \frac{C}{u} + \frac{A}{u} \Delta_0^2 \left(\frac{D^2}{3} + \frac{n}{2} \frac{D^2}{u} \right) \\ &= \frac{500}{3} + \frac{870,000}{125} \\ &\quad + \frac{3,600,000}{(147)(90^2)} \left[\frac{83^2}{3} + \frac{3}{2} \left(\frac{83^2}{125} \right) \right] \\ &= 166.7 + 6960 + 6942.8 + 249.9 \\ &= 14,319.4 \text{ yen/day} \quad (10) \end{aligned}$$

So the annual losses total 3.608 million yen. The mean time between failures for the optimal periodic checkup interval is computed as

$$u = \bar{u} \frac{D_0^2}{\Delta_0^2} = 147 \left(\frac{83^2}{90^2} \right) = 125 \text{ days} \quad (11)$$

Using Only Periodic Maintenance

The loss function for periodic maintenance L_2 is determined by a periodic maintenance cost and loss by failures occurring within a maintenance interval, calculated by the following equation:

$$\begin{aligned} L_2 &= (\text{periodical maintenance cost}) \\ &\quad + (\text{loss by machinery stop page}) \\ &= \frac{C'}{u'} + \frac{A}{2u'^2} u' \\ &= \frac{670,000}{84} + \frac{3,600,000}{(2)(147^2)} \quad (84) \\ &= 7976.2 + 6997.1 \\ &= 14,973.3 \text{ yen/day} \quad (12) \end{aligned}$$

This amounts to 3.773 million yen/year. Next, the optimal periodic maintenance interval u' was computed:

$$\begin{aligned}
 u' &= \sqrt{\frac{2C'}{A} \bar{u}} \\
 &= \sqrt{\frac{(2)(670,000)}{3,600,000}} (147) = 89.7 \quad (13)
 \end{aligned}$$

Since 89.7 days is equivalent to 4.3 months, by rounding it off to a simple number, we set the optimal periodic maintenance interval to 4.0 months (84 days).

Using Both Periodic Checkups and Maintenance

The loss function, L_3 , was calculated by the equation

$$\begin{aligned}
 L_3 &= (\text{periodic maintenance cost}) + (\text{checkup cost}) \\
 &\quad + (\text{maintenance cost}) + (\text{loss by machinery} \\
 &\quad \text{stoppage due to maintainable limit}) + (\text{loss by} \\
 &\quad \text{machinery stoppage due to periodic checkup}) \\
 &= \frac{C'}{u'} + \left[\frac{B}{n} + \frac{C}{u} + \frac{A}{u^* \Delta_0^2} \left(\frac{D^3}{3} + \frac{n D^2}{2 u} \right) \right] \\
 &= \frac{670,000}{126} + \left\{ \frac{500}{6} + \frac{870,000}{291} + \frac{3,600,000}{(343)(90^2)} \right. \\
 &\quad \left. \left[\frac{83^2}{3} + \frac{6}{2} \left(\frac{83^2}{291} \right) \right] \right\} \\
 &= 5317.5 + (83.3 + 2989.7 + 2975.5 + 92.0) \\
 &= 5317.5 + 6140.5 = 11,458.0 \text{ yen/day} \quad (14)
 \end{aligned}$$

On a yearly basis, this is equal to 2.887 million yen. The optimal periodical checking interval, u' , was estimated as follows. If periodical replacement is made at time u' hours, the mean time to the functional limit, Δ_0 , turns out to be \bar{u} with no maintenance. If we consider the case where maintenance of periodic replacement is implemented for u' hours, the periodic maintenance cost, C' yen, and mean time between failures, u^* , are estimated as

$$\text{maintenance cost } C' = \frac{C}{u} \quad (15)$$

Then

$$u^* = 2\bar{u} \frac{\Delta_0^2}{(D')^2} \quad (16)$$

$(D')^2$ is a root mean square of periodic maintenance characteristic differences from their standard values:

$$u' = \bar{u} \frac{(D')^2}{\Delta_0^2} \quad (17)$$

Substituting this into equation (16), we obtained the mean time between failures for periodic maintenance as follows:

$$u^* = 2\bar{u} \Delta_0^2 \frac{\bar{u}}{u'} \frac{1}{\Delta_0^2} = 2 \frac{\bar{u}^2}{u'} \quad (18)$$

Using this equation, the loss function when periodic replacement is implemented every u' hours is estimated as

$$L = \frac{C'}{u'} + \frac{u'}{2\bar{u}^2} \left(\sqrt{2AB} + \sqrt{\frac{4}{3}} AC \right) \quad (19)$$

Partially differentiating this equation with respect to u' , we set both sides to zero:

$$- \frac{C'}{(u')^2} + \frac{u'}{2\bar{u}^2} \left(\sqrt{2AB} + \sqrt{\frac{4}{3}} AC \right) = 0 \quad (20)$$

Transforming this equation, we calculated the optimal periodic maintenance interval as

$$\begin{aligned}
 u' &= \sqrt{\frac{2C'}{\sqrt{2AB} + \sqrt{\frac{4}{3}} AC} \bar{u}} \\
 &= \sqrt{\frac{(2)(670,000)}{\sqrt{(2)(3,600,000)(500)} + 870,000}} \quad (147) \\
 &= 117.3 \text{ days} \quad (21)
 \end{aligned}$$

For the sake of simplicity, we rounded 117.3 days up to six months (126 days). In this case the mean time between failures u^* is

$$u^* = \frac{2\bar{u}^2}{u'} = \frac{(2)(147^2)}{(21)(6)} = 343 \text{ days} \quad (22)$$

This is approximately 1.4 years. With equations (21) and (22), we computed the optimal periodic checkup interval, n , and maintainable limit, D . The optimal periodic checkup interval, n , was estimated as

$$n = \sqrt{\frac{2B}{A} u^*} = \sqrt{\frac{(2)(500)}{3,600,000} (343)} = 5.7 \text{ days} \quad (23)$$

5.7 days is rounded up to 1 week. Thus, we can perform one checkup a week.

The optimal maintainable limit D is calculated as

Table 2
Cost comparison among all maintenance methods

Maintenance Method	Cost (1000 yen)					Proportion (%)
	Normalization	Checkup	Maintenance	Periodic Maintenance	Machinery Stop	Total
Current management (operation management)	7660					7660
Preventive Maintenance						
Only periodic checkup		42	1754		1812	3608
Only periodic maintenance				2010	1763	3773
Both periodic checkup and maintenance		21	753	1340	773	2887
						100.0
						47.1
						49.2
						37.7

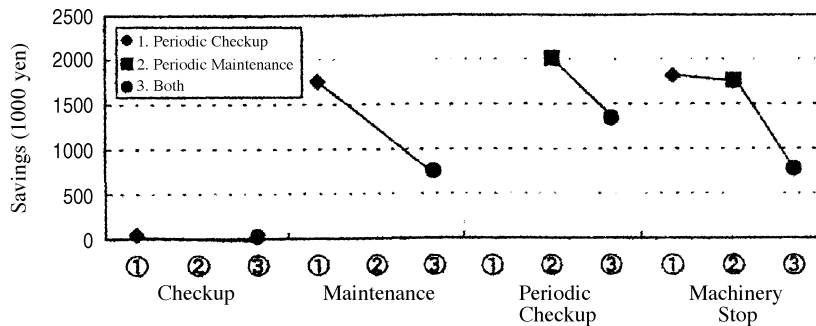


Figure 5
Effects of preventive maintenance methods

$$D = \left(\frac{3C}{A} \right)^{1/4} \Delta_0 = \left[\frac{(3)(870,000)}{3,600,000} \right]^{1/4} (90)$$

$$= 83.04\% \quad (24)$$

Now the mean time between failures turns out to be

$$u = u^* \frac{D^2}{\Delta_0^2} = 343 \left(\frac{83^2}{90^2} \right) = 291 \text{ days} \quad (25)$$

4. Conclusions

Table 2 and Figure 5 show the cost calculation results for each type of maintenance method. Looking at the ex post facto maintenance method, we can see that the repair cost amounts to 7.66 million yen. Among all the maintenance methods, simultaneous use of the periodic checkup and maintenance methods were regarded as being most effective in overall cost and the best balanced. Considering all of the above, we come to the following conclusions:

- As a maintenance method for chains, we perform periodic maintenance and checkups simultaneously. The following are the principal management concerns:
 - Optimal periodic maintenance interval*: once in six months
 - Optimal checking interval*: once a week
 - Maintainable limit*: 83%
- By taking advantage of both periodic maintenance and checkups, we can obtain an annual

improvement of 4.8 million yen compared with our current checkup method.

- As a result of implementing the optimal maintenance method, we have confirmed that there has been no sudden failure, and the wear of rollers and bushes in a chain has been found quite close to the maintainable limit.

While through our calculations we have concluded that simultaneous use of periodic maintenance and checkups leads to the minimum overall loss, we plan to study the following three improvements to reduce the loss further:

- Improved checkup procedure* (improvement in B). Because the checkup cost is low, by enhancing the accuracy we can balance this and other costs and decrease the overall loss.
- Improved maintenance method* (improvement in C and C'). We will review the current labor requirements and operations.
- Improved wear resistance* (improvement in \bar{u}). We changed the current material to a wear-resistant material and decreased the pressure at a bearing through increased chain size.

Reference

- Tadao Kondo, 1996. Design of preventive maintenance: combination of periodic maintenance and regular check of bucket elevator. *Quality Engineering*, Vol. 4, No. 6, pp. 30–35.

This case study is contributed by Tadao Kondo.