

Optimisation of Economiser Tubing System Renewal Decisions

Yong Sun, Lin Ma, and Colin Fidge

Abstract—The economizer is a critical component in coal fired power stations. An optimal renewal strategy is needed for minimizing the lifetime cost of this component. Here we present an effective optimization approach which considers economizer tubing failure probabilities, repair and renewal costs, potential production losses, and fluctuations in electricity market prices.

I. INTRODUCTION

Boiler tube failures are one of the major causes of unexpected outages in coal fired power stations [1-3]. An important part of the tubing system is the *economizer*, which preheats water entering the boiler using heat extracted from the furnace's exhaust gases. Among all boiler tube failures, about 10% are due to erosion of economizer tubes [1]. Therefore, reducing economizer tube failures can significantly improve the performance and profitability of power plants.

One strategy for reducing economizer tubing system failures is to renew eroded boiler tube segments before they rupture. However, to make this maintenance strategy effective, an optimal renewal interval must be identified.

There is much literature on decision making for power plant boiler tubes, although comparatively little on economizer tubing specifically. Vasudeva [4] proposed techniques for making operating and maintenance decisions for power plants generally, and with respect to boiler tubes in particular. He proposed increased use of automation in power plant control systems as a way of decreasing operation and maintenance costs. Berquist, Buckley and Bodon [5] promoted use of simulations as a way of evaluating the effects of power plant maintenance decisions. They used off-the-shelf simulation software to model maintenance characteristics of a power plant as a set of equations, frequency distributions and discrete rules representing properties such as power unit throughput, unplanned outage rates, planned maintenance frequencies and time-to-repair distributions. These characteristics were

then calibrated using data derived from an actual power plant's maintenance history. From the simulation model it was then possible to analyze the relationships between, for instance, operating hours and power generation rates versus maintenance costs.

A critical factor in boiler maintenance decisions is tube segment failure prediction. Intensive research has been carried out to understand, or control, rates of tube wear, in order to make tube leaks more predictable [6-11]. Parameters which influence economizer tube wear include grit particles in the exhaust gases, the effect of which depends on impact velocity, impact angle, impact frequency, particle size, particle shape, mechanical cohesion of the particles, and tube temperature [10]. Another consideration is ash build-up on the tubes which can change the rate of erosion [11]. Further factors include welding defects on tube fins, flue gas temperature, the types of minerals found in the coal, and particle build-up leading to falling clinker [2]. However, much of this research has been restricted to analysis of single tubes in isolation [6, 10] or simple arrangements of tubes [7] only.

Some of the work consists of metallurgical studies [8, 9]. While relevant, this research is not necessarily helpful for economizer maintenance in the context of an existing power station since it concerns technical factors that are largely outside the maintenance manager's control. A common starting point for predicting tube erosion based on a plant's operating conditions is the equation $E = kMV^n$, where E measures the lost metal, k is an energy transfer constant, M is the mass of impacting particles, V is the particle impact velocity, and constant exponent n is used to adjust the shape of the erosion curve [3].

Unfortunately, many of the factors mentioned in the theoretical literature are difficult to monitor in an operating power plant, so the value of this research for day-to-day plant maintenance is limited. In practice, maintenance engineers rely on physical *surveys* of tube thickness, which is measured with calipers or via X-rays. However, since surveys can be done only when the plant is shut down, the data obtained cannot be comprehensive and often contains measurement errors. To address this issue, Majidian and Saidi [1] used empirical survey data to compare two different algorithms, based on fuzzy logic and neural networks respectively, for predicting the remaining useful life of boiler tubes. They argued that the inevitable measurement errors in tubing survey data makes these 'approximate' algorithms more appropriate than simple extrapolative equations or curve fitting algorithms. Again, this is interesting approach, but it is not yet suitable for

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making large-scale maintenance decisions. Therefore, statistical analyses based on historical failure and condition data remains the most practical method for economiser tubing system failure prediction at present.

The overall goal of optimising economizer renewal decisions is to minimise its lifetime operation and maintenance costs. When making a renewal decision, three types of costs need to be considered: (1) the cost of fixing tube failures, which is termed as the repair cost; (2) the cost of doing renewal work, which is part of Preventive Replacement (PR) of the tubing system, and is termed as the renewal cost; and (3) production losses caused by the shutdown of the power generation unit to undertake repairs and/or renewal. It is almost impossible to minimise all these costs simultaneously. Increasing renewal intervals can decrease the renewal cost. However, reducing renewal costs in this way often leads to an increase in repair costs because longer renewal intervals normally mean more failures. Both repair and renewal jobs will result in production losses. The production loss depends on the outage's duration and its calendar time because electricity prices fluctuate with seasons and even times of day. Although some optimization models to minimize total asset maintenance costs have been developed [12], these existing models cannot be applied to economizers directly because of their particular physical structure, applicable maintenance methods and the fluctuating price of electricity. This paper attempts to develop an effective approach to fill this gap.

II. OPTIMIZATION APPROACH

As explained above, an economiser renewal decision is a *multiple criteria* decision involving: the failure rates of tubes; repair performance and cost; renewal location, area and cost; as well as the current or predicted electricity market price. Other non-technical factors such as maintenance staff and contractor availability, spare parts supplies, safety issues and legal requirements can also be constraints. Here we focus on the most critical technical factors only. The following assumptions were made in our analysis:

- (1) The economiser system needs to be fully renewed if over 30% of its tubes need to be preventively replaced.
- (2) Repairs to tube segments are perfect, i.e., the state of the segments after repair is 'good as new'.
- (3) Repair of a tube segment does not affect the conditions of other segments.
- (4) Preventive replacement duration and repair duration are random variables and independent of each other.
- (5) In current practice, maintenance people often do preventive replacement to a small range of tubes near a leak. To distinguish this preventive replacement from renewal work, it is considered as a 'repair' in this paper.
- (6) No two segments fail at the same time and each segment failure results in a repair.

- (7) The mean market price (A\$/MW per day) changes seasonally, but can be treated as a constant during a repair or a preventive replacement action.
- (8) The effects of interest and inflation are ignorable. The safety issue and legal requirements can also be ignored.
- (9) Maintenance staff, contractors, spare parts are always available.
- (10) The electricity market price is a periodic function of time with period one year.

In the following analysis, the failure probability of the tubes is converted into an expected repair cost and the electricity price is linked with production loss. Since the absolute cost values corresponding to different renewal intervals are not comparable, the cost per unit time, i.e., the cost rate, is applied in the following analysis. The renewal decision optimization aims to find the optimal renewal interval so as to minimise the expected total cost which is composed of the expected repair cost, the expected renewal cost and the expected production loss.

The optimization approach includes two steps. In the first, a local optimization is conducted. In this step, an economizer under consideration is divided into a number of groups based on their working conditions and erosion rates, and then the individual optimal renewal interval of each tube in each group is calculated. The second step is to conduct a global optimization, i.e., to calculate the optimal renewal interval for the entire economizer.

A. Expected Repair Cost

The expected repair cost rate of a group of segments of tubes, $R_{crp}(t)$ is assumed to be proportional to the failure probability of the segments, $f_{crp}(t)$. It is a function of Preventive Maintenance (PM or renewal) interval t . If every segment in the group has only one failure or no failure before being replaced, the repair cost rate of the group is

$$R_{crp}(t) = \frac{C_{rp} N \int_0^t f_{crp}(t) dt}{t}, \quad (1)$$

where N is the number of tube segments in the group. Here C_{rp} stands for the cost incurred during a repair and it normally changes randomly. For simplicity, in this paper, the repair cost is assumed to follow a Normal distribution:

$$C_{rp} \sim N(\mu_{rp}, \sigma_{rp}^2). \quad (2)$$

In Equation (2), μ_{rp} is the mean cost for each repair and σ_{rp} is the standard deviation of the repair cost.

According to probability theory, at time t , the expected repair cost rate $R_{crp}(t)$ will follow a Normal distribution

with a mean value $\mu_{crp}(t) = \frac{\mu_{rp} N \int_0^t f_{crp}(t) dt}{t}$ and a standard

deviation $\sigma_{crp}(t) = \frac{\sigma_{rp} N \int_0^t f_{crp}(t) dt}{t}$.

If the segments of tubes in the group have multiple failures and repairs before being replaced, the repair cost rate can be estimated using the following equation,

$$R_{crp}(t) = \frac{C_{rp} N n_{seg}}{t}, \quad (3)$$

where n_{seg} is the mean number of failures of a tube segment before being replaced.

In this case, $R_{crp}(t)$ is also Normally distributed with a mean value $\mu_{crp}(t) = \frac{\mu_{rp} N n_{seg}}{t}$ and a standard deviation $\sigma_{crp}(t) = \frac{\sigma_{rp} N n_{seg}}{t}$.

Fig. 1 shows the change of the expected repair cost rate with the renewal interval. In Fig. 1, t_o is the chosen renewal interval. Obviously, if the repair cost is considered solely, the interval shown in the figure is not optimal at all.

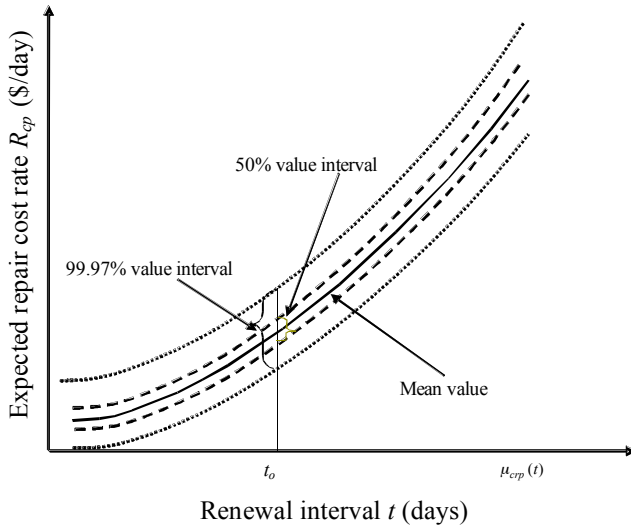


Fig. 1. Expected repair cost rate vs. renewal interval. It can be seen that the repair cost will increase with an increasing renewal interval. The figure also demonstrates the cost range with different confidence levels.

B. Expected Renewal Cost Rate

The expected renewal cost rate of a group of segments of tubes, $R_{crn}(t)$, is assumed to be proportional to the PM (renewal) frequency or inversely proportional to the PM (renewal) interval of the segments, t , hence it is a function of the PM (renewal) interval, i.e.,

$$R_{crn}(t) = \frac{C_{rn}}{t}, \quad (4)$$

where C_{rn} stands for the proportional scale for renewal of the group and is assumed to change randomly with a Normal distribution:

$$C_{rn} \sim N(\mu_{rn}, \sigma_m^2). \quad (5)$$

In Equation (5), μ_{rn} is the mean renewal cost for the group and σ_{rn} is the standard deviation of the renewal cost.

The expected renewal cost rate $R_{crn}(t)$ at time t will follow a Normal distribution with a mean value $\mu_{crn}(t) = \frac{\mu_{rn}}{t}$ and a standard deviation $\sigma_{crn} = \frac{\sigma_{rn}}{t}$.

Fig. 2 shows the change of the expected renewal cost rate with the renewal interval.

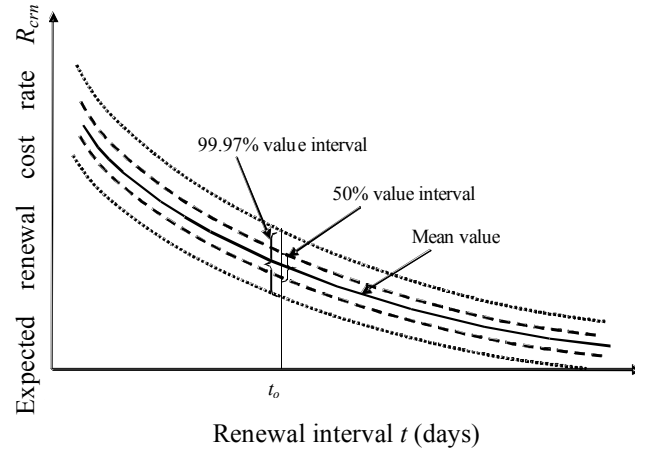


Fig. 2. Expected renewal cost rate vs. renewal interval. It can be seen that the renewal cost will decrease with an increasing renewal interval. The figure also demonstrates the cost range with different confidence levels.

C. Expected Production Loss Rate

The expected production loss includes two parts: loss due to failures (related to forced outages) and loss due to planned maintenance (PM) (related to planned outages).

The production loss rate due to the failures of the tube

segments in a group is assumed to be proportional to the failure probability of the segments, $f_{crp}(t)$, the forced outage duration of each repair, O_f , and the market price, $P(t_c)$. It is a function of the PM (renewal) interval t and the calendar time t_c :

$$R_{pl1}(t) = \frac{\int_0^t P(t_c) O_f N f_{crp}(t) dt}{t}, \quad (6)$$

where O_f is assumed to be randomly distributed following a Normal distribution:

$$O_f \sim N(\mu_{of}, \sigma_{of}^2), \quad (7)$$

In Equation (7), μ_{of} is the mean forced outage duration for each repair, and σ_{of} is the standard deviation of the repair duration.

The expected unplanned production loss rate $R_{pl1}(t)$ at time t will follow a Normal distribution with a mean value

$$\mu_{pl1}(t) = \frac{\mu_{of} \int_0^t P(t_c) O_f N f_{crp}(t) dt}{t} \text{ and a standard deviation}$$

$$\sigma_{pl1}(t) = \frac{\sigma_{of} \int_0^t P(t_c) O_f N f_{crp}(t) dt}{t}.$$

The market price is assumed to change seasonally and can be presented by the following equation:

$$P(t_c) = \begin{cases} P_1(t_c) & t_c \subseteq \{Dec, Jan, Feb\} \\ P_2(t_c) & t_c \subseteq \{Mar, Apr, May\} \\ P_3(t_c) & t_c \subseteq \{Jun, Jul, Aug\} \\ P_4(t_c) & t_c \subseteq \{Sep, Oct, Nov\} \end{cases}. \quad (8)$$

Figure 3 shows the changes of the market price over a year.

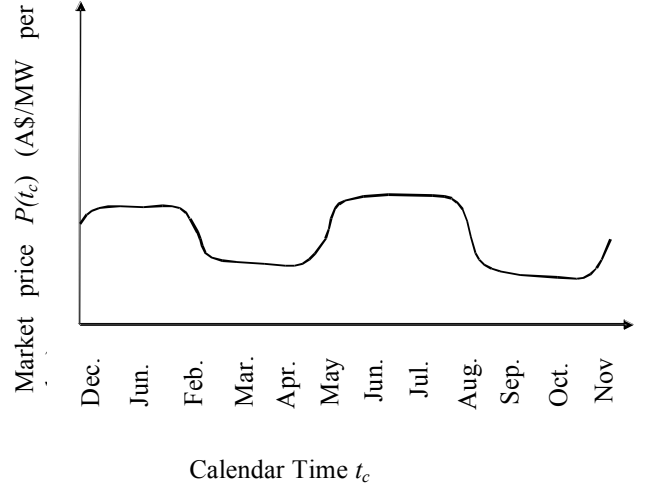


Fig. 3. Average electricity market price over a year. It alternates with the seasons. Note that the figure shows the changes at a macro level (monthly) only. The micro changes of the price (weekly, daily or even hourly) have not been presented.

According to Assumption (10),

$$P(t_c + 365k) = P(t_c), \quad k = 1, 2, \dots. \quad (9)$$

Note that in equation (6), term $\int_0^t O_f N f_{crp}(t) dt$ is the theoretical total forced outage duration until time t , which is calculated based on Assumption (5). However, in reality, multiple tube segments may fail at the same time and multiple failures may be fixed at the same time. Therefore, the actual forced outage duration until time t will be less than $\int_0^t O_f N f_{crp}(t) dt$. A solution to this problem is multiplying the theoretical duration by a percentage which should be determined by domain experts.

The production loss rate due to the planned maintenance (planned outages) of the segments in a group is assumed to be proportional to the planned outage duration O_p of each Preventive Maintenance action and the market price $P(t_c)$. It is a function of PM (renewal) interval t and the calendar time t_c :

$$R_{pl2}(t) = \frac{P(t_c) O_p}{t}, \quad (10)$$

where O_p is assumed to change randomly with a Normal distribution:

$$O_p \sim N(\mu_{op}, \sigma_{op}^2), \quad (11)$$

In Equation (10), μ_{op} is the mean planned outage duration for each PM, and σ_{op} is the standard deviation of the duration.

The expected planned production loss rate $R_{pl2}(t)$ at time t will follow a Normal distribution with a mean value

$$\mu_{pl2}(t) = \frac{\mu_{pl2}P(t_c)}{t} \quad \text{and a standard deviation}$$

$$\sigma_{pl2}(t) = \frac{\sigma_{pl2}P(t_c)}{t}.$$

Note that to decide the optimal renewal interval, the calendar time t_c needs to be converted into the renewal interval. When the built date of tubes t_{c0} is known, the calendar date at the renewal interval t can be easily obtained. The relationship between t_c , t_{c0} and t can be expressed as

$$t_c = f(t_{c0}, t). \quad (12)$$

Some software packages, e.g., Microsoft Excel have provided such a function.

The sum of the expected unplanned and planned outage losses gives the expected total production loss rate, $R_{pl}(t)$:

$$R_{pl}(t) = R_{pl1}(t) + R_{pl2}(t)$$

$$= \frac{\int_0^t P(t_c)O_f N f_{crp}(t) dt + P(t_c)O_p}{t}. \quad (13)$$

Since the unplanned outage loss is independent of the planned outage loss, based on probability theory, $R_{pl}(t)$ at time t also follows a Normal distribution:

$$R_{pl}(t) \sim N(\mu_{pl1}(t) + \mu_{pl2}(t), \sigma_{pl1}^2(t) + \sigma_{pl2}^2(t)) \quad (14)$$

Fig. 4 shows the change of the expected total production loss rate with the renewal interval.

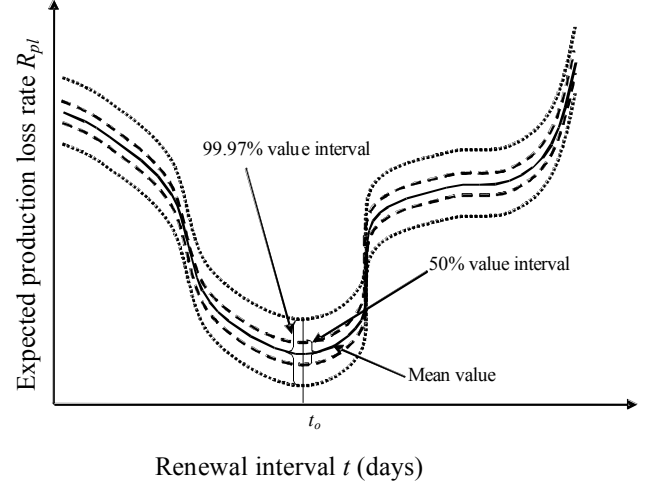


Fig. 4. Expected production loss rate vs. renewal interval. It changes alternatively. However, a minimum area exists. Note that the figure shows the changes at a macro (daily) level only. The micro changes (hourly) of the price have not been presented.

D. Expected Total Cost Rate

The expected total cost of a group of tube segments is given by

$$R_{ct}(t) = R_{crn}(t) + R_{crp}(t) + R_{pl}(t). \quad (15)$$

If every segment in the group has only one failure or no failure before being replaced, substituting Equations (1), (4) and (13) into Equation (15) gives

$$R_{ct}(t) = \frac{C_{rm}}{t} + \frac{C_{rp} N \int_0^t f_{crp}(t) dt}{t}$$

$$+ \frac{\int_0^t P(t_c) O_f N f_{crp}(t) dt + P(t_c) O_p}{t}. \quad (16)$$

If the segments of tubes in the group have multiple failures and repairs before being replaced, substituting Equations (3), (4) and (13) into Equation (15) gives

$$R_{ct}(t) = \frac{C_{rm}}{t} + \frac{C_{rp} N n_{seg}}{t}$$

$$+ \frac{\int_0^t P(t_c) O_f N f_{crp}(t) dt + P(t_c) O_p}{t} \quad (17)$$

The total cost rate at time t , $R_{pl}(t)$, follows a Normal distribution with a mean value $\mu_{ct}(t) = \mu_{crp}(t) + \mu_{crn}(t) + \mu_{pl}(t)$ and standard deviation $\sigma_{ct}(t) = \sqrt{\sigma_{crp}^2(t) + \sigma_{pcrn}^2(t) + \sigma_{pl}^2(t)}$.

Fig. 5 shows the change of the expected total cost rate with the renewal interval.

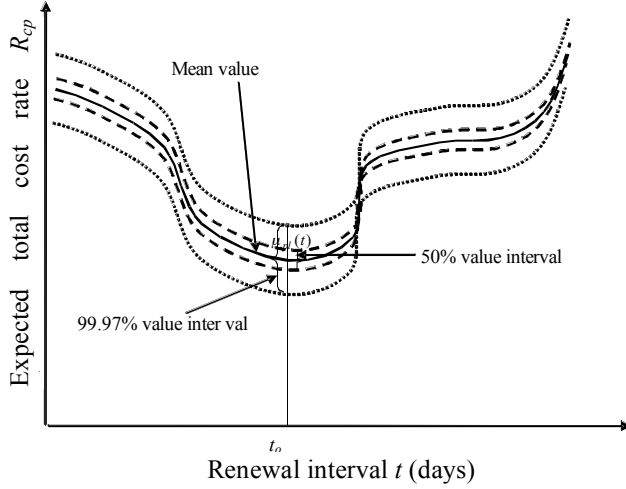


Fig. 5. Expected total cost vs. renewal interval. It changes alternatively. However, the minimum cost area exists. Its correspondent renewal interval is the optimal interval. Note that the figure shows the changes at a macro (daily) level only. The micro changes of the price have not been presented.

E. Optimal Renewal Time of the Economizer Tubing System

The procedure to calculate the optimal system renewal interval is as follows:

- 1) Calculate the optimal renewal interval for every tube segment as described in Subsections A to D.
- 2) If 30% of tube segments need to be renewed before a specific time T , the entire economiser tubing system should be renewed before this time according to Assumption (1).
- 3) Calculate the global optimal renewal time for this 30% of tube segments so that the total cost is minimised. This global optimal renewal time is the optimal renewal time of the economiser tubing system.

Assume that the number of tube segments which need to be renewed before time T is n . The expected total cost rate function of segment i ($i=1, 2, \dots, n$) is $R_{cti}(t)$. As

different tube segments may have different built times, the starting points of the age t of different segments can vary. To tackle this problem, a relative time coordinate τ which starts from the current time is introduced. Using the relative time coordinate, the expected total cost rate function of segment i ($i=1, 2, \dots, n$) becomes $R_{cti}(\tau + \tau_{0i})$. Parameter τ_{0i} is the age of segment i ($i=1, 2, \dots, n$) to the current time. Therefore, the whole expected total cost rate of these n segments, $R_w(\tau)$, is

$$R_w(\tau) = \sum_{i=1}^n R_{cti}(\tau + \tau_{0i}) \quad (18)$$

The overall renewal decision is therefore to find the optimal renewal time τ_{op} so that

$$R_w(\tau_{op}) = \min \{R_w(\tau)\} \quad (19)$$

III. CONCLUSIONS

This paper presents a practical approach to deciding the optimal renewal time for an economizer tubing system with consideration given to the failure rate of the tubing system, the repair cost, the renewal cost and the production loss.

Different time coordinates are used in the model to address the issue that repair costs and renewal costs change with the renewal interval, electricity market prices change seasonally, and tubes have different built dates.

The cost and outage time are assumed to be Normally distributed in the paper. However, other distributions can also be used (with a corresponding increase in mathematical complexity).

Finally, we note that renewal investments for long-lived assets like economizers span long periods of time, typically decades. In this case, the net present value of the asset should be calculated periodically and used for maintenance decision making.

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