Application of the delay-time concept in a manufacturing industry

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Abstract: This paper has been written to give a methodology of applying delay-time analysis to a maintenance and inspection department. The aim is to reduce downtime of plant items and/or reducing maintenance and inspection costs. A case study of a company producing carbon black has been included to demonstrate the proposed methodology.

Keywords: Maintenance, inspection maintenance, delay-time analysis

1. Introduction to delay-time analysis concept

Delay-Time Analysis (DTA) is a concept whereby the time *h* between an initial telltale sign of failure *u* and the time to actual failure can be modelled in order to establish a maintenance strategy. Delay-time is the period of time when inspection or maintenance could be carried out in order to avoid total failure. Figure 1 illustrates the delay-time concept (Christer & Waller (1984)).

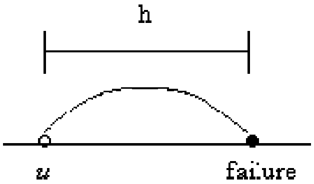

Figure 1. The delay-time concept

2. Methodology

In order to develop a maintenance model using delay-time analysis a methodology needs to be developed in order to give the process a framework. Delay-time analysis can be used as a tool for reducing the downtime, *D*(*T*) (Christer *et al*. (1995)) of a machine or a piece of equipment based on an inspection period *T*, given the probability of a defect arising within this time frame *b*(*T*). For a particular plant item, component or series of machines, delay-time analysis is useful because the equipment in question is generally high volume and high capital expense, therefore any reduction in downtime due to breakdown or over inspection can be beneficial. As with the modelling of downtime per unit time, it is also possible to establish a cost model, *C*(*T*) (Leung & Kit-leung (1996)), again based on an inspection period *T* and probability *b*(*T*), this model estimates the expected cost per unit time of maintenance. This modelling has also been used for safety criticality (Pillay & Wang (2003)) on a fishing vessel giving safety criticality of a failure and operational safety criticality.

<u>A methodology for applying delay-time analysis is proposed as follows:</u>

- Understand the process.
- Identify the problems.
- Establish data required.
- Gather data.
- Establish parameters.
- Validation of the delay-times and the distribution.
- Establish assumptions.
- Establish a downtime model D(T) and cost model C(T).

When the probability distribution function of a delay-time *f*(*h*) follows an exponential distribution, i.e. when the failure rate λ or 1/MTBF is constant over a specified time period, the distribution function, as shown in equation (1), is used to calculate the probability of a defect arising *b*(*T*):

$$f(h) = \lambda e^{-\lambda h} \tag{1}$$

The probability of a defect leading to a breakdown failure *b*(*T*) can be expressed as follows in equation (2).

$$b(T) = \int_0^T \left(\frac{T-h}{T} \right) f(h)dh \tag{2}$$

Inserting the distribution function *f*(*h*) into the breakdown failure probability *b*(*T*) gives

$$b(T) = \int_0^T \left(\frac{T-h}{T} \right) \lambda e^{-\lambda h} dh \tag{3}$$

This term can be further simplified as

$$b(T) = \frac{1}{T} \int_0^T (T-h) \lambda e^{-\lambda h} dh \tag{4}$$

It is important to note that $b(T)$ is independent of the arrival rate of a defect per unit time (k_f) but it is dependant on the delay-time h.

2.1 Downtime model *D*(*T*)

It has been demonstrated (Leung & Kit-leung (1996)), (Pillay *et al*. (2001)) that with establishing a probability for breakdown failure $b(T)$ it is also possible to establish an expected downtime per unit time function $D(T)$ as shown in equation (5).

$$D(T) = \left\{ \frac{d + k_f T b(T) d_b}{T + d} \right\} \tag{5}$$

where,

d = Downtime due to inspection.
k_f = Arrival rate of defects per unit time.
$b(T)$ = Probability of a defect arising.
d_b = Average downtime for a breakdown repair.
T = Inspection period.

Substituting $b(T)$ from equation (4) into equation (5) gives

$$D(T) = \frac{d + k_f T \left[\frac{1}{T} \int_0^T (T-h) \lambda e^{-\lambda h} dh \right] d_b}{T + d} \tag{6}$$

2.2 Cost model *C*(*T*)

Similarly, given the cost of inspection $Cost_i$, the cost of a breakdown C_B and the cost of inspection repair C_{IR}, the expected cost per unit time of maintenance of the equipment with an inspection of period T is $C(T)$, giving

$$C(T) = \frac{\left\lfloor k_f T \{ Cost_B b(T) + Cost_{IR} [1 - b(T)] \} + Cost_i \right\rfloor}{(T + d)} \tag{7}$$

where,

$C(T)$ = The expected cost per unit time of maintaining the equipment on an inspection schedule of period of time T.
$Cost_B$ = Breakdown repair cost.
$Cost_{IR}$ = Inspection repair cost.
$Cost_i$ = Inspection cost.

The cost of an inspection is shown in equation (8).

$$Cost_i = (Cost_{ip} + Cost_d)\, T_{insp} \tag{8}$$

where,

$Cost_{ip}$ = Cost of inspection personnel per hour.
$Cost_d$ = Cost of downtime per hour.
T_{insp} = Time taken to inspect.

The cost of a breakdown is calculated as the cost of the failure plus the costs of corrective action to bring the equipment back to a working condition. The details of a breakdown repair are shown in equation (9).

$$Cost_B = (M_{staff} + Cost_d)\,(T_{insp} + T_{repair}) + S_p + S_e \tag{9}$$

where,

M_{staff} = Maintenance staff cost per hour.
T_{repair} = Time taken to repair.
S_p = Spares and replacement parts cost.
S_e = Special equipment / personnel / hire costs.

The cost of an inspection repair is somewhat identical to the breakdown repair cost apart from the following:

- Inspection repair will not generally have equipment hire costs (S_e).
- The time to repair will be of shorter duration for inspection repair.

The time for an inspection repair having a shorter duration is mainly due to a breakdown having a greater knock-on effect. The equation for inspection repair is shown in equation (10).

$$Cost_{IR} = (M_{staff} + Cost_d)\,(T_{insp} + T_{repair}) + S_p \qquad (10)$$

A point to note regarding the cost model $C(T)$ (equation 7) is that it describes a worst case scenario. This worst case scenario is a fault leading to failure before an inspection takes place or a fault being detected at inspection. Conversely, a best case scenario would be no failure taking place before inspection and no fault being present at inspection.

3. Case study

In order to demonstrate the above models for downtime $D(T)$ and cost $C(T)$ a case study of a factory producing carbon black in the UK is given.

This particular process of creating carbon black is made up of three units A, C & D. The three units cover the whole process stream from the reactor, MUF (Main Unit Filter) which collects & separates the product from the gasses produced and conveying of the carbon black into storage containers. A low pressure air and natural gas produce a flame of high temperature (1500 degrees centigrade) in the combustion zone of the reactor. Heavy oil, which is known as feedstock, is sprayed into the flame and the carbon black reaction occurs. After the feedstock is exposed to the high temperature it is quenched with water in order to stop the carbon black formation reaction. At this point the basic form of carbon black is formed, carbon black powder. The filter is a bag type filter measuring approximately 10cm in diameter and 2.5m in length. The cost of a filter is around £28 each with a life expectancy of three to four years. There is a second manufacturer of the filter that has a cost of around £7.50 but it has a life expectancy of between 12 to 14 months with a lower tolerance to acid than the more expensive filter.

3.1 Costs of a failure

When a filter bag is to be changed the compartment has to be closed down. This requires 8 hours of cool down followed by a period of 6 and 24 hours downtime for repair and replacement then a further 2 hours to warm the unit back up, if a total re-bag is required downtime is generally around 7 days. When a unit is brought off-line it continues to burn gasses in order to keep the temperature in the reactor constant thus wasting energy. Also the system allows any energy created can be used by the facility and any surplus energy is sold back to the national grid, therefore any downtime can be costly in respect of not just wasting energy but also potential income from surplus energy. Sometimes specialist maintenance crews need to be brought in to deal with the problem. A typical example of a breakdown which took 7 days to repair and replace all bags is demonstrated below.

- Loss of production per hour: £1,500
- Burn of gasses per hour: £238
- Loss of export of energy per hour: £26
- Cost of maintenance personnel per hour: £28
- Cost of supervisor per hour: £36
- Cost of replacement filters (205): £40,180
- Jetting crew: £710
- Jetter hire: £300
- Cherry picker hire: £2,500

This gives a total cost for a breakdown resulting in 1,435 filters being replaced effecting 1 MUF for a period of 7 days to be £350,794.

3.2 Establishing a delay-time analysis

In order to establish a delay-time analysis for this example several parameters need to be known. The parameters used in this example are as follows:

- The arrival rate of a defect, k_f - 0.28 per day.
- Mean time between failure (MTBF) - 3 years.
- Downtime for an inspection, d - 0.1 days.

- Downtime for breakdown repair, d_b - 7 days.
- Breakdown repair cost, $Cost_B$ - £350,974.
- Inspection repair cost, $Cost_{IR}$ - £5,000.
- Inspection cost, $Cost_i$ - £67.

Applying the parameters to equation (6) it is possible to establish an inspection interval where a minimum downtime is of primary concern as illustrated in figure 2.

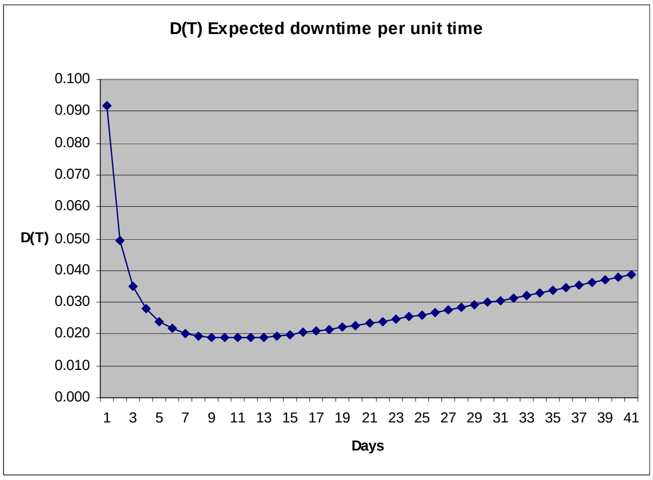

Figure 2. Optimal inspection period based on minimum downtime $D(T)$

As illustrated in figure 2 the minimum inspection interval based on minimum downtime $D(T)$ is 14 days. When the cost $C(T)$ is of primary concern the optimum inspection interval is 11 days with a cost of £940 as shown in figure 3. If the inspection interval was moved to 14 days in line with minimum downtime the cost would rise to £977 which is a nominal increase of £37.

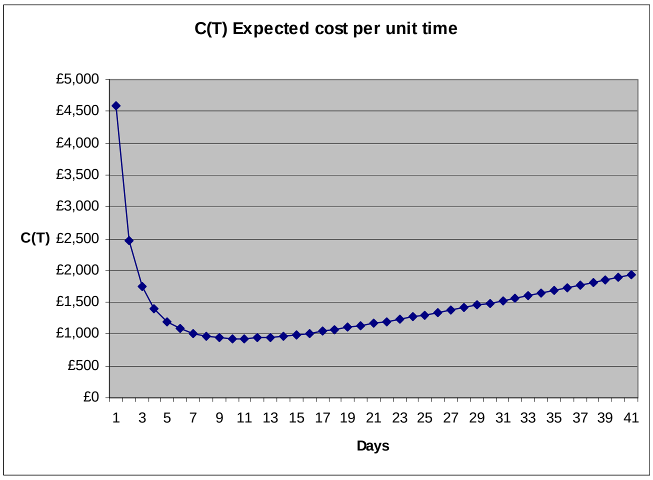

Figure 3. Optimal inspection period based on minimum cost $C(T)$

4. Validation

In order to analyse the effect of change to the results of $D(T)$ and $C(T)$ a sensitivity analysis was carried out on each model. The analysis varied certain input data by 5% and 10% resulting in the following.

4.1 Validation of $D(T)$

The optimal inspection interval remains very close to the original interval given an increase and decrease of 5% and 10%. The sensitivity analysis for $D(T)$ is shown graphically in figure 4.

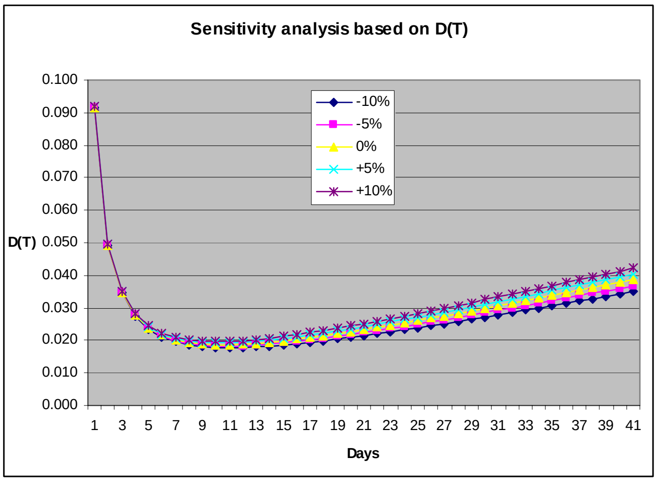

Figure 4. A graphical representation of the sensitivity analysis.

4.2 Validation of *C*(*T*)

A sensitivity analysis was carried out on the cost of an inspection repair and the cost of an inspection in order to analyse the effect of a change in the costs. The cost of an inspection repair and an inspection has been increased and decreased by 5% and 10%. The sensitivity analysis is shown graphically in figure 5. The optimal inspection interval remains very close to the original interval given an increase and decrease of 5% and 10%.

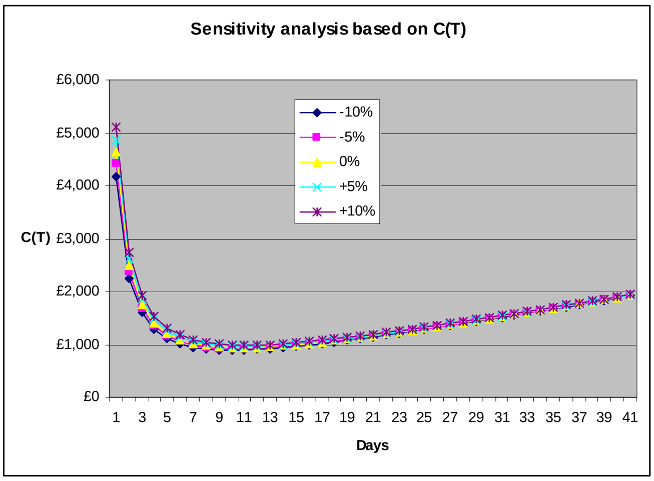

Figure 5. A graphical representation of the sensitivity analysis.

5. Discussion

It has been demonstrated in this case study that an optimal inspection interval taking into account a minimum downtime *D*(*T*) of 14 days has been established using the delay-time analysis technique. Using minimum cost *C*(*T*) as the criteria an inspection interval of 11 days with a cost of £940 was calculated.

Current practice at the company is that of a weekly inspection interval involving a flame check and a cloth check. It can be argued that this inspection interval could move to a 2 weekly interval but given the nature of the two inspection checks and the fact that it does not stop production, a weekly inspection interval appears reasonable.

6. Conclusion

This case study looked at a company in the UK producing carbon black. This paper demonstrates the delay-time concept for the use of minimising downtime and costs, setting inspection intervals to achieve this. Information was gathered form historical data as well as expert judgement, with parameters established from this information in order to develop the delay-time models.

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