# Quantitative Approach to Risk Based Maintenance Decisions

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## ABSTRACT

Maintenance is an important activity for asset intensive industries. It enhances life and reduces operating risks of plant and equipment. Effectiveness of maintenance is reflected in the bottom line of organisations through reduced costs of operation, downtime, injuries, repair and replacements, asset loss and insurance premiums. It is difficult to accurately predict the degradation and wear and tear of long life assets. Accurate cost of risks linked to injuries and compensation is another complex area for quantification. Understanding of the magnitude of risk in financial terms makes it easier for decision makers to use executive judgement for choosing appropriate design from available alternatives and/ or retrospective plant and process modifications. Quantitative risk models are helpful for cost effective operational and maintenance decisions. This paper is focused on how the failure characteristics of a component or assembly can be modelled mathematically. Quantitative approach to risk based maintenance decisions is proposed to estimate risks associated with failures and how to evaluate effectiveness of risk mitigation using alternative strategies.

*Key Words: Quantitative Models, Maintenance, Risks, Costs*

## 1. INTRODUCTION

Maintenance is an important activity for asset intensive industries. If carried out properly it is able to enhance life and reduce overall operating costs of plant and equipment and risks associated with unplanned down time and catastrophic failures. The effectiveness of maintenance is reflected in the bottom line of organisations through reduced costs of operation, downtime, injuries, repair and replacements, asset loss, compensations arising out of failures and insurance premiums. An asset manager will usually be confronted with decisions in relation to trade-offs between increasing inspection, maintenance or replacement activities and increasing costs from loss of reliability, availability, maintainability and safety (RAMS) affecting productivity.

Some of the multibillion dollar failures are: Hatfield rail accidents in UK in 2000 with cost tag of more than 734 million pounds due to rolling contact fatigue (RCF) killing 4 people and 34 injured, BP pipe failure in Alaska with more than 1 billion US dollar in 2006 with a massive environmental impact and steam pipe failure in New your in 2007 killing 3 people and shutting down 4 plants due to safety reason. RCF defects alone cost European Union railways around € 300 million per year and as these defects probably account for 15% of the total, the emerging cost of all defects is about 2 billion Euros per year. [1]

It is difficult to accurately predict the degradation and wear and tear of long life assets. Accurate costing of risks linked to injuries, environmental impact, compensation and goodwill are complex areas for quantification. However, quantitative risk models are important for cost effective operational and maintenance decisions. This paper is focused on how the failure characteristics of a component or assembly can be modelled mathematically. A quantitative approach to risk based maintenance decisions is proposed to estimate risks associated with failures. Understanding of the magnitude of risk in financial terms makes it easier for engineers and managers for taking appropriate decision from available alternatives and/ or retrospective plant and process modifications.

## 2. BACKGROUND

Asset intensive industries are typified by the establishment and use of large groupings of assets such as central power stations, steelworks, road transport networks including roads and bridges, rail networks, water and sewerage networks and electronic communication networks. The management of such assets involves decision making in many areas including design and maintenance which can have far reaching consequences. The objective of the top level of management is usually to maximise some function such as profit or utility to the community while minimising costs to the business. Income in monetary terms is relatively easy to quantify, while utility to the community can be more difficulty and may not be measured or reported in terms of monetary values. Costs have many components. Those that are measured and reported are capital and capital servicing, operating, cost of material inputs, direct maintenance cost. Some which may be overlooked are cost of life expenditure and risk [2].

It is common practice in heavy industry to describe risk in qualitative terms using a risk matrix, resulting in terms such as "catastrophic", 'serious", "high", "medium", "low" etc. These terms give no guidance on the magnitude of the issue, and hence there is a move to evaluate risk in quantitative terms, preferably in terms which can be used in normal business practices. Quantitative risk assessment in monetary terms is commonplace in the fields of insurance and finance. This paper deals with quantitative evaluation of risk.

## 3. PROPOSED QUANTITATIVE APPROACH

Risk is commonly defined as the probable outcome of an event. This is quantified by:

$Risk = P(t)xC$,

Where,

*Risk* = the probable outcome of a specific event.

$P(t)$ = probability that the event will occur.

This will usually be a function of time or of use. Most components will have a wear-out characteristic that results in a cumulative probability of failure that increases with time. It is useful to examine the change in probability with time [3].

$C$ = consequences of the occurrence of that event.

Consequences may include failures of plant and equipment with associated repair costs, consequential damage to other plant, injury to plant personnel and the public, environmental damage and associated cleanup costs, imprisonment for persons responsible for serious incidents, fines, legal actions and legal settlements. Loss of public image can be another important consequence for organisations involved in incidents which receive wide publicity. Consequences can appear to be in many different forms, but these can all be summarised into a single measure, expressed in monetary terms [4].

## 4. ILLUSTRATIVE EXAMPLE

Modern coal fired power stations are unitised, where a single boiler and turbogenerator are arranged as an isolated unit with no major process interconnections to other units. Each boiler is served by its own pulverisers, where coal of mixed lump size is reduced to very fine powder, also known as pulverised fuel (PF) in order to achieve fast, predictable and complete combustion when the fuel is injected through the burners into the furnace chamber. It is usual for each unit to be served by several pulverisers, with enough pulverising capacity being provided to allow at least one pulveriser to be taken out of service for maintenance while still maintaining full load capability on the unit. The operator has the ability to adjust the usage rates of the pulverisers so that the overhauls are approximately evenly spaced. Pulverisers are usually the largest single maintenance cost in a coal-fired power station.

Pulveriser wear life under known conditions is reasonably predictable, but in this example the data has been synthesised to indicate a greater spread in wear life.

The pulverisers are assumed to be large medium speed roll and table types, where the roll tyres and table segments may be replaced by identical new parts, or reclaimed by welded hard-facing. The hard-faced components can be designed to achieve an expected greater life than the original parts which are uniform castings. In reality, there could be various penalty effects, each being a different function of availability or some other performance measure. For simplicity, in this example all such effects have been rolled into a large financial penalty that has been applied as a single function of loss of availability.

In this example the assumptions in Table 1 apply:

| Quantity | Magnitude | Units | Symbol |
|---|---|---|---|
| Unit capacity | 500 | MW | $C_{U.nom}$ |
| Pulveriser capacity equivalent | 105 | MW | $C_P$ |
| Number of pulverisers | 6 | | N |
| Profit rate | $43.30 | $/MWhr | $R_P$ |
| Penalty for loss of availability | $200 | $/MWhr | $R_{LOA}$ |
| **Overhaul with parts replacement** | | | |
| Cost of O/H | 90,000 | $ | $Cost_{OH}$ |
| Time to O/H | 14 | days | $t_{OH}$ |
| Weibull scale parameter | 11,526 | hours | $\eta$ |
| Weibull shape parameter | 22.237 | | $\beta$ |
| Mean time to failure | 11,250 | hours | MTTF |
| Mean time between failures | 11,586 | hours | MTBF |
| Overhaul interval | 1 | year | $I_{OH}$ |
| Average probability of failure in 1 year | 0.0000528 | | $P_f$ |
| **Overhaul with hard-facing** | | | |
| Cost of O/H | 115,000 | $ | |
| Time to O/H | 7 | days | |
| Weibull scale parameter | 61,183 | hours | $\eta$ |
| Weibull shape parameter | 5.248 | | $\beta$ |
| Mean time between failures | 56,33 | hours | MTTF |
| Overhaul interval | 56,501 | hours | MTBF |
| Overhaul interval | 1, 2, 3, 4, 5, 6 | year | $I_{OH}$ |
| Average probability of failure in 1 year | 0.00624 | | |

Table 1: Assumptions applied to risk assessment

It is further assumed that individual pulverisers are capable of achieving their full rated capacity until they are worn out, after which their capacity is zero. Failure is considered to be due to wear-out only.

The failures are modelled as 2-parameter Weibull distributions, as this has been shown to be appropriate for cases such as these where wear is related to time in service. This is supported by other researchers working with similar conditions in power generation and other industries. The Weibull probability density function is expressed as

$$f(t) = \frac{\beta}{\eta}\left[\frac{t}{\eta}\right]^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

Figure 1 shows the plots used to estimate parameters for Weibull distribution for each of the two maintenance strategies.

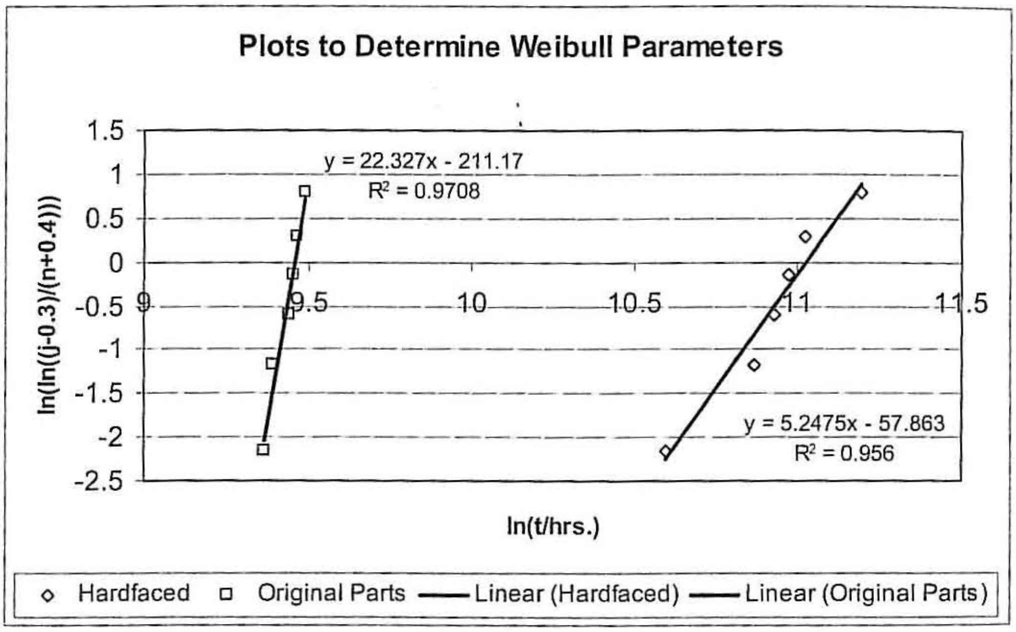


Figure 1: Parameter estimations

The hard-faced parts have the higher mean time to failure, as shown in Figure 2, but also a higher probability of failure at a low fraction of consumed life as shown in Figure 3. This second representation of the CDF is relevant because the time between overhauls in each case has been chosen to be close to the mean time to failure.

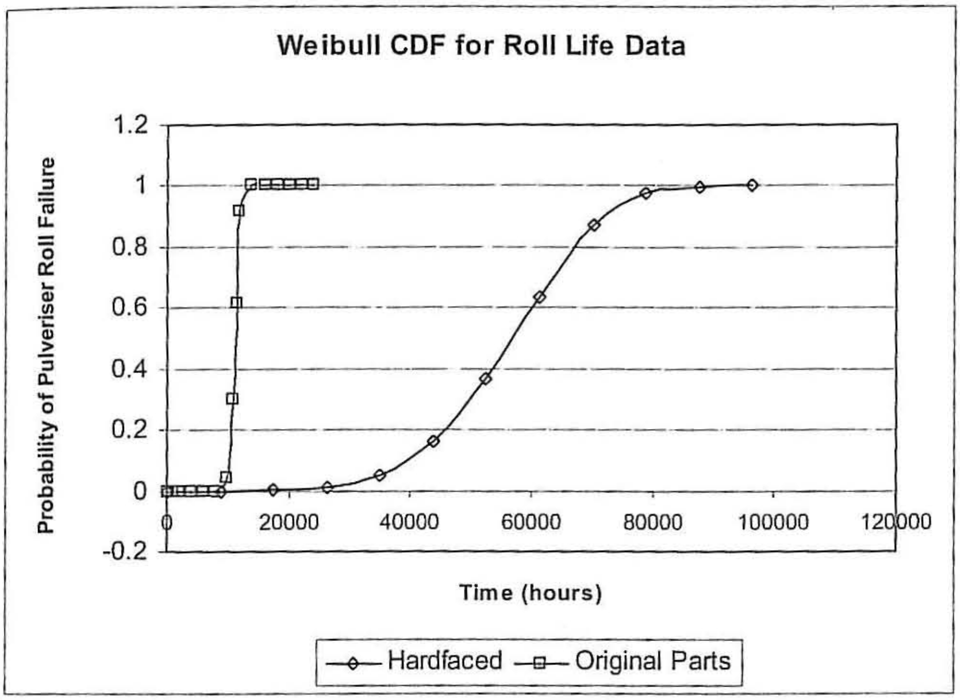


Figure 2: Cumulative failure distribution plotted in the traditional form of probability of failure vs. time.

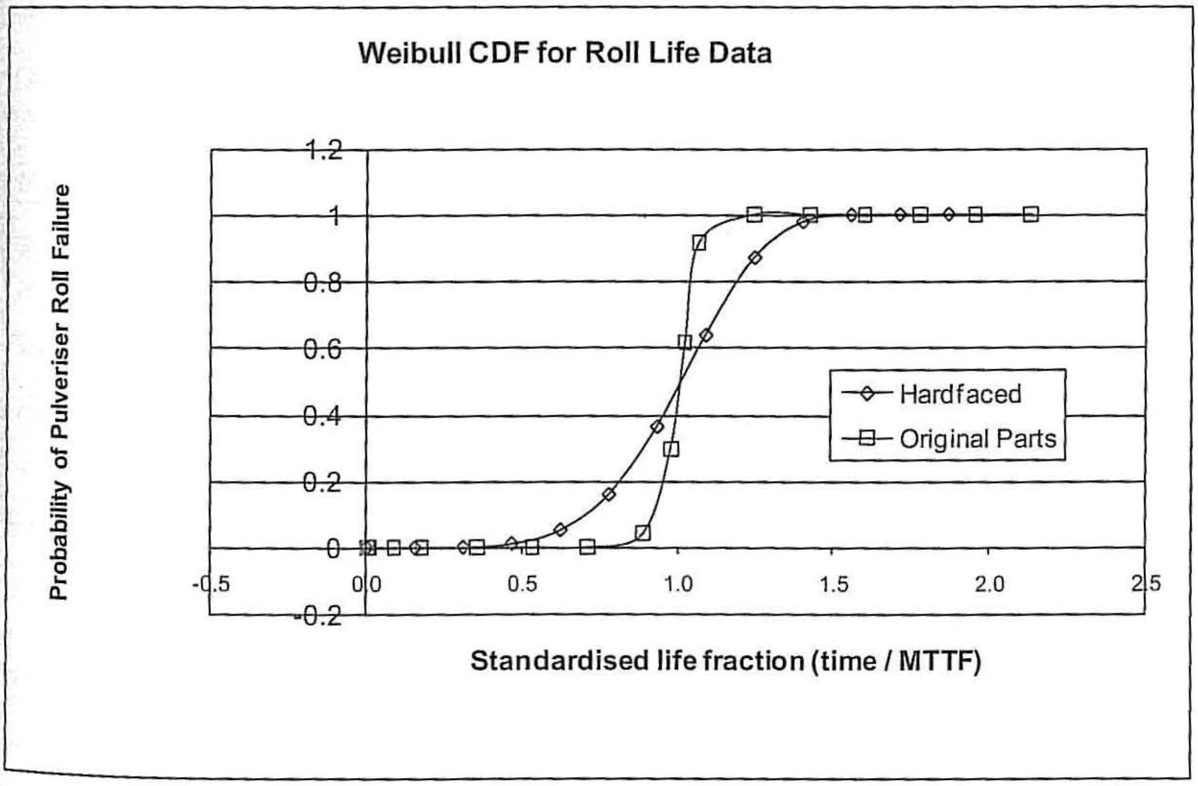


Figure 3: Modified cumulative failure distribution with probability of failure plotted against standardised time to failure, showing the more gradual failure process over the life of the component and the increased probability of failure early in the standardised life.

Further analysis has been simplified by restricting maintenance intervals to integer numbers of years. A more rigorous analysis would allow smaller divisions in maintenance intervals. The base case assumes that the overhaul interval with the original parts is 1 year. For the hard-faced parts, a range of overhaul intervals is considered.

For each overhaul interval the pulverisers will have their time since overhaul evenly spread across the interval. The following analysis shows the resulting failure probabilities for a unit having pulverisers with original parts and a 1 year overhaul interval, and for a unit having pulverisers with hard-facing and a 6 year overhaul interval.

When the probability of system failure in any year is evaluated for each system, the longer time between overhauls chosen for the hardfaced option results in a significant probability that there will be 1, 2 or 3 failures. The most likely state for the system with original parts and 1 year time between overhauls is 0 failures. This is shown graphically in Figure 4.

The direct maintenance cost and risk have been modelled as follows:-

| | |
|---|---|
| Annual maintenance cost, | $C_{MA} = Cost_{OH} / I_{OH}$ |
| Cost of failure repair, | $C_{FR} = Cost_{OH}$ |
| Annual risk (failure repair), | $Risk_{FR} = P_f * C_{FR}$ |
| Expected number of pulverisers available, | $N_A = N - P_f * N$ |
| Expected pulverising capacity, | $C_{Pulv} = N_A * C_P$ |
| Expected unit capacity, | $C_U = if(C_{Pulv} > 500MW, 500MW, else\ C_{Pulv})$ |
| Lost production, | $E_{LP} = (C_{U.nom} - C_{U}) * t_{OH}$ |
| Cost of lost production, | $Cost_{LP} = E_{LP} * (R_P + R_{LOA})$ |
| Annual risk (lost production), | $Risk_{LP} = P_f * Cost_{LP}$ |
| Total annual cost, | $Cost_{total} = C_{FR} + Risk_{FR} + Risk_{LP}$ |

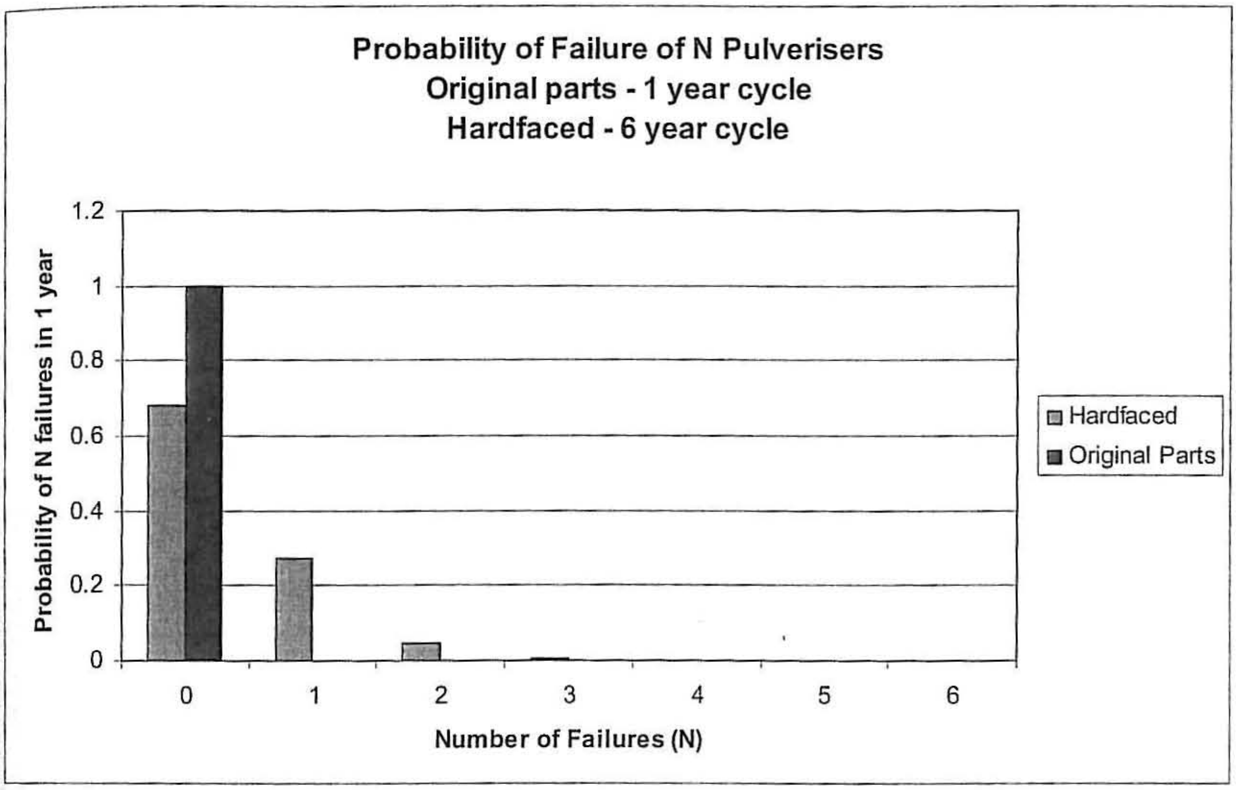


Figure 4: Analysis of Pulveriser Failure

This analysis is repeated for overhaul intervals for the hard-faced case of 1 to 6 years. The results are listed in Table 2 and shown graphically in Figure 4.

| Method of Overhaul | Original | Hard-faced | | | | | |
|---|---|---|---|---|---|---|---|
| Overhaul interval (yrs) ---> | 1 | 1 | 2 | 3 | 4 | 5 | 6 |
| **Annual costs per pulveriser** | $ | | | | | | |
| Risk (failure repair) | 5 | 1 | 25 | 210 | 938 | 2,941 | 7,173 |
| Risk (lost profit + penalties) | 345 | 19 | 712 | 5,967 | 26,857 | 85,242 | 213,128 |
| Overhaul cost | 90,000 | 115,000 | 57,500 | 38,333 | 28,750 | 23,000 | 19,167 |
| Totals | 90,350 | 115,019 | 58,237 | 44,510 | 56,546 | 111,182 | 239,468 |

Table 2: Variation of overhaul cost, risk, and total costs with overhaul interval.

It can be seen that the declining overhaul cost of the hard-faced examples with increasing overhaul interval seems attractive. When risk is taken into account, the increase in risk with time adds to total cost. The total cost is minimised with an overhaul interval of about 3 years. This effect would not be obvious without quantitative risk assessment.

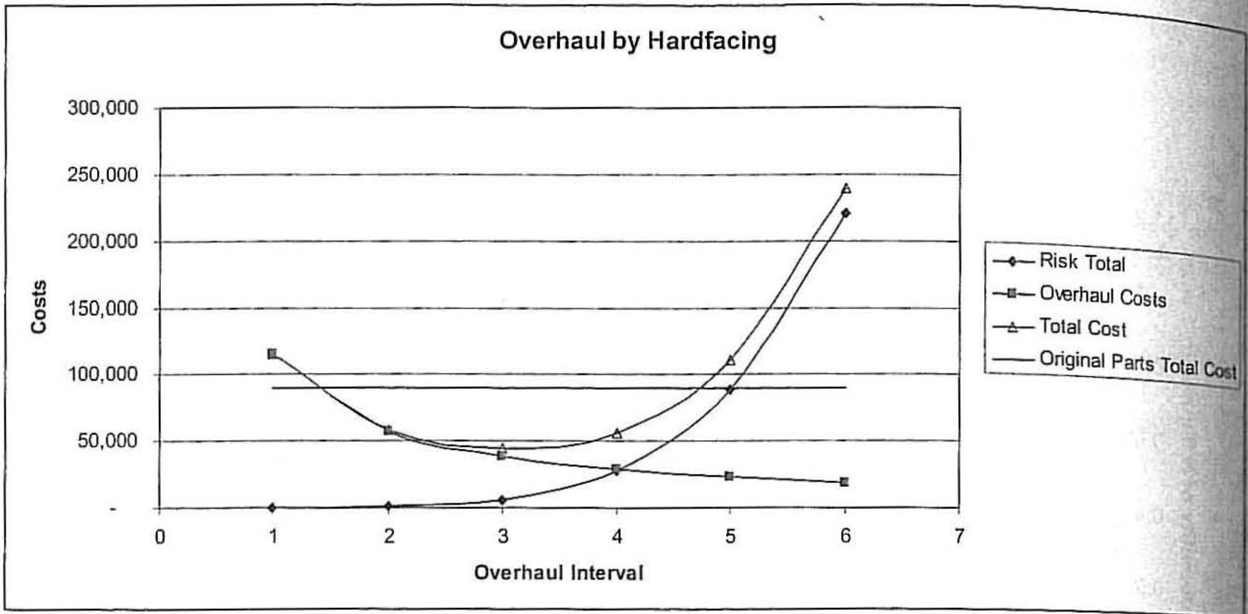


Figure 4: Overhaul decision analysis

## 5. CONCLUSIONS

Risk can be a substantial cost. In many cases it is used in qualitative way mainly because it is difficult to quantify. In this paper a quantitative approach is proposed where monetary value can be attached to risk. When risk is recognised, actions need to be taken for its monitoring and control. This may involve passing the risk to another party (through the normal insurance process) or by altering maintenance and operating decisions to minimise the total cost. The illustrative case studied here has ignored significant accounting effects such as depreciation and taxation. Maintenance decisions based on a narrow range of immediate costs can be far from optimal. When risk is evaluated in monetary terms and taken into account in maintenance planning, it may produce decisions which are markedly different from direct cost estimates alone. There is huge scope for applying this quantitative risk based maintenance model for managerial decisions.

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