

Condition Based Maintenance - A systematic method for counting the cost and assessing the benefits

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A mathematical model has been developed in order to predict the cost of repairs for batch process plant machinery in the pharmaceutical industry and thereby determine the associated cost benefits of practising a condition-based maintenance programme. The implications of consequential costs arising from the operation of fans is compared with pumps which have stand-by facilities. The situation with gearboxes where oil condition monitoring decreases the failure rate is also examined.

1. Introduction

The manufacture of pharmaceutical products, as with many other processes, demands a high level of performance, availability and reliability from the machinery installed to provide the transfer of power through many moving parts. This is highlighted even more so when the process time from inception to completion takes several weeks, during which the added value of the product increases many times, especially when it comes towards the end of the production cycle.

The kind of machinery which is typically utilised for this purpose can be broadly categorised in terms of major power transfer items such as motors and other prime moving equipment, pumps, fans, compressors and gear transmission systems. All these devices involve considerable tribological activity arising from interactions between rubbing surfaces. It is inevitable, therefore, that the tribological integrity of the plant will be brought into question from time to time in relation to failure of equipment and other malfunctions which cause delays in the smooth running of the operations.

Figure 1 shows in schematic form the layout for a pharmaceutical production process.

Table 1 lists the types of failure experienced over the past ten years in fans.

Table 1. Types of fan failure

No	Type of Failure	%
1	Impeller related (e.g. Deposit causing imbalance, chipped blade etc.)	35
2	Bearing failure	27
3	Belt problems	18
4	Other miscellaneous (e.g. loose foundation bolts, split bellows etc.)	20

Whilst good design and good housekeeping practices assist greatly in minimising the risk and occurrence of failure, the need to maintain equipment on some basis is inevitable. The four principal strategies presently employed in the maintenance of many such plants are(1) :

- ◆ Breakdown
- ◆ Time based (planned) preventative maintenance
- ◆ Reliability Centred maintenance
- ◆ Condition based maintenance

it should be noted here that although other strategies have been advocated such as e.g., Operational Criticality Based Maintenance (2) their use in the UK industrial sector is small.

This raises immediately two questions :

Which form of maintenance strategy is the best one to use ?

What is their cost effectiveness ?

In attempting to answer these questions, a study has been undertaken over the past three years which is based entirely on a single plant in the pharmaceutical industry which operates on a batch production basis. The product may be classed as a low volume, high added-value product. Disruption to the normal, planned operation of the plant can thus incur high losses even though only comparatively small volumes of product are affected. In addition to the normal risks associated with energy transfer, the biological and environmental hazards involved means that items such as fans are critical to the operation and well being of the plant and also the people in close proximity to the operation.

In a plant operating along these lines it is not surprising to find that all the above maintenance strategies can be utilised to good effect and can be cost effective. However, the basis on which a decision to make use of any one strategy for a given purpose is often quite complex and difficult to quantify.

In this paper the methodology used to predict the cost effectiveness of maintenance strategies for specific types of equipment such as pumps, fans, and gear transmission units is described. Reference to specific case studies serves to illustrate how the method can be used to decide which form of maintenance to adopt and how cost effective it is in relation to alternative strategies.

In relation to condition based maintenance, the monitoring techniques which have proved to be best suited for the class of machines used in this particular plant are:

- 1) Vibration analysis (two types)
 - a) High level using portable data collectors in which the data is analysed using Fast Fourier Transform (FFT) methods which pinpoint the component that is failing.
 - b) Low level using portable data collectors in which the overall vibration level is recorded to enable trends to be established leading to intrusive inspection when a pre-determined threshold is exceeded.
- 2) Lubricating oil condition
This is routinely monitored using 'grab' samples. A few basic parameters are trended, or action limits are imposed on the change relative to the 'as new' condition, which triggers action. The system is used to sentence the oil and is not directly used for providing insight into the machine condition. In the population of gearboxes studied this regime has led to a reduction in the failure rate.

It is important to note that since the operation is on a batch production basis, it is unnecessary to monitor the plant continuously.

2. Development of the methodology and the mathematical model

The comparative life cycle costs of the above maintenance strategies has not been fully investigated. A start was made by Jardine (3) who looked at different types of machine characteristics in order to arrive at replacement, inspection and overhaul decisions. Implicit in his methodology was an assumption that maintenance was to be part of operating costs but these would vary in a simple (possibly second degree curve) manner with time and hence, as operating costs varied, a replacement decision would become the correct option and this could be mathematically calculated. A number of different possibilities were considered whereby operating costs decreased with age, increased with age, had to be within a finite (bounded) time horizon, and where the unit was a stand-by machine with all the above possibilities. Using these types of model he also attempted to develop equations for "Inspection Decisions" (intrusive and hence, essentially the "planned maintenance" approach). These models are theoretically defensible but the level of data required to evaluate these equations is generally unavailable. Further, the problem of components with random failure modes is not addressed.

Moubray (4) questions what a failure is, and argues that this could be perceived very differently by people with differing viewpoints. An example quoted is that of a hydraulic system where even a small leak is seen as failure by the Safety Officer, a much larger leak as failure by the engineer and only the complete stoppage of the system as failure by the production staff. Therefore costs become dependent on the type of “failure” being investigated.

Alternatively, a failure could be judged against performance standards and costs similarly calculated against these standards. Again, the question of whether consequential costs are taken into account as well as direct costs needs to be addressed. Without taking into account consequential costs, Carter (5) calculates whole life cycle costs using a statistical approach in which he utilises a definition of failure in terms of the machine failing to perform to the required production standard.

For a model developed by the Solartron company (6) cost benefits are determined in relation to :

- 1) Operational safety effects on plant and environment.
- 2) Personnel safety risk.
- 3) Operational issues excluding safety e.g. severity of machine duty.
- 4) Technical issues.

The need for a mathematical model to be developed to assess the cost benefits becomes apparent when confronted by the fact that savings could be small for low capital value equipment. However, the number of machines involved must also be taken into account. Therefore, to determine the point at which each regime of condition monitoring activity becomes cost effective requires that a definitive (quantitative) model be established.

To be able to predict costs, the model proposed is formulated in two parts:

- a) The costs of damage to the machine itself and the associated direct costs of repair.
- b) The consequential costs in regard to loss of production due to down time, etc.

A number of mathematically-based models have been proposed previously(7), but in each instance the cost of repair has been treated as a known value. To be in a position to make “real” decisions it is argued here that it is essential to be able to predict the cost.

For type (a) situations the model we propose to develop is based on the following relationship :

$$C_d = C_i * I_p * I_c * I_{pr} * K_d \dots\dots\dots(1)$$

Where

C_d = direct costs of machine breakdown

C_i = initial costs of machine corrected to present day value

I_p = power index

I_c = criticality index

I_{pr} = process index

K_d = direct costs factor

The model proposed is based on the fact that the capital cost is known in each case and from which a non-dimensional factor K_d is derived from analysis of the model in order to predict the direct costs of machine failure. Likewise, in type (b) situations, a factor K_c is used to predict consequential costs.

The power index I_p is utilised to relate the power of a unit to its associated cost on a scale of 1 to 10, as follows:

Power (kW)	3	8	15	30	50	80	110	150	200
Power Index I_p	2	3	4	5	6	7	8	9	10

The Criticality Index is a measure of how critical the machine is to the process of which it is a part. This index is again a number on a scale of 1 to 10 and was again determined by studying the process and evaluating the criticality of the machine. However, if a machine was one of a series where a stand-by machine could be put directly into service without interrupting the process, the criticality index was automatically set at 1. If machine failure had the result of immediately stopping the entire process then it had a criticality rating of 10 (e.g. the failure of a motor or gearbox on the stirrer drive of a reactor vessel would immediately halt the reaction and would have a criticality index of 10). If the machine failure was such that the process could be maintained but only at reduced throughput then:

$$I_c = (\text{Through put available/ throughput possible}) \times 10.$$

The Process Index was evaluated on the basis of how much of value had been added to the product at that point in the overall process. This index is again a number on a scale of 1 to 10. Hence, all machines at the stage where the raw material is fermented would have a process index of 1 whilst all machines in the finishing suites would have a process index of 10. Figure 1 shows the process flow through the entire plant.

On this basis the direct costs factor is calculated as a function of the power of the unit and thus used to predict the costs of breakdown for any machine in a particular class.

To establish the model in the first instance, the frequencies of actual breakdown were obtained from plant maintenance field data recorded since 1989. For example, the records of 329 pumps in the solvent recovery area showed that 711 failures took place over a 5 year period giving a machine reliability of 0.649 per machine per year and that of fans using the sample of 93 fans was 0.691 per machine per year using the definition as proposed by Carter (5) after Carhart:

$R(t)$ = Cumulative probability function of occurrence of survival.

Planned maintenance costs and inspection costs were calculated using the company standard hourly rates and published prices for spares. Capital costs were taken from the company records and adjusted for inflation using the published Retail Price Index (RPI) figures. These figures were then compared with new quotations for the same machines from the manufacturers so that confidence could be gained in this method. With regard to the probability that condition monitoring techniques will actually detect failure, Neale et al (8) estimates that 75% of defects will be detected and hence this factor is also accounted for in the model.

3. Application of the model

3.1 Pumps

The initial experience of applying the model was undertaken for the total pump population at the company's production plant. Pumps were selected because most of them operated on a stand-by basis and hence without any consequential cost implications.

To determine K_d values, data from 329 pumps was analysed to produce a "best fit" relationship with pumping power - see Figure 2.

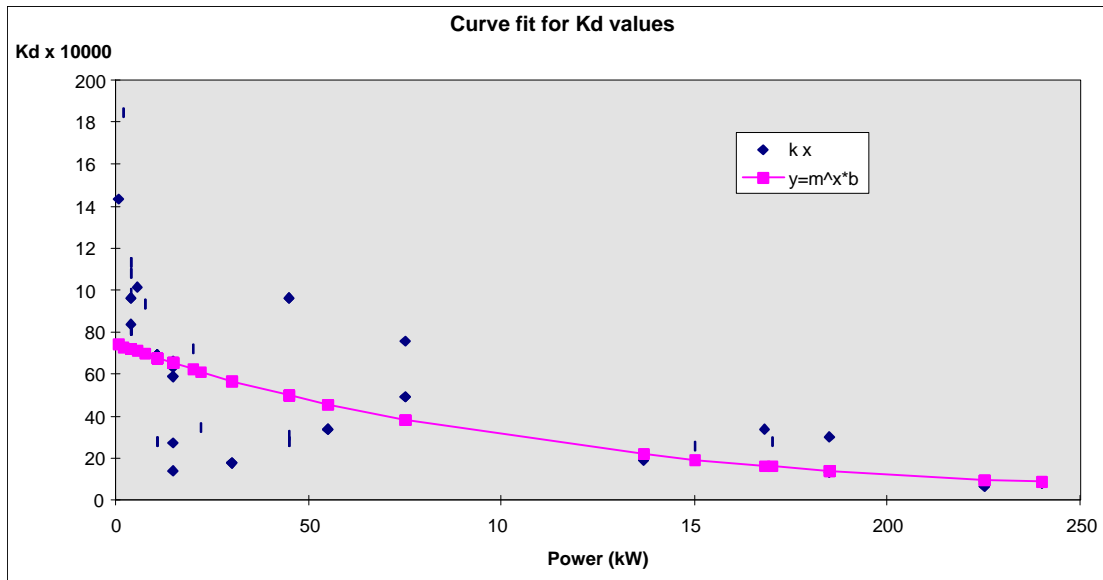


Figure 2

Based on the pump data for the period from 1990 the average saving from using vibration measurements to trigger maintenance against a time-based system was £1124 over the five year period; i.e., £224.80 per annum per pump. The monitoring costs were a one off purchase of a vibration meter in 1990 at £1750 (which has now been completely written off) and labour costs at 1.5 hrs per pump per annum, which at the company's present rates equates to £24.75 and hence, there is a saving of £200.05 per pump per annum.

From the above figures it is evident that if payback of two years is used as the criterion and the current cost of a vibration monitor is £4500 then a minimum of 11 pumps must be within the group for the system to be more cost effective than a time-based planned maintenance system.

Breakdown maintenance costs were difficult to acquire but using a small sample of pumps that had broken down it was estimated that breakdown costs were 1.8 times of planned maintenance costs per pump because of greater damage sustained within the pump. Using the data to estimate pump failure rate gave a figure of 0.43 per pump per year. The planned maintenance system generated 0.86 pump overhauls per pump per year. With properly targeted planned maintenance there were almost zero breakdowns and hence, with the population of 329 pumps studied, breakdown maintenance costs were only £7.7 per pump per year greater than if planned maintenance was used.

If a high level condition monitoring system was to be used, the capital cost of the instrumentation and software would be £26000. The cost of data acquisition and analysis is £153 per machine train per annum. If the capital costs are amortised over 10 years, the saving would be just £19 per pump per annum. Hence for this system to be cost effective with a payback period of two years, a minimum of 276 pumps need to be monitored. However, with a portable data collector and associated systems, it is possible only to monitor c.250 machines and hence this system would never be viable in this case.

These calculations are also coded into a spreadsheet which makes an assessment of whether condition monitoring will be cost effective for whatever payback period is selected. The "Frontsheet" of the MS Excel spreadsheet is shown in Appendix 2. Two separate examples are shown; one for a 22 kW pump and another for a 240 kW pump. The decision arrived at in each case was based on the predicted costs of repair which were as shown. The actual costs of repair of these pumps were £510 and £1050 compared with predicted values of £668 and £1209 respectively.

The cost saving per pump per year by using condition monitoring is given by

$$C_s = 0.8 * (\text{Predicted repair costs}) * (\text{Pump failure rate}) * (\text{Probability of detection})$$

$$- \left[\frac{\text{Capital cost of CM equipment}}{\text{No. of machines in the group}} \right] - (\text{Running costs of CM programme})$$

3.2 Fans

93 fans varying in size from 0.75 kW to 200 kW were studied. The direct repair costs were analysed using various curve fits. However, it was seen that the direct repair costs were influenced very little by either process or criticality. The major influence was only the size (power) of the fan. This is shown in the graph (fig.3) where a linear curve fit of power vs. Direct breakdown costs.

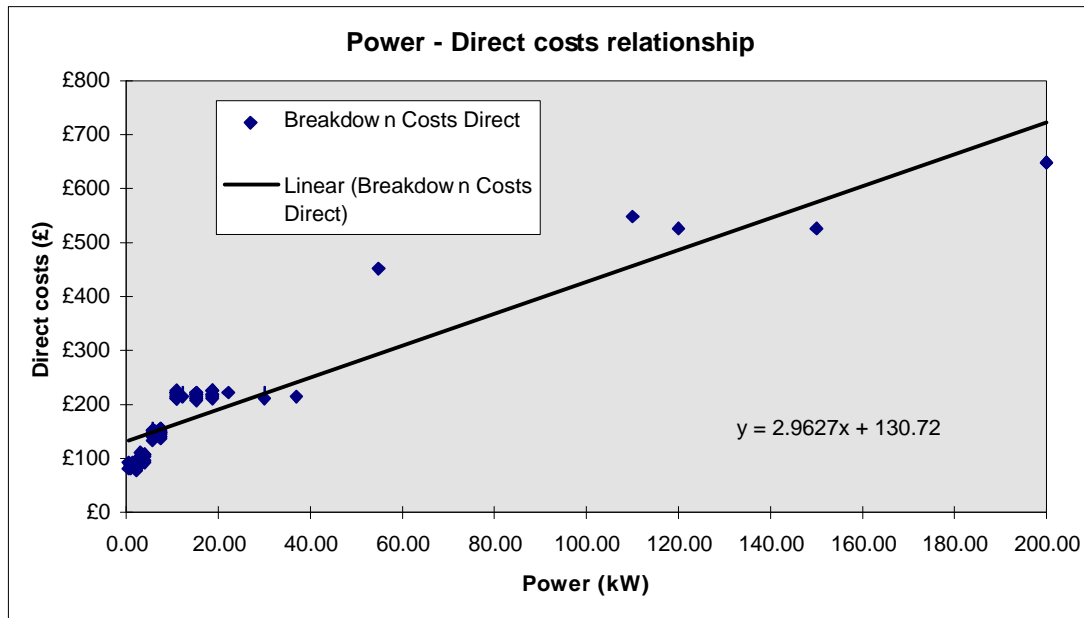


Figure 3

Evaluating the various curve fits using the Chi-square test yielded the linear fit as shown and hence this was used in subsequent analyses to predict the repair costs for fans.

All 93 fans were evaluated for their criticality to the process on which they were used. It could be seen that only 31 fans had any degree of criticality; i.e., $I_c > 5$. Figure 4 shows the results of analysis based on the proposed model in which the best fit to the data is the curve $K_c = 0.038e^{-0.02(\text{Power})}$.

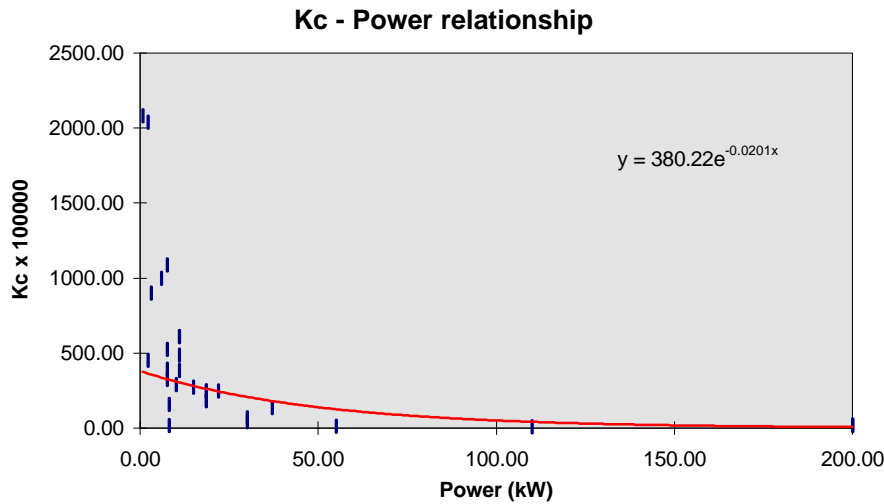


Figure 4

The failures being used here for the statistical analysis of the probability of failure is by counting the number of failures due to multiple causes in a fan population over a period of time. This type of analysis gives rise to a Poisson distribution and hence the characteristics of a Poisson distribution could be applied to the data in question. We have with the sample of 93 fans, 103 breakdowns recorded over 3 years. This gives a mean failure rate of 0.369 per fan per year. The characteristics of the distribution yield the following parameters:

Mean failure rate $I = 0.369$

Standard deviation of the distribution $= \frac{\sqrt{I}}{\sqrt{N}}$,

[where N is the number of samples in terms of machine years]

$$\therefore \text{Standard deviation} = \frac{\sqrt{0.369}}{\sqrt{(93 \times 3)}} = 0.036$$

Hence 95% confidence limits of the mean rate I is 0.369 ± 0.072

And the probability of no failures in a year (i.e. Reliability) $= e^{-I} = e^{-0.369} = 0.691$

To test the model against actual plant data, four fans which were not included in the original study, provided the means whereby the direct costs of repair and the consequential costs of failure could be predicted and compared with known costs. They were all critical to the process; i.e., $I_c = 10$ and were also used in the final stages of production and therefore, $I_p = 10$ also applied. None of the fans had a stand-by facility. The comparisons of predicted and actual values derived from records of the costs incurred when the fans had actually broken down and corrected to 1996 prices are given in the table below:

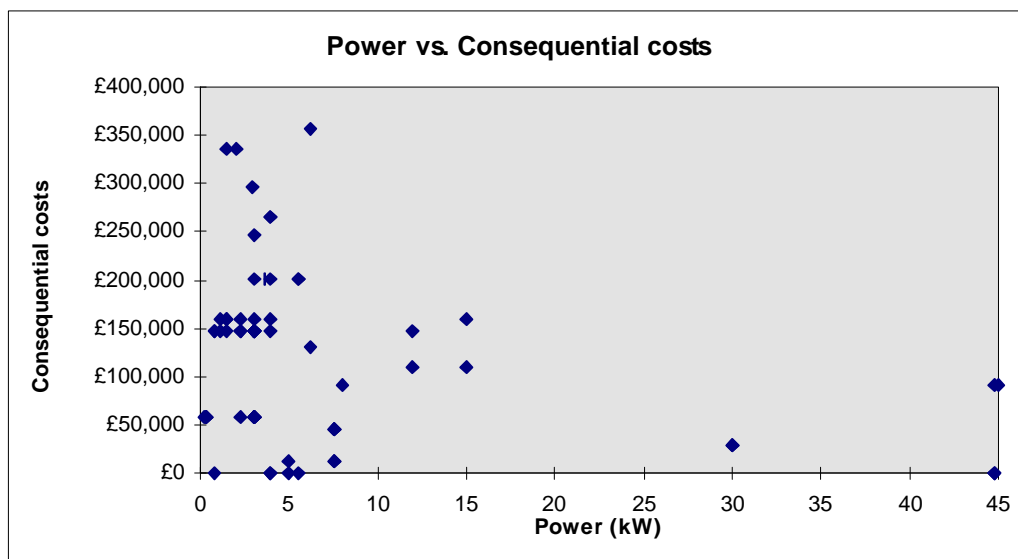
Table 2 - Comparison between predicted and actual costs for fans

	Predicted repair cost	Actual repair cost	Repair costs not including decontamination	Predicted consequential cost	Actual consequential cost
Fan A	£137	£684	£140	£6912	£13484
Fan B	£143	£768	£150	£15437	£17979
Fan C	£163	£936	£180	£32004	£26969
Fan D	£163	£936	£180	£32004	£26969

The reason for the marked difference evident between the predicted and actual repair costs is that the second set of figures reflects the fact that considerable preparation work must of necessity be undertaken prior to carrying out the repairs. This involves decontamination of area and housing which in reality could be thought of as consequential costs. The comparison otherwise is, on the whole, encouraging in that the predicted and actual costs move together, although it is evident that with consequential costs the predicted costs are just as likely to overestimate as underestimate the actual costs. It is nevertheless instructive to observe the extremely large disparity between the repair and consequential costs.

3.3 Gearboxes

Maintenance strategy for gearboxes: The maintenance of gearboxes in the plant require a different strategy to that employed, for example, with pumps and fans. The reason for this becomes self-evident in the light of consequential costs associated with their failure, as illustrated in Fig.5, which is based on the analysis of a range of individual gearboxes located on plant. It also reveals that the costs incurred is not a direct function of the power transmitted.



type reduction gearboxes in which considerable wear and misalignment can be tolerated before complete failure occurs.

The use of condition monitoring techniques has to be considered very carefully for gearboxes operating under these conditions. Higher power gearboxes (>150 kW) are routinely monitored using oil analysis. This is done primarily to sentence the oil rather than detect incipient failure. Vibration analysis is utilised with gearboxes which attract high direct repair costs simply to minimise the damage within the box before repairs are effected.

To summarise: Whereas, in the main, consequential costs are minimised by over engineering the product, there is a price to be paid in a much higher level of capital cost incurred.

Analysis of direct and consequential costs: This analysis is based on a sample of 87 gearboxes across the plant. Over a 5 year period there were 74 failures of these gearboxes and hence,

$$\text{Failure rate } I = \frac{74}{5 \times 87} = 0.17$$

and, assuming that the failure distribution is Poisson,

$$\text{Reliability } R_i = e^{-I} = e^{(-0.17)} = 0.844 \quad (1)$$

Direct costs of gearbox failure were acquired using the same method as for fans and pumps. These have been analysed using the same model as for fans and pumps; i.e., $C_d = C_c \cdot I_p \cdot I_c \cdot I_{pr} \cdot K_d$

where, C_d = Direct repair costs
 C_c = Capital cost of gearbox
 I_p = Power index
 I_c = Criticality index
 I_{pr} = Process index
 K_d = Direct costs factor

The relationship between K_d and power was found to be of the form:

$$y = 34.54 \cdot e^{-0.0053x} \quad (2)$$

In terms of the relationship between repair costs and power, there is considerable scatter below 50 kW; nevertheless, a linear fit is obtained of the form:

$$y = 24.60x + 1018 \quad (3)$$

With regard to consequential costs the relationship is of the form:

$$C_q = C_c \cdot I_p \cdot I_c \cdot I_{pr} \cdot K_c$$

where, C_q = Consequential costs
 K_c = Consequential costs factor

Again, from inspection of the data it was evident that there was considerable scatter and that it was better to divide the data into two distinct power ranges, ≤ 15 kW and >15 kW, as shown in Figures 6 and 7, respectively.

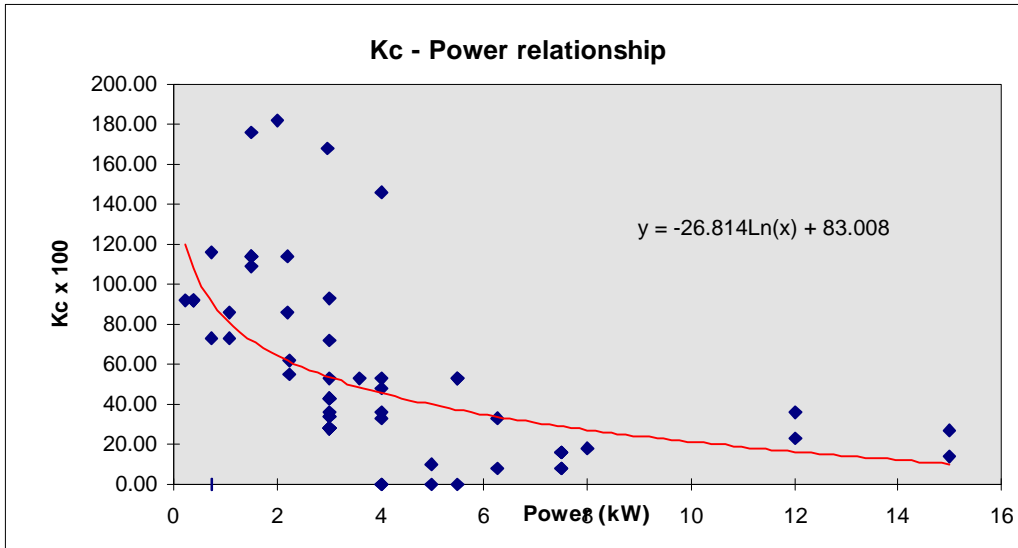


Figure 6 - Consequential costs factor, K_c versus Power (< 15 kW)

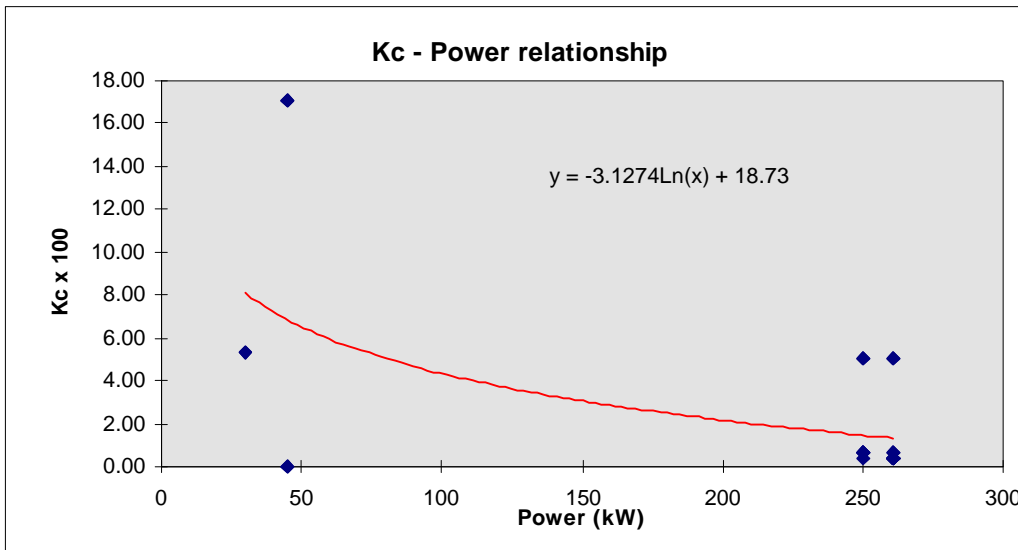


Figure 7 - Consequential costs factor, K_c versus Power (>15 kW)

Testing the model: Three gearboxes, which had not been included in the study, were selected and their direct and consequential costs ascertained and compared with those predicted using the above relationships. The gearbox details are presented in Table 3 below.

Table 3 - Gearbox details

Class of	Machine	Corrected	Direct	Consequential	Power	Criticality	Process
Machine	Description	Cost*	Costs*	Costs*	Index	Index	Index
Gearbox	Gbox 'A'	£2,442	£222	£159,512	1	10	9
Gearbox	Gbox 'B'	£3,519	£1,852	£45,530	2	10	4
Gearbox	Gbox 'C'	£5,345	£1,652	£28,542	5	10	2

(*) These figures are in pounds sterling, as is also the case in Tables 4 and 5 below.

The formulae tested were:

1) Direct costs as predicted by $K_d \times 10^4 = 34.541e^{-0.0063(\text{Power})}$ and $C_d = C_c * I_p * I_c * I_{pr} * K_d$

2) Direct costs as predicted by $C_d = 24.595(Power) + 1017.9$

3) Consequential costs as predicted by $K_c \times 10^2 = 83.008 - 26.814 \ln(Power)$

(For gearboxes with input power <15 kW)

$$K_c \times 10^2 = 18.73 - 3.1274 \ln(Power)$$

(For gearboxes with input power >15 kW)

The results based on the predictions are listed in Tables 4 and 5 below:

Table 4 - Direct costs

Machine description	Predicted direct costs (1)	Predicted direct costs (2)	% difference (1)	% difference (2)
Gearbox 'A'	754	1,045	240	370
Gearbox 'B'	927	1,202	-50	-35
Gearbox 'C'	1,528	1,756	-7.5	6.2

Table 5 - Consequential costs

Machine description	Predicted Consequential costs	% difference
Gearbox 'A'	176,845	11
Gearbox 'B'	81,578	79
Gearbox 'C'	43,260	52

Clearly, the agreement at low powers is not good, but improves considerably at higher powers.

4. The basis for making the decision

The purpose here is to use the model proposed in the foregoing to provide an appropriate means for plant engineers to decide whether the use of condition monitoring methods as part of a condition-based maintenance strategy is justified in terms of cost benefit analysis and, if so, what type of monitoring is best employed; e.g., low level or high level vibration analysis. Table 6 below shows a sample spreadsheet for two small powered fans 11 kW and 5.5 kW, respectively. The logic and calculation procedure used to generate the data is presented in Appendix 1.

Table 6 - Decision spreadsheet

Master sheet for assessing cost effectiveness for fans		
Enter power of the fans in kW	11	5.5
Enter number of fans in the group	5	10
Enter number of fans in the group with no stand-by fan	1	1
Enter capital cost of the fan at time of purchase	£3,500	£2,200
Enter year of purchase	1995	1995
Enter criticality index of the fans with no stand-by fan	10	10
Enter the process index for the fan group	10	10
Enter the hourly rate for labour	£16	£16
Enter capital cost of low level vibration monitoring equipment	£2,200	£2,200
Enter capital cost of high level vibration monitoring equipment	£20,000	£20,000
Enter annual cost of maintenance of CM equipment (as percentage of capital cost)	5.00%	5.00%
Enter year of purchase of vibration monitoring equipment	1995	1995
Enter payback period for assessment	2	2
Enter mean failure rate	0.37	0.37
Enter probability of detection of deterioration using low level CM	0.61	0.61
Enter probability of detection of deterioration using high level CM	0.73	0.73
Enter cost ratio between hourly rates for technicians vs. craftsmen	1.19	1.19
Enter number of years for amortisation of asset	10	10
Enter internal rate of interest	5.00%	5.00%
Is use of low level equipment justified ?	Yes	Yes
Is use of high level equipment justified ?	No	No
Predicted capital cost of purchase of fan on the current date	£3,865	£2,430
Power Index	3	2
Kc x 10000	304.7982	340.4268
Predicted consequential costs	£35,343	£16,541
Predicted fan repair cost	£163	£147
Corrected cost of low level CM equipment	£2,430	£2,430
Corrected cost of high level CM equipment	£22,087	£22,087
Discounted divider	6.14	6.14
Predicted pump condition monitoring cost (low level)	£103	£64
Predicted pump condition monitoring cost (high level)	£776	£417
Cost saving with use of low level equipment (per fan) - Fan with stand-by	-£74	-£37
Cost saving with use of high level equipment (per fan) - Fan with stand-by	-£741	-£385
Cost saving with use of low level equipment (per fan) - Fan without stand-by	£7,903	£3,696
Cost saving with use of high level equipment (per fan) - Fan without stand-by	£8,805	£4,083
Years for payback with low level equipment	0.32	0.72
Years for payback with high level equipment	3.78	35.63

5. Discussion

5.1 A simple mathematical model can be used to predict both direct and consequential costs of machinery failure.

5.2 Using these predicted figure it is possible to set up a decision system to evaluate the cost effectiveness of various maintenance regimes.

5.3 An essential part of the decision is the reliability of the machinery class and the probability of detection of machinery deterioration using the condition monitoring technique. The use of condition monitoring techniques becomes harder to justify the more reliable the plant. The probability of detection by using any one of the techniques available can be estimated using the LEO technique proposed by Birchon (9).

6. Conclusions

6.1 No consequential costs - pumps

- I. A simple mathematical model has been developed to predict the costs of repair which are related directly to the capital cost and power of the unit in which the agreement between predicted and actual costs improves markedly as pump power increases.
- II. Capital cost of purchase can only be meaningfully extrapolated using the original cost for a comparatively short time span (< five years).
- III. The costs of maintenance, based on three different maintenance strategies are :
 - a) Breakdown maintenance
 - b) Planned maintenance
 - c) Condition based maintenance
 - High level vibration analysis
 - Low level vibration analysis
- IV. Breakdown maintenance is only marginally more expensive than planned maintenance. A slight increase in pump reliability will bring down breakdown maintenance costs below that of planned maintenance.
- V. The break even point rises dramatically between using the low level system and the high level system and hence, in the introductory stages, a low level system will deliver benefits much more positively than a high level system.

6.2 With consequential costs - Fans & Gearboxes

- I. The higher reliability of the fan population and the even higher reliability of the gearbox population changes the cost effectiveness of the different maintenance regimes. Condition-based maintenance now becomes more expensive than breakdown maintenance when consequential costs are not involved.
- II. The use of oil analysis is very cost effective for gearboxes as it improves the failure rate.
- III. Where consequential costs are involved, they completely outweigh all other factors and some form of condition based maintenance is the most effective method.

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References

- 1) The development of a cost benefit analysis method for monitoring the condition of batch process plant machinery. - B.S.Rajan and B.J.Roylance Proceedings of the Joint Conference - Integrated Monitoring, Diagnostics and Failure Prevention - Mobile, Alabama, April 1996, pp 725-736.
- 2) Tischuk. J. - The Tischuk OCA system - Private correspondence 1996.
- 3) Maintenance, Replacement and Reliability - A.K.S.Jardine & S.Kennedy - Pitman Publishing Ltd., 1973.
- 4) Reliability Centred Maintenance - J.Moubray - Butterworth 1991.
- 5) Mechanical Reliability - A.D.S.Carter - 2nd edition - Macmillan 1986.
- 6) Solartron Instruments - Cost benefit analysis methods for Condition Monitoring -Technical note No.27 - 1994
- 7) Maintenance, replacement and reliability - A.K.S.Jardine & S.Kennedy - Pitman Publishing Ltd., 1973.
- 8) Michael Neale and Associates (for the Department of Industry) - A guide to the Condition Monitoring of Machinery - HMSO 1970.
- 9) D.Birchon - The LEO technique - Engineer, 226, Pages 478 to 481, London 1968.

Appendix 1

Input variables

Power of the fan	P	
Number of fans in the group		N
Number of fans in the group with no standby fan	N_1	
Capital cost of the fan at time of purchase	C	
Year of purchase	Y	
For fans with no stand-by fan - Criticality index	I_c	
Fan process index		I_{pr}
Hourly rate for labour	L	
Capital cost of low level condition monitoring equipment	V_l	
Capital cost of high level condition monitoring equipment	V_h	
Year of purchase of CM equipment		Y_p
Payback period for assessment	A	
Reliability of fans		R_t
Probability of detection of machine deterioration using CM	D	
Cost ratio between hourly rates for technician vs. craftsman	T	
Internal interest rate for assets	R	
Number of years for amortisation of the asset	Y_a	

The input variables are as shown above, and from this the following can be derived:

- 1) Predicted capital cost of purchase at the present date by using a lookup table of compounded inflation, the year of purchase and the capital cost at purchase.
- 2) Hence repair cost can be predicted as shown in section 3 above using a lookup table for the correlation between power and the direct costs factor. The consequential costs factor can also be read off as shown above.
- 3) Using the two 'K' factors the direct and consequential costs of failure for the group can be calculated.
- 4) Condition monitoring costs consist of the capital cost of equipment and the running costs of the programme. These are calculated using the capital costs of the CM equipment at any particular date corrected to today's prices and labour costs are derived assuming 15 minutes labour per machine per month for high level monitoring and half that for low level monitoring. (High level monitoring labour charges are enhanced by the factor T). The costs of maintaining the equipment and associated software is incorporated into the internal interest rate.
- 5) The cost savings are calculated using the 0.8 margin factor, probability of detection, unreliability (i.e. failure rate) and the direct and consequential costs of failure.
- 6) The nett saving is the difference between the saving (as calculated in 5 above) and the costs of CM (as calculated in 4 above).
- 7) The nett saving is then compared to the capital cost on a "per machine" basis to establish years for payback.
- 8) If the payback period, as calculated in 7 above, is less than the payback period A specified then a "Yes" answer results otherwise a "No" response is generated.