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Can equipment failure modes support the use of a Condition Based Maintenance Strategy?

David Baglee, Erkki Jantunen

University of Sunderland. UK. David.baglee@sunderland.ac.uk
VTT Technical Research Centre of Finland.Erkki.Jantunen@vtt.fi

Over recent years, the importance of maintenance, and therefore maintenance management within manufacturing organizations has grown. This is a result of increasing pressure upon manufacturing organizations to meet customer and corporate demands, and equipment availability and performance is central to achieving these. Condition Based Maintenance (CBM) is widely accepted and used as a financially effective maintenance strategy. The economic benefit of CBM is achieved if the tools and techniques associated with CBM are applied to the right equipment. In particular the degradation behavior of the equipment needs to be understood. Understanding of degradation is strongly related with failure models However, very little is known or published about the importance and the role of various failure models. Thus, if failure models are not analyses and understood the use of CBM could be directed to the wrong equipment and therefore achieve incorrect and expensive results. The paper examines the relationship between the failure patterns observed in industrial maintenance practice and the corresponding impact on adoption and potential benefits of Condition-Based Maintenance (CBM). The paper will explain the need for accurate and up to date equipment information to support the correct maintenance approach. The paper suggests the importance of further supporting such investments by appropriately addressing the need to collect relevant data as a basis upon which to make the right decisions.

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1. Introduction

Maintenance engineering represents an area of great opportunity to reduce cost, improve productivity and increase profitability for manufacturing companies throughout the world. There are examples of best practice what we may call World Class Maintenance which delivers great benefits. In addition, the maintenance of the infrastructure of modern industry has become an increasingly important, and complex, activity – particularly as automation increases and the global marketplace in manufacturing squeezes profit margins. The opportunity exists for many companies in Europe to see substantial improvements to their competitiveness and profitability by improving their maintenance performance. Condition monitoring of plant and equipment has now been identified as a major technique in establishing the optimum repair and maintenance periods to ensure in service reliability and maximum utilization of assets. A complete CBM system comprises a number of functional capabilities: sensing and data acquisition, signal processing, condition and health assessment, prognostics and decision aiding. Companies are moving from traditional corrective and preventive maintenance program to CBM to reduce the maintenance cost and unnecessary maintenance schedules. A CBM program consists of three key steps [1]:

- Data acquisition, to obtain data relevant to the system health
- Signal processing, to handle the data or signals collected in step 1 for better understanding and interpretation of the data
- Maintenance decision making, to recommend efficient maintenance policies based on diagnosis and prognosis extracted from the data.

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Unfortunately without a plan or path CBM strategies can be unsuccessful. This is often due to lack of understanding with regard to the degradation behavior of the equipment. If failure modes are not identified and understood the use of CBM to support a maintenance strategy will be based upon false or inaccurate information.

This paper will present the results of a survey carried out with different maintenance experts to obtain information about failure models. This research activity aims at encouraging the research community to examine and discuss the importance and understanding of various failure models before embarking on a condition based maintenance strategy. As the gathered data clearly shows differences between various industrial sectors do exist. In addition, findings outline a need for accurate data to support similar studies. In the light of this study it is clear that all investments to support modern maintenance technologies have relatively short payback time. Naturally, the highest benefits can be gained in industrial sectors where the production forms a chain i.e. one breakdown can affect the entire production process.

2. CBM Modelling

In recent years there has been an increase in the use of CBM as companies need to reduce maintenance and logistics costs, improve equipment availability and ensure that mission critical equipment is available when required. The diagnostic capabilities of predictive maintenance technologies have increased in recent years with advances made in sensor technologies. These advances in component sensitivities, size reductions, and most importantly cost have opened up an entirely new area of diagnostics to the companies who until recently were either unaware of the benefits or unsure on how to best make use of the equipment. A complete CBM system comprises a number of functional capabilities including a range of sensors and data acquisition techniques. Condition Monitoring tools have proven successful in reducing unplanned downtime by preventing equipment or process failure. This is achieved by providing asset managers with the information they need to implement real-time and need-based maintenance for deteriorating equipment. However, in order to be successful in terms of cost to implement or equipment availability it is important to:

a) Determine the cost of failures
b) Determine the cost-benefit of avoiding failure.

This requires detailed cost analyses of the current cost of maintenance and the necessary investment required to increase planned maintenance activities. First attempts in this direction have been provided by Jantunen et al. (2010) and Fumagalli et al. (2010) and more recently in Arnaiz et al. (2013). Nevertheless, demonstrating the magnitude of the savings that can be generated using CBM is difficult. This is due to internal accounting systems but mostly due to the inherent difficulties in estimating the often indirect positive impact that CBM has on savings. In order to identify the financial and productivity benefits from a CBM strategy it is necessary to start with a detailed range of functions from which to collect and analyse data in order to develop and implement specific maintenance actions. The functions that facilitate CBM include but not limited to:

- sensing and data acquisition
- signal processing and feature extraction
- failure or fault diagnosis and health assessment
- identification of remaining useful life
- management and control of data flows or test sequences
- Modelling to identify deterioration.

Modeling to identify deterioration is often overlooked. It is important to use an appropriate method for modelling deterioration to identify the different conditions and their effects, and the optimal selection and scheduling of inspections and preventive maintenance actions. Theoretically there are different types of failure characteristics often grouped in six categories (Tutorial Part 14, 2013):

1) Bathtub curve, infant mortality, useful life, rapid wear out (Fig. 1);
2) Rapid wear out after long useful life (Fig. 2);
3) Gradual wear out after long useful life (Fig. 3);
4) No infant mortality followed by indefinite useful life (constant failure rate) (Fig. 4);
5) Indefinite useful life (constant failure rate) (Fig. 5);
6) Infant mortality followed by indefinite useful life (Fig. 6).

The first three (1, 2 and 3) can be monitored, whereas it is impractical to monitor the remaining three (4, 5 and 6) as there is no or little change that could be used to justify the diagnosis of maintenance need (e.g. sudden/random failure of electronic components).

Fig. 1. Bathtub curve: Infant mortality – useful life – rapid wear out.

Fig. 2. Rapid wear out after long useful life.

Fig. 3. Gradual wear out.

Fig. 4. No infant mortality followed by indefinite useful life.

Fig. 5. Indefinite useful life.

Fig. 6. Infant mortality followed by indefinite useful life.

It is immediately apparent that differences do exist between what the experts think regarding similar industry sectors in different countries. For example, table 2 shows the comparison of the process industry data, (presented in table 1) from 5 different countries.

3. Data collection

Data were collected using interviews, questionnaires, scientific company profiles from approximately 60 companies from 12 countries. In addition, maintenance professionals from companies who provided maintenance consultancy were contacted. The aim was to collect, analyse and present a varied and 'uncensored' view of maintenance strategy development. Interviews were carried out with senior managers while questionnaires were distributed to shop floor personal. The interviews allowed a range of experiences, situations and knowledge that would otherwise be hidden, to be discussed and analysed. The questionnaires were used, in certain situations, to support the views of senior management, and in many situations dispute the views of senior managers.

The questions were similar to each organisation i.e. "who, what, when, where and how". Although the interviews were open they did provide a systematic description on:

- Their current maintenance practices.
- Their justification for using this maintenance method.
- How management decisions are taken when examining their maintenance practices.
- The strategies employed to collect and analysed data to inform future maintenance
- Their understanding of useful and remaining life, mortality and how CBM could be sued to support maintenance decisions.

The results are shown in table 1 below.

Table 1. Data analyses

Industrial sector	Country	Bathtub curve, infant mortality, useful life, rapid wear out %	Rapid wear out after long useful life, in %	Gradual wear out after long useful life, in %	No infant mortality followed by indefinite useful life, in %	Indefinite useful life, in %	Infant mortality followed by indefinite useful life, in %	Logical to use CBM
Process industry	France	30 %	30 %	30 %	3 %	3 %	3 %	90 %
Aerospace	UK	10 %	10 %	70 %	0 %	0 %	0 %	90 %
Chemical industry	Finland	10 %	10 %	70 %	0 %	0 %	10 %	90 %
Mechanical components	Spain	10 %	30 %	50 %	0 %	5 %	5 %	90 %
Tyre industry	Russia	5 %	10 %	70 %	5 %	10 %	10 %	85 %
Process industry	UK	60 %	15 %	10 %	10 %	5 %	5 %	85 %
Rail	Spain	15 %	60 %	5 %	10 %	10 %	0 %	80 %
Process industry	Russia	10 %	20 %	50 %	0 %	0 %	20 %	80 %
Mining industry	Canada	30 %	20 %	30 %	0 %	10 %	10 %	80 %
Home electronics	UK	30 %	37 %	13 %	2 %	0 %	2 %	80 %
Process industry	Sweden	10 %	50 %	10 %	10 %	15 %	5 %	70 %

Electric motors/batteries	Spain	5 %	35 %	30 %	0 %	30 %	0 %	70 %
Manufacturing	Italy	5 %	20 %	40 %	20 %	14 %	1 %	65 %
Mining industry	Sweden	10 %	30 %	25 %	5 %	20 %	10 %	65 %
Lifts	Spain	0 %	35 %	30 %	0 %	35 %	0 %	65 %
Robotic systems	Spain	0 %	30 %	30 %	0 %	35 %	5 %	60 %
Manufacturing industry	Spain	10 %	25 %	25 %	0 %	30 %	10 %	60 %
Machine tools	Spain	10 %	40 %	5 %	0 %	40 %	5 %	55 %
Cars	UK	10 %	21 %	22 %	10 %	13 %	14 %	53 %
Paper industry	Turkey	10 %	20 %	20 %	10 %	20 %	20 %	50 %
Process industry	Belgium	10 %	10 %	15 %	20 %	5 %	10 %	35 %
Mechanical components	Portugal	5 %	10 %	15 %	20 %	25 %	25 %	30 %
Paper industry	Sweden	4 %	6 %	15 %	18 %	20 %	37 %	25 %
Ships	USA	0 %	17 %	0 %	0 %	42 %	29 %	17 %
Aircraft	USA	4 %	2 %	5 %	7 %	14 %	68 %	11 %

Table 2. Comparison of the process industry data from 5 different countries.

Country	Infant mortality, useful life, rapid wear out %	Rapid wear out after long useful life, in %	Gradual wear out after long useful life in %	No infant mortality followed by indefinite useful life, in %	Indefinite useful life, in %	Infant mortality followed by indefinite useful life, in %	Logical to use CBM
France	30 %	30	30 %	3 %	3 %	3 %	90 %
UK	60 %	15%	10 %	10 %	5 %	5 %	85 %
Russia	10 %	20%	50 %	0 %	0 %	20 %	80 %
Sweden	10 %	50%	10 %	10 %	15 %	5 %	70 %
Belgium	10 %	10%	15 %	20 %	5 %	10 %	35 %

It is evident from the data that there are certain similarities i.e. the figures which represent gradual wear out after long life are within 1%-5%. This is contrasted by the use of CBM figures which fall within 90% - 35%. This firstly questions validity of the data supplied by the respondents; in addition it is unclear if the same or similar equipment is used with the respondent countries.

In the UK, 60% of the respondents stated that they suffer from infant mortality with useful life and rapid wear out. This high figure seems to be unique to the UK. This raises the question of the type and efficiency of current maintenance practices.

The figures for Belgium indicate that they suffer from inefficient maintenance practices across the range of categories. This, as with the UK suggests they employ a range of ineffective maintenance practices, or the data collected is inaccurate and not be validated.

If we return table 1, it is interesting to note that 11% of the USA aerospace industry claim CBM is needed. In an industry which is highly regulated and components are made to exact tolerances it would follow that industries within the aerospace supply chain would benefit from CBM.

Automotive production in the UK, which includes Nissan, Toyota, Honda, is increasing with approximately 1.5 million cars produced in 2013. This is a year by year increase of approximately 12% since 2009. The data presented in the table suggest that the industry could benefit with a wider uptake of CBM. This is true on assembly lines operated by robots where the majority of robots weld, form and assemble small fixtures. Little or no monitoring of robots takes place. This is an area of great interest to the UK auto-manufacturers. In Spain, the table reports, 65% of robotic systems have an infant mortality followed by indefinite useful life. This is an interesting claim and one which should be examined by the UK auto-industry.

On the other hand, there might be some consensus, according to the manufacturing companies surveyed, about the importance of the wear failure models regarding mechanical components, such as spindles, gear boxes, hydraulic pitches or bearing systems. In these components electronics are still kept to a minimum and therefore mechanical failures are predominant.

Wear mechanisms are also important in other sectors, such as machine tools and lifts. However, in these two the increased product complexities and the process characteristics involving incorrect product usage increase the importance of indefinite useful life, with random failure events difficult to prevent.

The next stage would be to use failure modes to categorise the data into quantifiable problems. This would include simple analyses to determine what could go wrong, why would the failure happen, and what would be the consequences of each failure. The aim is to evaluate processes for possible failures and to prevent them by correcting the processes proactively rather than reacting to adverse events after failures have occurred. However, this was outside the scope of this initial investigation and requires in-depth analyses of the data and data sources to be able to confidently develop a set of failure modes. A detailed data mining process would need to be developed in order to extract valid, previously unknown, comprehensible information from the organisations and individuals who supplied the data for this study.

4. Conclusion

This paper presents a discussion of how different sectors can benefit from the introduction of Condition-Based Maintenance strategies. The discussion is based on an analysis of expert views regarding the type of failures occurring in different types of industries (Jantunen et al., 2014). One observation made from the survey results is that the apparent failure types seem to follow quite a different pattern in different sectors. It is evident that the cost-efficiency of introducing a CBM strategy can be accessed on the face of evidence from occurring failure types across a range of organizations.

Although the maintenance community has for long been aware of the importance of studying such failure statistics, little data is available to enable a truly data-driven decision. In such circumstances the decision can be out of necessity taken on the basis of expert views. Still such views would ideally need to be validated by actual observation in industrial practice. The conclusion is that there is an increasing and rather urgent need for organizations to establish accurate recording of the failure events, so as to facilitate more informed choices regarding the introduction of CBM strategies. While this is so, the current evidence from the expert perception of failures occurrences is that CBM has significant potential to bring substantial savings in different sectors, most typically in transport (aerospace, rail) and in process and manufacturing industries.

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