A Review of the Essential Elements Linked with the Adoption of Condition-Based Maintenance

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Abstract: This paper empirically examines the relationship between the failure patterns observed in industry and the potential benefits to the introduction of a Condition-Based Maintenance (CBM) strategy. Industry appears to often misunderstand this relationship although for an informed decision the correct recording and analyses of failure data is important. Publicly available relevant data of wear are, at best, limited. A large number of academic and industrial papers are available which compare the efficiency of various maintenance strategies within a range of different industries. However, the conclusions clearly state that (1) they are large differences between various industrial sectors and (2) the relationship between data analyses and maintenance strategy development is, at best, limited. Wherever such data collection mechanisms are not in place, maintenance decisions rely mostly on intuition and expert views. This 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 development and efficient and effective maintenance strategy.

Keywords: wear of machinery components, wear model, wear statistics, condition monitoring, Condition-Based Maintenance (CBM)

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1 Introduction

In today's economic climate, there is an increasing emphasis and need to reduce the cost of manufacturing through increased efficiency tools and techniques. Once such technique is the introduction of an advanced maintenance strategy, based upon reliable, accurate, up-to-date equipment, and production data. In addition, the increasing sensibility for safety, the high quality requirements, the sustainability needs and the goods preservation are becoming, critical considerations for companies' competitiveness. In order to address theses a scientific, technological and organizational upgrade of maintenance is required. In order to develop a new approach in this discipline it is vital that these new 'strategies' are based on science and engineering and not large volumes of often old and inappropriate data which is rarely accurate and therefore not required. However, if deciding upon a new strategy it is important to state that maintenance is not about preventing failures, it is about preventing the consequences of failure therefore it is important to examine and understand equipment failures Baglee et al. (2004).

Predictive maintenance technologies, or equipment condition monitoring, attempts to detect the onset of equipment degradation with the aim of correcting that degradation prior to significant deterioration in the component or equipment. 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 has opened up an entirely new area of diagnostics to the maintenance team Baglee et al. (2004). This area has slowly moved from being a "new technology" requiring vast amounts of technical expertise for effective operation, to being a tool now accepted and used by industry. Cost reductions of several orders of magnitude have also been realized during the same period.

High efforts have been set into the development of new sensors, mainly in the fields of manufacturing technology, sensor structure and signal processing (Olfa Kanoun et al. 2004). Efforts have been made to examine the need and use of internal sensors in order to avoid the use of unnecessary additional sensors and therefore extra data which provides no additional benefit (Bravo-Imaz et al. 2014). However the actual increase in the availability of sensors is due to the reduction in cost and by the technological advances in the field of sensor networks (Chong et al. 2003). The advances in sensor technology supports the next 'big revolution' the internet of things (Xia et al. 2012) which is pushing to a more connected industry which will produce large volumes of information or Big Data. This may help to maintain the historical data or show companies the need to collect quality information, which is usually an issue in industry.

Despite its acceptance, there are still a wide range of opportunities where maintenance requirements are of a repeatable and therefore predictable nature, which would benefit from the application of predictive tools to remain competitive in an increasing changing environment (Bengtsson and Salonen 2009). Last and Sinaiski (2011) have tested an interesting data mining approach to develop the prognosis of vehicle failures. The use of a multi-target probability estimation algorithm (M-IFN) was included to an integrated database of sensor measurement and warranty claims with the purpose of predicting the probability and timing of a failure in a given subsystem.

Commonly enterprises have followed three strategies regarding maintenance as Crespo et al. (2004) exposed:

1. They simply copy the maintenance policies of the leader Enterprise in the sector. This approach generates low effort in becoming the leader of the sector.
2. They impulse punctual projects, as new acronyms appear in the maintenance sector. In this approach there is a short time focus, risking losing the objectives of the company.
3. They rely in external consultants. It is hard to obtain a good implication using external agents, unless there is some special implication.

The focus should be in the long term results which are often overlooked. There must also be an implication of the management, which will support the implementation of a change management approach when establishing and introducing a new set of objectives.

Wessels (2009) underlined the importance of realizing a reliability analysis before the implementation of a CBM program. Nowadays, there is a selection of sensor systems, at reasonable prices, but not all of the sensor systems are suitable to all of the problems i.e. one size does not fit all. Thus it is convenient to make a reliability analysis before adopting the solution.

To support the competiveness of a modern enterprise, production and operations activities need to be characterised by a high level of reliability, availability and safety. To obtain maximum performance, the organizations must be prepared for changes in three main interconnected areas (Bengtsson and Salonen 2009):

1. Organization and people within the organization to be committed to change.

2. Processes, strategies, workflows to help the organization to develop the desired changes (e.g. doing more inspection, better information retrieval, etc.).
3. Technologies and tools to facilitate or enable the organization to be able to develop the adequate processes.

However, few organizations develop a clear plan involving these three organizational transformation pillars regarding maintenance as the importance of change is often underestimated. In order to bring such change, several interventions are necessary on the enterprise's strategy involving improved human capital and technological innovation management.

With regard to point 3 above, ‘technologies and tools’, there is substantial room for improvement in the direction of establishing improved data collection mechanisms. It is essential to provide maintenance with methods and tools that could make it a science based on evidence and data, rather than improvisation. Within Maintenance Engineering or Reliability Engineering, several approaches, tools and techniques have been developed in order to provide a scientific basis to maintenance activities. Linking them with observations data, especially regarding failure patterns would enable a sound basis upon to reach maintenance decisions.

In particular, one of the main drivers for competitiveness in recent years is related to the increase of application of Predictive Maintenance (PdM) processes. Jiang (2011) introduces a simplified view of wear development in which he states that the relationship between the mean degradation measurement and time is usually monotonically and non-linearly increasing or decreasing. According to Jiang (2011) there is a time point after which the degradation rate rapidly changes. He calls this point the degradation change point.

The concept of maintenance is slowly evolving from a corrective attitude (maintenance intervention after a failure), to a predictive attitude (maintenance intervention fixed to prevent the fault). This can be achieved through a maintenance service which is effective (i.e. able to look ahead for possible breakdowns and failures) and efficient (i.e. able to minimize maintenance costs). To this end, research has been looking for techniques and tools for diagnosing and predicting the degradation of the health state of components, machines, etc. thus, anticipating failures or breakdowns.

In this context, a difficulty is represented by the costs of already available solutions. In fact, many technologies (sensors, diagnostic systems, etc.) are available today in order to improve safety, availability, and reliability often they are rarely adopted due to their deployment costs (1) cost of software/hardware solution, (2) cost of maintenance engineering methodologies and processes, and (3) cost of the organizational changes needed for the implementation. This is also true in the manufacturing sector where cost and complexity of diagnostic systems provide a difficult obstacle in order that failures are to be anticipated (Fumagalli et al. 2009).

The introduction of new technologies may bring costs down; therefore it is critical to identify clearly what are the areas of improvement where CBM technologies could be beneficial. Furthermore a clear understanding of the causes of equipment failure and the likelihood of failure occurring in a given period must be developed if a condition based program is to be successfully implemented (Telford et al. 2010). A way to approach this is to analyze the different information related to the six main failure mechanisms in order to understand how the application of CBM techniques to the different sectors could be beneficial.

It is important to briefly mention that all equipment will suffer from continual degradation. Using a number of different and diverse methods to calculate the rate of failure has been used in the past from Mean Time to Failure (MTTF) to simple guess work. Random failures are difficult to estimate as exact timing is often difficult or impossible to predict. Therefore it is difficult to implement a planned maintenance strategy to help reduce the likelihood and impact of failure. However, CBM techniques have been developed to combat this problem. Jiang (2011) elaborates with the mathematical presentation of degradation change point quite extensively. The practical example he presents is a valve. The link to CBM is that the idea is that any degradation process can be divided into two phases (both linear) around the degradation change point and then the later line can be used for the prediction of the optimal time for maintenance. In fact the degradation point can be considered as the first possible time for maintenance. In the light of the research the authors of this paper have carried out Jiang’s approach seems to be over simplified but on the other hand it is way much better than just assuming that wear takes place linearly which is the most commonly used assumption.

The analysis presented in this paper presents the information gathered in an earlier study Fumagalli et al. (2009), which in turn was based on the recollection of scattered studies and surveys recently carried out in the area of maintenance, as well as the analysis of scientific and technical data publicly available regarding the statistics about failure types in different industrial sectors. This is supported by the addition of new data gathered through a questionnaire carried out among maintenance professionals. The maintenance professionals were asked to state their best understanding of the industrial sector they predominantly work within.

As can be seen in Table 1 the study reports results from several European countries and key industrial sectors. For these sectors the failure occurrence patterns of machinery are critically discussed. Nonetheless, it would constitute the important backdrop upon which to examine the benefits that can be achieved by adopting CBM.

After the Introduction the second section discusses the economy of CBM. Section III presents the industrial results from various countries. Section IV describes a critical review of the gathered data. In section V an artificial simplified case of a bearing fault is presented to support the CBM approach. Section VI will present an industrial 'point of view' and finally section VII will presents the main conclusions.

2 Economy of CBM

CBM is not the only maintenance technique available. Regarding time-based maintenance, TBM, Ahmad (2012) showed an overview over TBM and CBM, presenting the potential benefits and drawbacks of implementing each of the methods. It was found that CBM is more realistic, thus making it more worthwhile to apply.

CBM concepts and applications have emerged in several industries including automotive, aerospace, military, and manufacturing where the benefits such as efficiencies in production and cost savings have been embraced (Prajapat et al. 2012). Condition Monitoring is a maintenance strategy designed to predict failures before they happen by monitoring the condition of different parameters. If a parameter surpasses certain limit or condition actions are taken. In recent years there has been an increase in the use of CBM as companies need to reduce maintenance and logistic costs, improve equipment availability and ensure that mission critical equipment is available when required.

A complete CBM system comprises of a number of functional capabilities including a range of sensors and data acquisition techniques. The implementation of a CBM system usually requires the integration of a variety of hardware and software components. 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, 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 and 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. (2014) and Jantunen et al. (2010) and more recently in Fumagalli et al. (2010). Demonstrating the magnitude of the savings that can be generated using CBM is difficult. This is due to often complicated internal accounting systems but mostly due to the inherent difficulties in estimating the often indirect positive impact that CBM has on savings. The cost to monitor, which could be significant, must be weighed against the cost 'not' to monitor.

Decisions based upon trend analyses are commonly used to identify deterioration or 'change' based upon previous or known levels. In order for CBM to be successful it is important to use an appropriate method for modelling deterioration, 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 (Stoneman 1998)

1) Figure 1 shows high incidence of failure, or infant mortality, followed by constant or gradually increasing conditional probability of failure, followed by a rapid wear out
2) Figure 2 shows constant increasing conditional probability of failure, with rapid wear out (after long useful life)
3) Figure 3 shows a slow increasing probability of failure, with no indefinable wear out age after long useful life
4) Figure 4 shows low probability of failure when the item is new followed by indefinite useful life (constant failure rate)
5) Figure 5 shows a constant probability of failure at all ages (constant failure rate)

6) Figure 6 shows a high Infant mortality followed by a constant probability of failure

Of these three first (1, 2 & 3) (e.g. related to continuous degradation of mechanical elements) can be monitored, whereas it is impractical to monitor the remaining three (4, 5 & 6) as there is no such change that could be used to justify the diagnosis of maintenance need (e.g. sudden/random failure of electronic components). In their paper Last and Sinaiski (2011) emphasize the benefits of CBM and point out how that strategy relies upon condition monitoring measurements. They also refer to the well-known bathtub curve (shown in Figure 1) and discuss how that can be represented with Weibull distribution or in fact with three Weibull distributions. It is worth noticing that Last and Sinaiski (2011) describe the Weibull distribution as very flexible although three different distributions are needed. The used data has not been published but the limited information that has been shown would actually suggest that there is some infant mortality i.e. that chosen car battery example follows the curve shown in Figure 6.

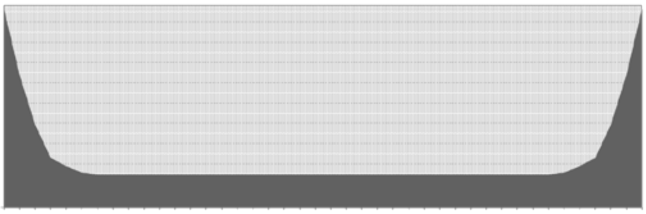

Figure 1. - Infant mortality, useful life, rapid wear out.

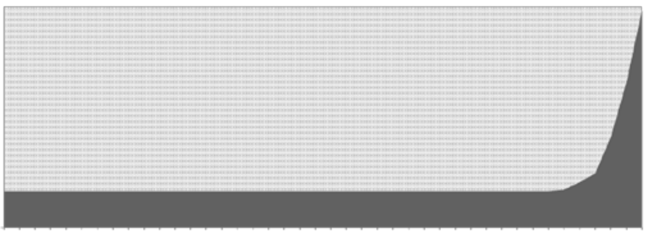

Figure 2. - Rapid wear out after long useful life.

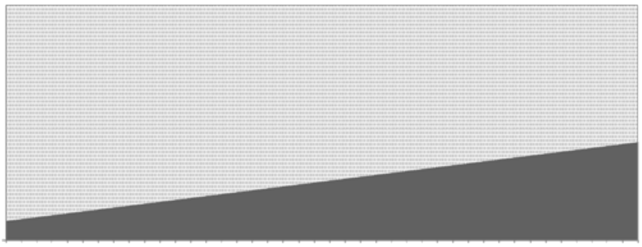

Figure 3.- Gradual wear out.

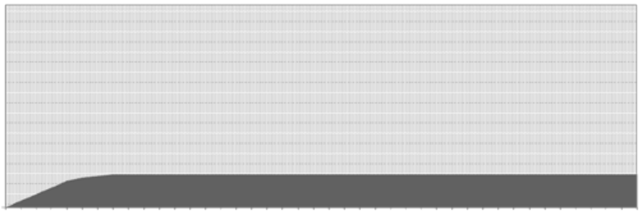

Figure 4. - No infant mortality followed by indefinite useful life.

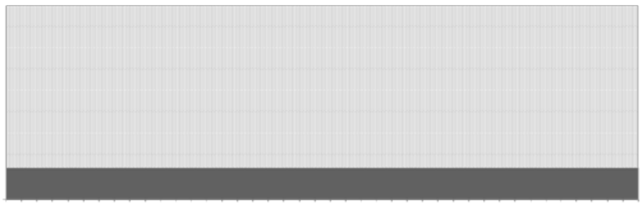

Figure 5. - Indefinite useful life.

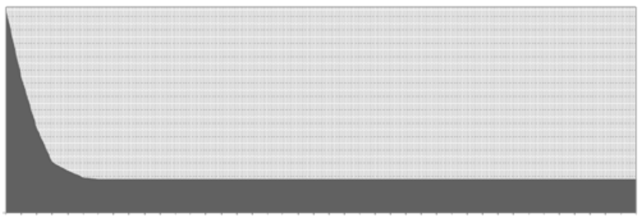

Figure 6. - Infant mortality followed by indefinite useful life.

3 Historical Aspects of Wear Modelling

Of the above described models the first one i.e. the so-called bathtub curve is by far the best known and most widely used. To determine equipment ageing parameters, frequency statistics or Bayesian probabilistic inference can be used. The frequency statistic inference uses field data to determine an adequate representative ageing law. Generally, this law is the two-parameter Weibull distribution (the well-known bathtub curve-Fig.1), or alternatively, the lognormal, the gamma or the step models. The choice of the distribution depends on the physical nature of the problem. Note that the two-parameter distributions such as Weibull, lognormal gamma or beta are quite flexible and so they can fit a wide variety of problems. But unfortunately, a great deal of failure data is generally needed to determine their parameters in a frequency inference.

It is somewhat surprising to notice how simplified the approach is in the above described reference which supposedly represents the best knowledge at European level regarding to statistics of ageing (wear) phenomenon. If the above statement is compared to the results that are presented later in this paper it would seem that the reality is rather complex. However, it should be noted that Peterson (2006) examines a number of real life examples and also more complex mathematical approaches the type of statistical view of the role of different wear models is completely missing.

Historically it is interesting to notice that Higgins (1988) does not make any difference between the different wear features of different type of components even though the handbook covers many aspects of maintenance quite thoroughly and there are also numerous industrial examples from different industrial fields. An updated handbook written by Stoneham (1998) discusses technologies including CBM Total Productive Maintenance (TPM) while introducing the bath tub curve. It has been claimed by several critics that the the bathtub curve is frequently invoked as a conceptual rather than a mathematical model for the instantaneous failure rate of a system over its whole life. It has been shown that the concept does not apply to a number of electronic components and it is doubtful whether it can apply to component parts generally. There is also some doubt about its applicability to unmaintained systems." However, Stoneham (1998) does not give any statistics i.e. between the wear models of various components.

Again it is surprising the Williams et al. (1994) only very briefly refer to different kind of wear curves even though describe CBM and TPM technologies together with rather detailed discussion of Failure Mode and Criticality Analysis etc. type of techniques. Williams et al. point out that it must be remembered that linear trending will not always be appropriate since in many instances the drift towards failure may follow, for example, exponential or ‘S’ shaped curves. Often, this very simple method of detecting faults meaning alarm levels are not sensitive to the presence of faults until they reach severe levels. This is particularly true in the case of rolling-element bearings. For such faults the overall vibration levels only exhibit significant increases in the final stages of condition degradation and thus offer late warnings of failure and the need for maintenance.

Jardine and Tsang (2006) discuss the bathtub curve rather thoroughly and link it to the hazard rate and different kind hazard rate distribution. The mathematical background is clearly presented but no statistical data is given for various machinery components or industrial sectors.

CBM has been recognised as an economic maintenance strategy in many industrial sectors. It is interesting to note that great benefits of proactive maintenance have not technically been fully realised as genuine proactive maintenance i.e. maintenance based on prognostics, has not been possible in case of machinery components that suffer from wear. Of the listed maintenance related “handbooks” only the most recently published fully recognises the different kind of hazard rates i.e. wear models. However, this reference does not provide statistical summaries or indications how probable are each of the wear model types. Consequently, the authors of this paper are surprised about the number of prognostics related articles in the literature Jardine and Tsang (2006) even though they seem to lack the most basic understanding of prognostic models.

4 Data Analysis

The discussion in this paper is based on data of which a large portion was employed in a study presented at the Euromaintenance Conference Fumagalli et al. (2009). In that study, a mixture of specific field surveys were made (e.g. machine tool and mechanical components in Spain), publicly available data and expert opinions. Furthermore, in that study a questionnaire was distributed to maintenance professionals and industry experts in a number of countries and industry sectors in order to collect data on how they perceive their equipment performs based upon a number of failure types listed above. More details on the survey and the resulting data are found in Fumagalli et al. (2009). According to Fumagalli et al. (2009) the survey findings are essentially representing expert’s opinions on the posed questions, regarding the six failure categories mentioned earlier.

This paper is concerned with discussing a number of findings from that survey with a view to analyzing potential impact for CBM. Table 1 summarizes the findings of the study, adding one column to offer a 'crude' but necessary quantification of how important CBM technologies could be for a specific sector.

TABLE 1. FAILURE PATTERNS

Industrial sector	**Country**	**Bathtub curve, infant mortality, useful life, rapid wear out**	**Rapid wear out after long useful life**	**Gradual wear out after long useful life**	**No infant mortality followed by indefinite useful life**	**Indefinite useful life**	**Infant mortality followed by indefinite useful life**	**Logical to use CBM (sum of 3 first wear models)**
Aerospace	UK	10 %	10 %	70 %	0 %	0 %	0 %	90 %
Chemical industry	Finland	10 %	10 %	70 %	0 %	0 %	10 %	90 %
Process industry	France	30 %	30 %	30 %	3 %	3 %	3 %	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 %
General 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 %
Manufacturing industry	Spain	10 %	25 %	25 %	0 %	30 %	10 %	60 %
Robotic systems	Spain	0 %	30 %	30 %	0 %	35 %	5 %	60 %
Machine tools	Spain	10 %	40 %	5 %	0 %	40 %	5 %	55 %
Automotive	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 %
Marine repair	USA	0 %	17 %	0 %		42 %	29 %	17 %
Aircraft	USA	4 %	2 %	5 %	7 %	14 %	68 %	11 %

5 Critical Review of Gathered Data

The table reflects several issues that could be understood as ‘straightforward’ and according to the expectations, but there are some others that may be a source for further analysis.

It is immediately apparent that differences do exist between what the experts think regarding similar industry sectors in different countries. For example the expert opinion on process industry within the UK claims that 60% of equipment suffers from infant mortality and rapid wear out as opposed to a figure of 10% in Sweden. Does this suggest the UK suffers from inappropriate use of equipment and inefficient maintenance tasks, or that the Swedish have a different metric for measuring rapid wear out which could be adopted by UK companies?

It could be assumed that the aerospace industry in the UK, which is predominantly an assembly process as the manufactured parts are shipped from within Europe, should, in theory, have similar figures to the aircraft industry in the USA, as parts are shipped from Europe and different parts of the USA to a central assembly hub. However, the two are at opposite ends of the table. This clearly needs further investigation as to the validity of the data from both the USA and the UK and the metric used to determine each failure.

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 most predominant ones.

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

As discussed above it is commonly accepted that CBM is the most economic strategy in maintenance and it is especially suitable for the components of rotating machinery. In rotating machinery one of the key elements is the bearing (Figure 7). The wear of rolling bearings is a very complicated phenomenon as it is the result of a number of factors. First of all the wear can be abrasive, adhesive, fatigue or chemical wear i.e. all the main principal wear models can influence the bearing wear. In addition the relation of different wear mechanisms depends on issues like previous wear, loading, lubrication, cleanliness of the lubricant etc. Consequently the life time of a bearing can, for example, vary from two months to thirty years in a similar machine. Following this it can be claimed that the only way to know when a bearing has to be replaced is to rely on condition monitoring. This claim can easily be justified by the imaginary example shown in Table 2.

TABLE 2. BEARING LIFETIME (ARTIFICIAL EXAMPLE)

Lifetime (Years)	1	3	5	7	9
Number of bearings	6	4	8	4	6

In a simple case as shown above the average lifetime would be 5 years. If a conservative maintenance strategy would be followed all the bearings would be changed after one year when the average bearing would still have a lifetime of about four years. The opposite policy to this would be to change the bearings after eight years of use which would results in tens of unplanned production stoppages.

In the light of the simplified artificially created (in reality the scatter could easily fall into a wider range of years) example it is also possible to understand how important it is to know what sort of wear model the component in question suffers from. This knowledge can actually give basis to the prediction of the expected remaining life of a component. At the same time here lies an interesting dilemma as the data in Table 2 does not follow any of the wear model patterns presented earlier in this paper, or one could ask, does it?

The problem is the real meaning of the six patterns presented earlier. What do they describe? If they are supposed to show the statistical distribution of component failures as a function of time they in the light of the example cannot be used for components that suffer from wear that can be a function of such factors as loading, cleanliness and previous maintenance actions.

The closest statistical presentation would be the one shown in Figure 5 (Indefinite useful life). On the other hand if the patterns are supposed to present possible wear/failure models they might be a bit closer to the truth. It is well known that such components as bearings follow the pattern shown in Figure 2, i.e. wear develops rapidly after long useful life.

If we critically examine the six patterns shown in Figures 1-6 we can argue, are they of any importance? Earlier in this paper the data shown in Table 1 has been criticized (especially the lack of such data), and now at the same time that the technical meaningfulness of the six patterns is criticized, we could claim that this kind of information would be of high value. How can this be true? The justification for the importance of this information is based on the original claim made in this paper i.e. in order to use CBM strategy a lot of information is needed. It is essential to understand meaning of condition monitoring i.e. the condition of the equipment (need for maintenance) has to be defined in some way. The lack of statistics of the six patterns and the bearing case are proof of the unreliability of relying on statistical approaches in defining the optimal time for maintenance. In addition to the definition of the state of the components in question, the further development of wear has to be known in order to be able to predict the remaining life and to be able to define the optimal time for maintenance.

6 Industrial Point of View

One of the key claims in this paper is that in order to follow CBM strategy the maintenance organization needs to understand the wear of production equipment is developing. Based on the published literature it seems that the wear process of production equipment is not well known. Also the results of the questionnaire published in this paper would indicate that there is wide range of variation in the results which is difficult to explain and is most probably the result of lack of real knowledge i.e. reliable data. In private discussions the authors of this paper have been advised that the problem the paper tries to discuss does not exist due to the lack of published material. Assuming this is true the logic is sound i.e. if real data is available the statistical information would not be of any value.

Unfortunately the experience the authors of this paper have does not support the idea that the industry has large amounts of reliable data. On the contrary the opposite seems to be true. The industry might have large amounts of data but the quality of the data seems to be poor. The most commonly reported ‘fault type’ is other fault or it is simply indicated that there is a fault, thereby proving the lack of credible data. The most common reported maintenance action seems to be “the fault has been repaired” or just plain simply “repaired”. Again the authors of this paper do not have any statistics to support the above claim which is simply based on what they have seen and learned in discussions with industry. The aim here is not to morally criticize the industry. In fact the lack of reliable data can easily be understood. The first priority is to ensure equipment availability and reliability, and from this identify which data is required. Also we can ask have the maintenance engineers and technicians the necessary tools for reporting on individual faults. On the other hand the statistics of the use of spare parts is often very reliable information but also here the usability of the data is doubtful as in many cases the environmental conditions and the use and the loading have been the main causes of failure.

Referring to the previous text in this paper time based is not the explaining factor in most cases. The artificially created bearing example emphasizes this issue. A high percentage of faults are related, in addition the machinery has been used without the knowledge of previous issues or the use of historical data and therefore there is no basis for making a prognosis of the development of faults. Unfortunately the development of wear often is nonlinear i.e. when certain loading conditions are fulfilled the wear starts and the opposite is also true whereas certain limits are not surpassed there is limited wear. Consequently the best way to define how the future looks for a machine or rather part is to introduce machine condition monitoring. Returning to the definition of CBM this is actually the first assumption or rule, maintenance should be based on real need which should be defined through condition monitoring. If this data and subsequent results of condition monitoring and maintenance actions are used then detailed information about a particular or a set of faults is gathered. This provides an excellent basis for CBM.

7. Conclusions

This paper presents a critical discussion of how different sectors can benefit from the introduction of CBM strategies. The discussion is based upon an analysis of expert views regarding the type of failures occurring in different types of industries Jantunen et al. (2014). The paper has shown that the objective of condition monitoring is to prolong asset life. Although is used incorrectly it could reduce asset life and increase manufacturing cost. To support the use of a condition monitoring system the paper has suggested, through observations that the cause of failure should be known and used to develop maintenance actions. 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 evidence from occurring failure types across an organization’s assets. 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. It would make sense to use continuous monitoring systems to allow reactive and timely maintenance across all industries, and therefore increase resilience to changing external influences i.e. financial recession.

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 proper 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) but also in process and manufacturing industries.

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