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A SURVEY ON CONDITION MONITORING SYSTEMS IN INDUSTRY

Philip A. Higgs/Lead Author
Loughborough University
Holywell Building, Holywell Way,
Loughborough
Leicestershire
LE12 9EL
UK
Tel: + 44 (0) 1509 266578
Fax: + 44 (0) 150 928 6577
phil.higgs@lboro.ac.uk

Rob Parkin/Co Author
Loughborough University
Holywell Building, Holywell Way,
Loughborough
Leicestershire
LE12 9EL
UK
Tel: + 44 (0) 150 922 6570
Fax: + 44 (0) 150 928 6577
R.M.Parkin@lboro.ac.uk

Mike Jackson/Co. Author
Loughborough University
Holywell Building, Holywell Way,
Loughborough
Leicestershire
LE12 9EL
UK
Tel: +44 (0) 150 922 7570l
Fax: +44 (0) 150 922 6571
m.r.jackson@lboro.ac.uk

Amin Al-Habaibeh/Co Author
School of Computing and Technology
The Nottingham Trent University
Burton Street, Nottingham,
NG1 4BU
UK
Tel: +44 (0) 115 848 2564
Fax: +44 (0) 115 8486166
Amin.Al-Habaibeh@ntu.ac.uk

Farbod Zorriassatine/ Co Author
Loughborough University
Holywell Building, Holywell Way,
Loughborough
Leicestershire
LE12 9EL
UK
Tel: + 44 (0) 150 922 6570
Fax: + 44 (0) 150 928 6577
F.Zorriassatine@lboro.ac.uk

Jo Coy/Co Author
Royal Mail
Services and Innovation
Engineering Services
Swindon, Wiltshire
UK
Tel: + 44 (0) 150 922 6570
Fax: + 44 (0) 150 928 6577
joanne.coy@royalmail.com

ABSTRACT

Advances in networking technologies are opening integration opportunities for Condition Based Monitoring (CBM) systems, presenting further possibilities for increasing CBM system functionality. This paper presents the results of a CBM Survey designed to determine present applications of CBM systems within industry. Understanding how industry applies practices such as CBM in the work place offers valuable research results for CBM system providers, consultants and business users alike.

The survey acts as a CBM application indicator for 2004. It targets 6 key areas: 1) Respondents' company information, 2) The type of CBM technique/s applied by the respondents' company, 3) Incentives that led the respondents' company to implement their CBM system, 4) Technological and integration issues associated with respondents' application of CBM, 5) Implementation issues associated with the respondents' CBM system, and 6) Reliability and consequential maintenance awareness issues following implementation.

An international response shows CBM to be a globally accepted maintenance practice.

In addition to the survey results, the paper discusses developments in remote CBM systems using the Internet, with particular regard for developing suitable user interface designs.

"Key Words: Condition Based Monitoring, Survey, Maintenance, CBM techniques, Incentives, Technology and Integration, Implementation, Reliability

1. INTRODUCTION

The acronym CBM is also associated with Condition Based Maintenance, a predictive maintenance technique. CBM is the method adopted to monitor and diagnose the condition/s of the process, machinery, or component/s under investigation. CBM therefore links directly with Condition Based Maintenance, a technique of diagnosing failure mechanisms and making a prognosis of the remaining useful life before failure. This enables corrective maintenance action to be undertaken on the identified failing component/s at a convenient time before anticipated time of failure.

Understanding how industry applies practices such as CBM in the work place offers valuable research results for CBM system providers, consultants and business users alike, good motivational reasons for conducting a CBM survey. Questions to be addressed fall into six categories: 1) Industrial sector; 2) CBM & NDT techniques; 3) Implementation Incentives; 4) Technology and Integration; 5) Method of implementation; 6) System reliability.

A similar CBM questionnaire with fewer questions and fewer replies was conducted in 2002. [1]. Where similar questions were used, a results comparison is made.

The paper consists of a discussion of advancing CBM technologies, describes technologies associated with intelligent CBM, distinguishes between Standalone CBM, Remote CBM, and Internet CBM, describes the survey technique adopted, and goes on to discuss the survey results. Results to each category of question are discussed, with supporting evidence gathered from a literature review. Conclusions, acknowledgements and references are followed by an extensive appendix consisting of the survey results.

2. ADVANCES IN CONDITION BASED MAINTENANCE TECHNOLOGIES

Advances in CBM systems are being driven by commercial demands for improvements in: productivity, quality, inventory control, and expenditure on plant and machinery. Technological advances take place gradually as new scientific discoveries are made, accepted and applied to CBM systems. Recent technological advances include improved knowledge of material failure mechanisms, advancements in failure forecasting techniques, advancements in monitoring and sensor devices, advancements in diagnostic and prognostic software, acceptance of communication protocols, developments in maintenance software applications and computer networking technologies to name a few.

G. Vachtsevanos and P. Wang [10] state that fuzzy logic, neural networks and the application of Dempster Shafer theory are technologies designed to aid the performance of CBM systems. This is a statement based on the knowledge that CBM system capabilities are judged on their ability to accurately diagnose failure conditions and then predict (prognose) remaining working life before machine / process failure.

2.1. Intelligent CBM

The term intelligent implies a CBM system is capable of understanding and making decisions without human intervention. Technologies making this possible include: sensors with built in intelligence (SMART Sensors) capable of transmitting relatively rich, high grade information [11]; re-programmable on-line sensors [12], designed to be reconfigured with new rules in the event that detectable recognisable patterns change; algorithms, fuzzy logic and neural networking, designed to analyse trends within recovered sensory data, and produce decisions on the likelihood of failure of monitored plant items [12]; artificial intelligence algorithms capable of providing proxy data as a substitute for failing or a failed sensor, whilst the malfunctioning sensor is repaired [13].

Further intelligence is possible through integration of a CBM system with a companies computerised purchasing system, thus automating parts ordering [11].

As technological advancements have fed into CBM so the method of deploying CBM systems and integrating them with other business systems has changed. Two recognised deployments are: Localised CBM, and Remote CBM.

2.2. Localised CBM

Localised CBM is an independent predictive maintenance practice, likely to be undertaken within immediate proximity of the components being monitored, by a maintenance engineer (technician) or operator. A typical procedure involves taking and recording CBM data at periodic intervals in order to determine the condition of the component being monitored, and then deciding whether the condition of the component is acceptable or not.

2.3. Remote CBM

Remote CBM systems can be either standalone or networked to another business system/s. Remote CBM involves monitoring the condition of a component at a location away from the immediate vicinity of the component in question. Monitoring will be undertaken automatically or manually depending upon the systems capabilities at intermittent time periods. Diagnosing the condition of the component may be either automatic or manual, again depending upon the systems capabilities. Wireless sensors present opportunities for placing sensors in difficult-to-reach locations, electrically noisy environments, and mobile applications where wire cannot be installed. Discussion on the latest developments in wireless sensors is presented by F. Zorriassatine [14].

Presenting CBM information through web pages accessible by Internet browsers, is given the name 'Internet CBM', or 'E-Monitoring Machine Health System'. Internet CBM takes remote CBM to another level, i.e. providing global remote capabilities. Since browsers reside on many platforms, Internet CBM systems may be accessed by multiple users working on any type of operating system. This presents the opportunity for employees to monitor their machinery whilst away from the factory, i.e. overseas on business calls. Unauthorised access to an Internet CBM system is prevented with the inclusion of user name and password access on the index web page (first page) for the web site. User name and password access may also be used to control access rights onto specific web pages and degree of user system interaction.

V.R. Kennedy [15] explains how interaction between users and the Internet CBM system is performed using Active Server Pages (ASPs). ASPs, programmed using VBScript and JavaScript working behind the scenes within the Web server, offer flexibility to system designers. They carry out programmed instructions within the web server, define how the HTML is assembled and presented to users, providing users with the power to interact with the user interface and make choice selections. As an example, Lloyd Dewey Lee [16] explains how vibration or process levels may now easily be transmitted over the Web and presented to the end user as gauges, reporting the condition of the remote machine in real time. Further examples presented by Rolf Orsagh et al. [13], include displaying graphs showing performance trends, and tables of performance parameters, anomalies, and diagnosed faults.

Further reading concerning the main components of a web based maintenance diagnostic system and methods of representing condition monitoring values onto a web site are discussed by U. Kunze [17]. Also of interest is Alan Friedman [18] discussion concerning the importance of database replication and database synchronisation as part of a multi machinery multi site CBM set up, under centalised control.

3. SURVEY TECHNIQUE

It is no longer necessary to rely solely on sending hundreds of letters to suitable survey recipients in order to receive sufficient replies for a conclusive survey result. Today we have the Internet for global instant questionnaire circulation.

Advantages of conducting a survey using the Internet are:

Low cost hosting fee, real time feed back, access to a wide audience, the ability to display a controlled selection of survey results to respondents in real time, personal flexibility concerning the amount of effort put into circulating the questionnaire, and an easier and faster method for respondents to complete and submit their questionnaire replies.

Disadvantages of conducting a survey over the Internet include:

Failing to reach individuals within organisation who do not have Internet access or do not find time, or choose not to browse maintenance forum web sites, and the freedom text boxes provide respondents to submit advertisements rather than answer the question.

The questionnaire was designed and distributed in accordance with the following stages:

- Select a suitable set of questions to meet the survey objectives.
- Design the questionnaire, taking into account web browser presentation for online Internet accessibility, visual presentation, question layout, question legibility, and questionnaire length with respects to an average persons attention span.
- Select a suitable questionnaire web hosting company, taking into account hosting costs, functionality and flexibility of questionnaire design application, length of hosting time, and ease of use. www.CreateSurvey.com was the chosen provider.
- Advertise the questionnaire over the Internet using every approach you can think of in order to receive a wide and varied response. Approaches used in this case included: Asking online maintenance magazines to advertise the questionnaire on their web sites, advertising on maintenance related online forum web sites[2 – 9], using email addresses left on maintenance forums as contacts for possible respondents.

4. SURVEY RESULTS AND DISCUSSION

4.1. Company Information

Answers from a broad industrial representation are exhibited in the survey. This implies a wide take up of CBM techniques within industry as a whole. Table 1, refer to appendix, identifies Manufacturing-Petroleum refining, chemicals and associated products as being the most popular industrial sector for using CBM systems. This would imply CBM is most widely used by this industrial group, or that individuals in this industrial group have more free time than others to spend completing questionnaires and browsing Internet maintenance forums. The same result was true in a CBM questionnaire undertaken in 2002 [1]. The second most popular industrial group was classified as “other”. An indication that a future survey of this nature could include a larger listed selection of industrial and business groups.

Responses were received from over 15 different countries, including the Americas, Europe, Japan, Australasia, South East Asia, Middle East and Africa. Indicative of the worldwide application of CBM as a maintenance practice, and the effectiveness of questionnaire distribution over the Internet.

4.2. Condition Monitoring and Non Destructive Testing Techniques

Survey results to the question, ‘which CBM and NDT technique do you apply?’, represented in table 2 indicate the four most widely used CBM and non destructive testing (NDT) techniques to be: Vibration Analysis, Oil Analysis, Infra-red Thermography, and Human Senses. A similar result to the 2002 CBM survey [1].

Every CBM and NDT technique listed as an option has been selected by one or more respondents in reply to the question, and a further 37 additional CBM and NDT methods identified, refer to table 3. The variety of additional CBM techniques listed represents a small number of the huge variety of CBM and NDT techniques available to industry today. Many CBM and NDT techniques appear to be custom designed for a particular requirement.

4.3. Incentives

Table 4 shows a combined 85% of respondents either agree or strongly agree they introduced CBM in order to adopt the practice of predictive maintenance into their company. Less than 3% of respondents showed disagreement. An interesting result considering recent discussions on online forums questioning whether CBM is a predictive or preventative maintenance technique.

Table 5 shows a combined 95% of respondents either agree or strongly agree they introduced CBM to reduce the number of unscheduled machine breakdowns. This provides a positive indication that in most cases CBM is associated with reducing unscheduled machine breakdowns.

Table 6 shows a combined 83% of respondents either agree or strongly agree their business adopted CBM to save money. This provides a positive indication that in most cases CBM is associated with saving money. Only 2.5% of respondents indicated disagreement.

Table 7 shows a combined 79% of respondents either agree or strongly agree their organisation introduced CBM for competitive reasons. Determining organisations competitiveness is a high level (Director/Chairman) business decision. Because the questionnaire has been randomly distributed, it is quite acceptable to expect a notable 15% of neutral responses.

29 additional comments were received as reasons why respondents' businesses implemented CBM. Receiving a selection of reasons why businesses implement CBM can be expected because the four optional selections are quite broad in nature, and will not cover specific individual organisational reasons for implementing CBM.

For clarity each comment has been categorised as being associated with, quality, production, maintenance systems and maintenance strategy and other.

4.3.1. Quality Incentives

1. QS9000 requirements.
2. As a vital part of our manufacturing test program to assure a high quality product.
3. Design improvements – weight reduction.
4. To create benchmarking with in the affiliate concerns.
5. To offer a means of documenting quality repairs within our facility.

All five comments above indicate the companies in question adopted CBM to improve the quality of their products in line with internal company quality standards, or to satisfy an independently regulated quality standard.

4.3.2. Production Incentives

1. To increase output through better reliability.
2. For safety purposes as we operate with chemicals.
3. Reduction of machine downtime due to avoidable failures.
4. Reduce shutdown/repair time. Eliminate secondary damage. Enhance spare parts inventory.
5. Too many time based WO which did not serve purpose. We couldn't reduce them without other alternatives, like CM.
6. To eliminate breakdowns as an issue. Maximizes utilisation of investment and offer uninterrupted operation.

All six comments above present a strong production driven case for implementing CBM, including: to improve production output, to avoid or reduce the number of unscheduled failures leading to production stoppage, to maximise utilisation of investment, reduce secondary damage resulting from the failure of any one component within a system, improve spare parts inventory control, and improve health and safety.

Reducing production costs to a minimum in order to maximise production output is described by Sandy Dunn [19] as, 'Asset Effectiveness', the need to extract maximum profits from the minimum investment in plant and equipment.

4.3.3. Maintenance Systems and Maintenance Strategy Incentives

1. We were carrying out a very labour intensive annual shut down and replacement program CM reduced this dramatically.
2. It's common sense, how else can you plan and schedule.
3. Used as a change mechanism for tradesmen, to teach them 'maintenance'.
4. Interest by maintenance personnel to understand machine condition.
5. As a strategy to enable reliability monitoring of the equipment.
6. We previously used the services of a contractor until two years ago when we implemented our own in-house program.
7. Because management saw others using it and wanted to show due diligence.
8. It was an uncoordinated and not very well thought out implementation. In fact it was an implementation just some instrument engineer purchasing some CM equipment he had for his budget.
9. As a catalyst to change the organisations maintenance culture from reactive to proactive.

Each of the nine comments above provides an indication that CBM was adopted because the companies in question recognised the need to alter the way they were applying existing maintenance practices.

Reasons presented appear very individual, e.g. to avoid an annual maintenance shut down, improve maintenance planning and scheduling, to act as a maintenance training catalyst, monitor the reliability of equipment, follow the example set by other businesses, and move from a reactive to a proactive maintenance culture.

Discussion by Geert Waeyenbergh and Liliane Pintelon [20] appears to back up this result, by explaining how maintenance concepts should be tailored to the needs of the company in question. They continue with a recommendation for reviewing your maintenance concept periodically in order to take into account the changing systems and the changing environment.

Using CBM to act as a maintenance training catalyst ties up with discussion by James C. Taylor [21] and Michael C. et al. [22]. They explain that positive attitudes towards and during a CBM implementation will lead to greater communication, co-operation, co-ordination and performance quality. Therefore improving the likelihood that staff will consider CBM as a beneficial system to aid their current job assignment, motivating individuals to use and learn about the system.

4.3.4. Other Incentives

A further eight comments were provided, mainly from companies in the business of providing services for the CBM market.

4.4. Technology & Integration

Survey results shown in table 8 indicate charts to be the most common method of presenting CBM information to users. All other options (discrete values, alarms, and graphics and animation) received a similar percentage of replies. This Implies CBM graphic user interfaces (GUI) should offer a variety of different mediums in which to present data and information to users.

Of the 403 selections made, 201 or nearly 50% of selections indicated respondents CBM systems incorporated either charts or graphics and animation. Both options are associated with high visibility graphical prompting aids. This suggests a preference for representing CBM information through diagrammatic aids.

Table 9 provides feedback on 21 additional comments concerning alternative mediums for displaying CBM information to users. A common trend is presenting information to users through written or computerised reports. Comment 17 provides a good example of the type of information you would expect on such reports namely, severity of faults, and trends of individual fault severity, specific repair recommendation and priority.

Table 10 shows a majority of 62% of respondent organisations use stand alone CBM systems as opposed to 38% whose system is networked.

Following in line with results from table 10, table 11 shows 63% of respondents indicate their organisations CBM system is not connected to the Internet, as opposed to 38% whose systems do have Internet connectivity.

Table 12 shows 73% of respondents CBM systems do not integrate with a computerised failure diagnostic system, whereas 27% do.

Table 13 shows 67% of respondents organisations maintenance systems link directly with a computerised stock reordering system, as opposed to 33% whose systems do not.

4.4.1. CBM User Interface Design

Selecting a man-machine interface is perhaps the most crucial element of a computer system as its design determines eventual user acceptance and utilisation. [22] Michael C. et al.

Survey results have already indicated that all popular methods of representing information and technical data over a CBM GUI, refer to table 8, are realistic possibilities. We have also identified maintenance systems will be tailored to a businesses own requirements and circumstances. Therefore it follows that a GUI should also be tailor designed to a customers own business activities and CBM system, offering the possibility for presenting CBM information and statistics through a number of different mediums, i.e. charts, tables, distinct values, alarms, graphics and animation, and detailed reports.

Designing a GUI capable of satisfying your own requirements can be simplified through the application of various design tool frameworks and simulation tools. Human Centered Design (HCD), Cognitive Engineering and iterative design represent three such popular frame works. Martin Maguire [23] describes Human Centered Design (HCD) as being concerned with incorporating the user's perspective into the software development process in order to achieve a usable system. Andrew Harnden [24], goes on to say, "identifying user requirements prior to designing the user interface is critical for setting the usability requirements of a graphical user interface, because different users demand different interaction styles."

Tom Kontogiannis and David Embrey [25] explain the application of cognitive engineering as a method for examining GUI design in the context of system demands, cognitive processes and problem representations. They explain how user participation can contribute to both the analysis of machine interactions and the acceptance of design decisions. This indicates new systems should not be introduced simply to catch up with technological advancements, but support operators in their tasks. This assumes that the task and business objectives remain on a similar track. To this extent, system demands, operator tasks and psychological processes must be studied in depth using a cognitive engineering approach

Kent Sullivan [26] describes iterative design as repeating or reassessing a design over and over following usability testing, therefore fine-tuning prototypes prior to final product release. Simulation represents a valuable iterative design aid. N.P. Archer and Y. Tuan [27] describe how simulating and testing a user interface design during the design process and prior to system roll out on a group of employees is highly recommendable. For example, systems operated using a user interface rely upon users ability to interact appropriately through the user interface and make correct decisions. Simulating a user interface therefore improves the success rate of workable user interface design.

As well as human factors engineering considerations, design frameworks should never fail to recognise technological constraints. Key technological constraints for a GUI are identified by A. D. Jennings et al. [10] as being data storage, extraction and presentation, e.g., as the size of database tables increase, so does the time to run a query, extract data, build it into HTLM web pages and present it to the user through a GUI.

4.5. Implementation

Table 14 shows two comparable results emerge concerning the chosen method for implementing CBM systems. 45% of respondents used a mixture of resources consisting of internal company expertise and resources, external consultants, and vendors, and 36% used only internal company expertise and resources.

4.6. Reliability

Table 15 shows a combined 77% of respondents agree or strongly agree their CBM system meets expectation. Approximately 3.5% indicated disagreement. A very positive response towards the application of CBM as a maintenance practice.

Table 16 shows a combined 80% of respondents agree or strongly agree operator and engineer awareness of maintenance issues has increased since their companies started using CBM. 3.0% indicate disagreement. A very positive response towards the educational usefulness CBM systems generates towards maintenance within an organisation.

Table 17 shows a combined 46% of respondents disagree or strongly disagree initial costs of the CBM system exceed the benefits gained, a 14% larger proportion than the combined 32% of candidates who agree or strongly agree to the same question. Not a very clear-cut result either way. Such a narrow difference of opinion can be expected, because every CBM system implementation is unique and open to different cost critical variables. One organisation may perform a smooth implementation keeping costs down, quickly seeing measurable cost saving, and another may encounter difficulties during implementation, resulting in higher than expected operation costs.

Table 18 shows a combined 76% of respondents agree or strongly agree further maintenance initiatives have resulted following the implementation of a CBM system. Only 1% indicate disagreement. This matches with the earlier result confirming CBM to have led onto improvements in engineer and operator awareness of maintenance issues. With an increased awareness towards maintenance issues, identification of further maintenance initiatives can be expected.

Table 19 shows a combined 81% of respondents agree or strongly agree CBM has introduced predictive failure capabilities into their business, improving maintenance scheduling. An expected result considering the earlier result showing 84% of respondents agreeing or strongly agreeing they introduced CBM in order to adopt the practice of predictive maintenance into their business. This re-emphasises the fact that respondents associate predictive maintenance with CBM.

A further 39 comments were received from respondents specific to their CBM implementation. For added clarity comments have been categorised according to: implementation, operational, reliability, future initiatives, feed back relevant to the questionnaire, and advertisements. Each group is discussed below.

4.6.1. Implementation Guidelines

Comments associated with CBM implementation present a case for spending time and effort throughout the process of selecting, implementing and training staff to use CBM equipment and systems in order to improve the prospect of a trouble free introduction. Comments included:

- Depends heavily on the skills of the technicians. Needs a lot of engineering support in the initial introduction.
- It is important you use a technique suitable for what you are monitoring, the collection of data can be a routine, but turning it into information may not be possible, or of value.
- It's very hard to get through to some engineers, especially the older generation.
- The drive for increased reliability and reduced costs are strong motivators for CBM. If CBM cannot be established all at once, start with what you have and move forward.
- CBM as a tool is very powerful but you need good support from management to really make it work.
- We have experienced difficulty in gaining maintenance personnel acceptance and support.
- The technology is easy, but sowing the correct seeds to make company wide changes in established practices is extremely slow, hard and sometimes painful.

Closer examination of these comments presents an opportunity for suggesting a set of CBM implementation guidelines, aimed at assisting the smooth introduction of CBM into an organisation:

- Obtain backing and support from top management, before implementation.
- Recognise and plan for a change in the way maintenance is applied and viewed, i.e. reassess your organisations entire maintenance approach (strategy) in every affected department.

- Select and match a system capable of doing the job, taking into consideration your own resources, and the level of employee expertise.
- Train and educate employees to appreciate the idea and philosophy behind CBM as a predictive maintenance practice. Train employees to use, understand and correctly act upon feedback from the CBM equipment.

Literature published by Rockwell Automations [28] describes five alternative implementation guidelines:

- Document Financial "Gains". Analyse and document the costs savings that are a direct result of a condition based maintenance program, including material costs, labour costs, and fuel costs.
- Upper Management Support: Senior management will be expected to explain the strategic importance of a Condition Based Maintenance program.
- Full Integration of condition based practices into overall maintenance philosophy.
- Integrate Test Technologies: Integrate Condition Based Maintenance information from multiple sites.
- Assessment Process: Every three years conduct a formal assessment of your condition-based maintenance program. Performing a SWOT analysis to assess where your CBM systems is leading.

Habaibeh et al. [29] indicate implementation guidelines vary from one company to another, dictated by the types of machines, company size and the nature of the products. For example, some companies cannot apply intelligent systems due to their high cost. Others find it difficult to extract useful information from their systems due to the complex nature of the technology involved.

A successful CBM implementation will have encountered and overcome numerous challenges along the way. J.A.Brandon [30] identifies a number of challenges likely to be encounted.

- Resistance to new automated technologies into an organisation is inevitable to a certain extent, and not simply because it represents change.
- Mistrust of automated systems per se.
- A threat to expertise based organisation status.
- Erosion of supervisory based organisation status.
- A threat to the entire control structure within an organisation.
- The general workforce may also consider automation as a move towards the thinning of employees.

Brandon goes on to recommend methods to overcome these challenges:

- Make sure you understand the problem before embarking on the solution.
- Select staff with intelligence and initiative.
- Define the boundaries of the problem as widely as possible.
- Give them authority and leave them to get on with the job.

Sometimes the simple act of getting employees to use a system in the first place can be a challenge in itself. Rommert Dekker [31] states that people will only use computer systems to make or assist in making decisions if they can easily communicate with them and understand what they are doing. Users must have confidence in their own understanding of information gleamed from a system. Maintaining user understanding comes through regular use, especially if the system is not necessarily intuitive. Kumar Rajaram, Ramchandran Jaikumar [32], agree with this idea, by explaining that diminished productivity can result from the implementation of easily acquired new technologies in the absence of a thorough understanding of their potential benefits.

4.6.2. CBM operation guidelines

Comments from five respondents concerning operational issues associated with CBM follow:

- Condition maintenance was introduced in 1987 and runs smoothly, resulting in great maintenance cost reductions. The problem for us was convincing "New Management" of the cost benefits in continuing with our CM programme.
- We need to continue to work on equipment reliability and not just data gathering.
- We use a route based scheduled condition monitoring program for critical equipment. Other equipment is monitored by shop floor personnel using vibration meters. The plant personnel rely so much on the program that we are the first to be called, if any abnormality is noticed.
- The trick in an organisation that is financially driven, resulting in a smaller maintenance workforce, is to strike a balance that allows the savings the business expects (hard savings), with the goals of maintenance in reducing downtime, increased quality and output, and maximizing equipment life, regarded by some GM's and the accounting fraternity as soft savings.
- Focusing on failure is too restrictive; focusing on healthcare to prevent avoidable wear is better.

Closer examination of the above comments presents an opportunity for suggesting a set of CBM operational guidelines:

- Use data and information gathered from the CBM system wisely, e.g.
    - To monitor the reliability of your machinery.
    - To monitor the reliability of spare parts following numerous spare part replacements.

- To assist purchase of new machinery, especially where comparison and performance are being taken into account.
    - To improve the way you schedule your production.
- Use targets to justify the benefits of a CBM system, making a comparison of the before and after implementation, e.g.
    - Machine down time.
    - Machine output.
    - Quality of service or product.
    - Production output.
    - Machine / equipment life.
- Maintain support and enthusiasm for your CBM system by remaining focused on targets year in year out.

Overlap between implementation guidelines and operational guidelines may seem present. Ideally implementation guidelines will feed onto real life operational outputs. Rolf Orsagh et al. [13] indicates that ideally operational guidelines for an Internet CBM system should result in improved maintenance scheduling and reduce the machinery life cycle costs. Posting CBM information on a web-site makes it readily available to all authorised personnel, improving information access, and therefore awareness towards machinery health.

Deciding who has access to a CBM system and who makes decisions based on the data and information they interpret will more than likely have been decided early on at the design phase. Ideas concerning Total Productive Maintenance (TPM) presented by Shuo Wei Zeng [33], suggest preventative work (CBM interpretation) is identified and issued by the maintenance personnel but carried out by the operators. Such a scenario implies operators are able to cope with light maintenance work. This will enhance the responsibility and motivation of operators, whilst at the same time providing the maintenance team with more time to develop more important predictive maintenance programs.

Data from a smoothly operating and correctly run CBM system enables production to operate machinery at an optimum performance, whilst minimising operational costs, maximising quality of service and therefore yield maximum returns. J.Coy et al. [11] rightly identify this as being the key to reducing payback period, often a highly contentious issue amongst board members in deciding whether to support a new proposal.

4.6.3. Reliability Issues

Feedback from twelve respondents presents a positive feeling towards the usefulness and improvements their companies have witnessed since implementing CBM. Only two of the twelve comments presented a less than positive image towards the reliability of CBM. Comments identified the following benefits since the introduction of a companies CBM system: a reduction in unexpected failures, a more proactive approach to maintenance, increased machine utilisation, availability of scientific data on which to base maintenance decisions, less secondary damage to components and machinery, improved safety record, and fewer catastrophic failures.

Determining a systems reliability always involves comparing before the event and after the event. Statistical comparisons are the favored approach, as they provide a black and white greater than and less than figure. Inevitably a business must have kept statistical records of the values to be compared for this to be possible. Shuo Wei Zeng [33] suggests two reliability measures as trouble-free working time and overtime.

In their description of a CBM implementation Steve Weinstein and Don Werner [34] describe how the number of planned maintenance tasks that have been traditionally undertaken at a paper mill reduced in number, resulting in a reduction in maintenance, repair and operations costs. Savings linked to the extra maintenance information generated by the companies CBM system.

4.6.4. Future CBM Initiative Issues

Feedback from five respondents indicates all companies intend conducting future CBM initiatives within their own businesses or externally by encouraging their customers to adopt such techniques.

Future initiatives are often based upon ones own immediate experiences. This presents a physiological reason why certain individuals find the process of learning completely new working methods, foreign to previous experiences, very difficult. The challenge for business leaders is to keep their eyes open to advancing technologies offering cost and quality benefits, whilst keeping their feet on the ground.

Discussion in section 2.0 identified advancing CBM technologies. Looking towards the future Sandy Dunn [19] identifies six key trends, listed below, where condition monitoring is going in the 21st. century

- The development of smart sensors, and other low-cost on-line monitoring systems that will permit the cost-effective continuous monitoring of key equipment items.
- The increasing provision of built-in vibration sensors as standard features in large motors, pumps, turbines and other large equipment items.
- Increasingly sophisticated Condition Monitoring software, with rapidly developing “expert” diagnosis capabilities.
- A wider acceptance for using Condition Monitoring for all maintenance operations, leading to an increase in Condition Monitoring utilisation by production operators as part of their day-to-day duties.
- An increasing focus on the business implications and applications of Condition Monitoring technologies, leading to the utilisation of Condition Monitoring technologies to improve equipment

reliability and performance, rather than merely predict component failure.

- A reduction in the cost-per-point of applying Condition Monitoring technologies-possibly leading to more widespread use of these technologies.

5. CONCLUSION

The survey acts as an application indicator for industrial usage for CBM systems in 2004. A broad selection of industrial and business sectors are represented in this survey, from over 15 different countries.

CBM is most widely used within the Manufacturing-Petroleum refining, chemicals and associated products business sector.

Vibration Analysis is the most widely used CBM and NDT technique. Besides the conventional 10 identified techniques, numerous other CBM and NDT techniques are presently in use.

The main incentives for implementing CBM systems are: to adopt predictive maintenance techniques, to reduce unscheduled machine breakdowns, and to save money. Additional comments indicate further incentives to be: improve product quality or meet quality standards, various production improvement reasons, and to adopt change or improve upon existing maintenance practices.

Technological and integration trends present in todays usage of CBM systems indicate a variety of different mediums being readily used for presenting information through GUIs. Popular mediums include: discrete values, charts, alarms, graphics and animation. Presenting CBM information to users through highly visual mediums such as charts, graphics, and animation are preferred. Further comments suggest written or computerised reports are also commonly used for passing on CBM data and information.

Stand alone CBM systems are presently more wide spread than those with networking and system integration capabilities. At the present time approximately a third of maintenance systems integrate with failure diagnostic systems and / or parts reordering systems.

Two similarly popular CBM system implementation approaches emerge: 1). Using internal company expertise and resources; 2). Using a mixture of resources consisting of internal company expertise and resources, external consultants, and vendors.

A strong positive feeling (averaging at 78%) exists towards the reliability of CBM systems following implementation with respects to: meeting expectations, increasing operator and engineer awareness of maintenance issues, creating further maintenance initiatives, and introducing predictive maintenance. A small majority of businesses do not believe CBM implementation costs exceed the resulting benefits.

Further comments concerning respondents feelings towards their CBM systems highlights four key system life cycle stages. Implementation, Operation, Reliability and Future Initiatives. Each of these stages consists of elements representative of success or failure in a CBM system implementation and operation exercise. Time and effort is therefore recommended to understand each stage, initially from a broad subject perspective and then from a more focused customised business perspective.

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7. REFERENCES

[1] 2002 Condition Monitoring Survey Results, 2002,

[2] Toast Forums : Maintenance and Reliability Discussion Forum, 2004, http://www.idcon.com/toastforum6503/toast/toast.asp

[3] Reliability Magazine® Message Boards, 2004, http://www.reliability-magazine.com/ubb2000/cgi/Ultimate.cgi

[4] MAXIMO-Users.net Discussion Forum, 2004, http://www.maximo-users.net/

[5] Mining-Services.Com Industry Forums, 2004, http://www.mining-services.com/forum/cgi-bin/YaBB.pl

[6] ReliaSoft Discussion Forum, 2004, http://www.reliasoft.org/discus/board.html

[7] VibeTalk™ E-Mail Discussion Forum, 2004, http://www.vibrationschool.com/

[8] The Society for Maintenance & Reliability Professionals, or SMRP: Message boards, 2004, http://www.smrp.org/discussion/index.html

[9] Vibration Institute - Discussion Zone, 2004, http://www.vibinst.org/vibezonenew_toc.htm

[10] G. Vachtsevanos and P. Wang, 2001, "An intelligent approach to fault diagnosis and prognosis", School of Electrical and Computer Engineering, Georgia Institute of Technology

[11] J.Coy, R.M. Parkin, M.R.Jackson, N.Steward, 2001, Proceedings, Int Conf Mail Technology; Evolution to e-Revolution, 24-25 April, Hilton Brighton Metropole, UK, ISBN 186058 327X, 99 383-391

[12] Philip Jacob, 1994, "Ideas for the explotation of distributed intelligence in condition monitoring systems", Maintenance Engineering Research, The University of Manchester

[13] Rolf Orsagh, Mike Roemer, and Ben Atkinson, 2000, "An internet-based machinery health monitoring

system", MFPT Committee Meeting, Virginia Beach, VA, May 2000

[14] F Zorriassatine, R M Parkin and M R Jackson, J-P Crusem, J Coy, 2003, "Wireless sensors for intelligent condition monitoring – a survey", *Proceedings ICOM03, International Conference on Mechatronics* , 18th June 2003, pp 427-434, ISBN 1 86058 420 9 .

[15] V.R. Kennedy, A D Jennings, R I Grosvenor, J.R. Turner and P W Pricket, 2000, "Process monitoring using web pages (e-monitoring)", *Comadem 2000 13th International Congress on Condition Monitoring and Diagnostic Engineering Management*, Society for Machinery Failure Prevention Technology (MFPT) (2000) 877-883 ISSN 0963545027

[16] Lloyd Dewey Lee, 2001 "Remote Machinery Condition Monitoring Using Wireless Technology and the Internet", MAARS Inc.

[17] U. Kunze, 2003, "Condition telemonitoring and diagnosis of power plants using web technology", Prog. Nucl. Energy, 43, 129-136. July 2003. Siemens AG, Erlangen, Germany

[18] Alan Friedman, 2003 "Web Based Vibration Analysis Programs", DLI Engineering Corp.

[19] Sandy Dunn, 2002, "Condition Monitoring in the 21st Century", The Plant Resource Centre

[20] Geert Waeyenbergh and Liliane Pintelon, 2000, "A framework for maintenance concept development", Int. J. Production Economics 77 (2002) 299-313

[21] James C. Talylor, 1997, "The evolution and effectiveness of maintenance resource management (mrm)", International Journal of Industrial Ergonomics 26 (2000) 201 - 215

[22] Michael C. Zanino, Ritu Agarwal, Jayesh Prasad, 1994, "Graphical user interfaces and ease of use: some myths examined", Proceedings of the 1994 computer personnel research conference on Reinventing IS**,** 142 - 154

[23] Martin Maguire, 2001, "Methods to support human-centred design", International Journal of Human-Computer Studies, Volume 55 , Issue 4 (October 2001) Pages: 587 - 634

[24] Andrew Harnden, 2001 "Beating the Odds and Delivering Truly Usable Systems", Classic System Solutions, Inc.

[25] Tom Kontogiannis and David Embrey, 1997, "A user-centred design approach for introducing computer-based process information systems", Applied Ergonomics Vol 28. No. 2.pp 109-119

[26] Kent Sullivan, 1996, "The Windows 95 User Interface: A Case Study in Usability Engineering", Microsoft Corporations

[27] N.P. Archer and Y. Tuan, 1995, "Comparing telephone-computer interface designs: are software simulations as good as good as hardware prototypes?", International Journal of Human-Computer Studies, Volume 42 , Issue 2 (February 1995), Pages: 169 - 184

[28] Rockwell Automations Publications Department, 2000, "Baltimore Gas & Electric Company Case study by: Rockwell Automation", Rockwell International Corporation

[29] A. Al-Habaibeh, D. R. Whitby, R. M. Parkin, and M R Jackson, 2003, "The development of an internet-based mechatronic system for remote diagnostic of machinery using embedded sensors", *Proceedings ICOM03, International Conference on Mechatronics* , 18th June 2003, pp 297-302, ISBN 1 86058 420 9

[30] J.A.Brandon, 2002, "Automated diagnostic systems: the human dimension", *15th Congress on Condition Monitoring and Diagnostic Engineering Management* , Birmingham September 2002 561-564 ISBN 0954130707

[31] Rommert Dekker, 1995, "On The Use of Operations Research models for Maintenance Decision Making", Microelectron. Reliab., Vol. 35, Nos 9-10, pp. 1321-1331

[32] Kumar Rajaram, Ramchandran Jaikumar, 1999, "An interactive decision support system for on-line process control", Anderson Graduate School of Management, The University of Calafornia

[33] Shuo Wei Zeng, 1995, "Discussion on maintenance strategy, policy and corresponding maintenance systems in manufacturing", *European Journal of Operational Research*, 138, 3, 554-568 (1 May 2002)

[34] Steve Weinstein and Don Werner, 2002, "Predicting the future", PPI Pulp and Paper International, v44, n3, (March 2002), p28-29

8. APPENDIX

Table 1

What type of industry does your business belong to?	
Manufacturing-Petroleum refining, chemicals and associated products	39 (24.84%)
Other	15 (9.55%)
Manufacturing-other	12 (7.64%)
Utilities-Electrical Generation	12 (7.64%)
Oil and Gas-Oil and gas extraction	12 (7.64%)
Manufacturing-Metal products	11 (7.01%)
Mining-Metal ore	9 (5.73%)
Choice-Manufacturing-Wood and paper products	9 (5.73%)
Services-Contact Maintenance/Repairs	8 (5.10%)
Services-Other	7 (4.46%)
Services-Business Services/Consulting	6 (3.82%)
Manufacturing-Food, beverages, tobacco	5 (3.18%)
Manufacturing-Machinery and equipment	4 (2.55%)
Services-Education/Academia	3 (1.91%)
Utilities-Water, sewerage, drainage	2 (1.27%)
Services-Transport	2 (1.27%)

Table 2

Which Condition Based Monitoring and NDT techniques do you apply?	
Vibration Analysis	148 (17.29%)
Oil Analysis	113 (13.20%)
Infra-red Thermography	99 (11.57%)
Human Senses	92 (10.75%)
Motor Current Analysis	77 (9.00%)
Dye Penetrant Examination	74 (8.64%)
Ultrasonic Thickness Testing	73 (8.53%)
Ultrasonic Crack Detection	63 (7.36%)
Magnetic Particle Inspection	56 (6.54%)
Acoustic Emission Analysis	39 (4.56%)
Other	22 (2.57%)

Table 3

Other, please identify the Condition Based Monitoring technique you use if not listed in question 3	
1.	Metallurgical examination hardness measurement risk based maintenance optimization
2.	Monitoring of system performance by built-in software that keeps record of system operating parameters, e.g. rolling stock traction system, telecomm. systems, etc.
3.	Wear debris Analysis
4.	Routine preventative maintenance inspections
5.	Alloy analyzer x ray
6.	Software diagnostics
7.	Strobe light
8.	Dial indicator and laser alignment
9.	Boroscope
10.	Shock Pulse
11.	On-line equipment monitoring
12.	Ultrasonic vibration
13.	Motor Operated Valve Diagnostic Testing, Air Operated Valve Diagnostics, Check Valve Non-Intrusive Testing
14.	Process data analysis Performance Monitoring Rechip-Trap Analysis on reciprocating machinery
15.	Welding control; hydraulic test pressure test radiography control,
16.	Reciprocating performance system - Rechip BETA and Windrock Analyzer
17.	Use a software to monitor & archive data
18.	Power Quality Electromagnetic fields
19.	Performance model (physical or Neural network)
20.	Shaft magnetism
21.	Wear Debris, Extensive on line monitoring of Motor management relays (1200 online)
22.	Dissolved Gas Analysis
23.	Passive ultrasonic inspection, (airborne and contact)
24.	Radiographic testing
25.	We only use the POSMON Ford's System
26.	Creator of diagnostic/prognostic software agents applicable to any machinery instrument with sensors
27.	Sound Analysis Air Testing
28.	Mostly on smps electronic
29.	Not continuos
30.	Flooded member detection Long range ultrasonic Iris/center tube bundle inspection
31.	Ultrasound leak detection for boiler leaks. Ultrasound lubrication system.
32.	laser guided precision alignment
33.	Sensors appropriate to specific parameters, P,T,T,F
34.	SPM, Smart methods per IDCON's CMS. Wear Particle analysis, laser deviation alignment, Ultrasonic leak detection
35.	IR Spot meter. [Alignment with laser, foundations and couplings. Balancing, shop and on site. Modifying operation as well as designs to be correct.]
36.	Offline motor insulation testing
37.	Reciprocating machines Analyzer

Table 4

The desire to adopt predictive maintenance techniques motivated our business to adopt Condition Based Monitoring?	
Strongly Agree	69 (43.95%)
Agree	64 (40.76%)
Neutral	14 (8.92%)
Does Not Apply or Do Not Know	6 (3.82%)
Strongly Disagree	3 (1.91%)
Disagree	1 (0.64%)

Table 5

We implemented Condition Based Monitoring to reduce the number of unscheduled machine breakdowns?	
Strongly Agree	111 (70.70%)
Agree	39 (24.84%)
Does Not Apply or Do Not Know	5 (3.18%)
Neutral	2 (1.27%)

Table 6

Our business adopted Condition Based Monitoring to save money?	
Strongly Agree	76 (48.41%)
Agree	55 (35.03%)
Neutral	16 (10.19%)
Does Not Apply or Do Not Know	6 (3.82%)
Disagree	3 (1.91%)
Strongly Disagree	1 (0.64%)

Table 7

Our business adopted Condition Based Monitoring to improve the organisations competitiveness?	
Strongly Agree	74 (47.13%)
Agree	51 (32.48%)
Neutral	24 (15.29%)
Does Not Apply or Do Not Know	6 (3.82%)

Table 8

In what medium does your Condition Based Monitoring System present information to user?	
Charts	124 (30.77%)
Alarms	101 (25.06%)
Discrete values	100 (24.81%)
Graphics and animation	78 (19.35%)

Table 9

Alternative Mediums not listed.	
1	Written reports describing faults and their frequencies of interest and recommendations.
2	Condition entry in web browser program
3	Report
4	Written reports. Alarms are used for analysis
5	Full written report on machines in exception condition and recommendations of repair
6	inspection list (check sheet) mostly visual notes
7	written reports
8	In the form of report, with conclusions and suggested remedy, if required
9	Web develop and internet application to show the organisation at any level the condition of the whole equipment the graphic manner.
10	Alerts, delivered to ANY computing or telephone device, 24/7 any where
11	Alarms by exception
12	Our contractors only supply appropriate reports - our own people only supply tabulated data.
13	Our report also incorporates exact nature of actions need to be taken in case of abnormalities detection.
14	CM is carried out by Contractor who produces monthly reports on machine condition and 24 hr exception reports.
15	We do not have an integrated System, we still work with individual reports
16	Action reports to customers.
17	Machine condition Report includes severity of faults, and trends of individual fault severity. Report includes specific repair recommendation and priority.
18	Monitoring is undertaken at intervals not continuous
19	Written reports on weekly basis
20	Written diagnostics, various calculations. A lot of real world values of many parameters and also detailed maintenance method descriptions/instructions
21	Spectrum Analysis

Table 10

Is your condition based monitoring system connected to a network for remote access?	
No	98 (62.42%)
Yes	59 (37.58%)

Table 11

Can your condition based monitoring system be accessed through a company Intranet or over the Internet?	
No	99 (63.06%)
Yes	58 (36.94%)

Table 12

Can your condition based monitoring system integrate with a computerised failure diagnostic systemt?	
No	114 (72.61%)
Yes	43 (27.39%)

Table 13

Does your maintenance system link directly with a computerised stock reordering system?	
No	105 (66.88%)
Yes	52 (33.12%)

Table 14

How did you implement your condition based monitoring system?	
A mixture of the above	71 (45.22%)
Using only internal company expertise and resources	56 (35.67%)
An external consultant was contracted	15 (9.55%)
Other	9 (5.73%)
It was supplied and fitted by a vendor	6 (3.82%)

Table 15

Does your Condition Based Monitoring System meet expectations?	
Agree	84 (53.50%)
Strongly Agree	37 (23.57%)
Neutral	24 (15.29%)
Does Not Apply or Do Not Know	6 (3.82%)
Disagree	4 (2.55%)
Strongly Disagree	2 (1.27%)

Table 16

As a result of implementing a Condition Based Monitoring system operator and engineer awareness of maintenance issues has increased?	
Agree	74 (47.13%)
Strongly Agree	52 (33.12%)
Neutral	22 (14.01%)
Does Not Apply or Do Not Know	4 (2.55%)
Disagree	3 (1.91%)
Strongly Disagree	2 (1.27%)

Table 17

The initial costs of the Condition Based Monitoring system exceed the benefits gained?	
Disagree	45 (28.66%)
Agree	31 (19.75%)
Strongly Disagree	27 (17.20%)
Neutral	25 (15.92%)
Strongly Agree	20 (12.74%)
Does Not Apply or Do Not Know	9 (5.73%)

Table 18

As a result of implementing a Condition Based Monitoring System it has led to further maintenance initiatives?	
Agree	83 (52.87%)
Strongly Agree	37 (23.57%)
Neutral	25 (15.92%)
Does Not Apply or Do Not Know	9 (5.73%)
Strongly Disagree	2 (1.27%)

Table 19

The Condition Based Monitoring system has introduced predictive failure capabilities into our business, improving maintenance scheduling?	
Agree	70 (44.59%)
Strongly Agree	58 (36.94%)
Neutral	19 (12.10%)
Disagree	5 (3.18%)
Does Not Apply or Do Not Know	3 (1.91%)
Strongly Disagree	2 (1.27%)