THE IMPACT OF PROCESS CONDITION MONITORING ON CRITICAL EQUIPMENT IN THE PROCESS INDUSTRY

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ABSTRACT

The process industry is faced with increasing competitiveness and cost reduction drives across the sector that pushes the ageing infrastructure to run for longer periods to sustain production output. This highlights the need to have stringent maintenance focus on the critical equipment to minimise the risk of production losses as well as safety and environmental hazards. Condition monitoring (CM) is a predictive maintenance technique that forms a critical part of mitigating these risks and ensuring the company's sustainability. It is however a costly and resource intensive technique. The aim of this research study was to assess the impact that process condition monitoring (PCM) can bring to the existing CM toolbox. Process condition monitoring entails using process parameters to monitor the condition of equipment and make key maintenance decisions.

The process plant used for this case study has equipment at different lifecycle stages ranging from 30-40 years old. The plant is further divided into 6 units and this study included physical assets from all 6 units. Primary and secondary data, mainly through interviews, were collected to determine 1) What are the traditional CM tools used on critical equipment in a typical process plant?, 2) What PCM tools are available to supplement and improve the traditional CM techniques with regards to maintenance decision making on critical equipment for a typical process plant?, 3) Are these PCM tools recognised by key decision makers in making maintenance decisions?, and 4) What are the costs and benefits of incorporating the PCM tools into the traditional condition monitoring toolbox for critical equipment in a typical process plant?

In assessing the CM and PCM coverage of the critical equipment (turbines, compressors, pumps, and heat exchangers) on an Oxygen plant, the CM technique of choice for turbines and compressors was online vibration monitoring (90%) followed by tribology (80%). Pumps favoured ad hoc vibration monitoring (29%) with heat exchangers showing minimal CM coverage (<3%). PCM showed lower coverage on turbines (27%) and compressors (33%), comparative coverage on pumps (15%) and significantly better coverage on heat exchangers (13%).

Interviews conducted with key decision makers showed extensive usage of PCM techniques by the maintenance senior management on the turbines and compressors but a lower usage of PCM techniques on the foremen level. All interviewees unanimously agreed on the usefulness of PCM techniques in their day to day and long-term decision making. Finally, a cost benefit analysis indicated the financial benefits of using PCM in the CM toolbox with positive net present values for all PCM techniques ranging from $130 000 to $19.8m.

Several equipment in industry could benefit from process condition monitoring but this study was limited to the process industry and the equipment selected for the study were turbines, compressors, pumps, and heat exchangers. The findings can therefore not be generalised for all process equipment but are useful for the specific equipment mentioned.

Key words: Maintenance management, condition monitoring; Process condition monitoring; Critical equipment; Performance

INTRODUCTION

The South African process industry is of prime importance to the developing economy and is a key constituent of the country's major industries. Petroleum, chemical products, rubber, and plastic products contribute approximately 23% of total manufacturing sales (Statistics SA, 2012).

The industry which saw significant growth in the 1970's to 1980's is in the maturity phase of its lifecycle with most of its facilities older than 30 years. There is also the increasing industry competitiveness and cost reduction drives across the sector that pushes the ageing infrastructure to operate for longer durations to sustain production output and satisfy market demand. This further highlights the need to have stringent maintenance and operational focus on the critical equipment to operate them within their agreed limits and ensure minimal excursions which could result in production losses, costly maintenance activities and severe safety and environmental hazards. CM is a predictive maintenance technique that forms a vital part of mitigating these risks and ensuring the company's sustainability.

Traditional CM techniques focus on vibration, tribology, and thermography to monitor equipment health. These techniques are costly and resource intensive hence the need for more economical and practical tools. PCM entails using process parameters to monitor the condition of equipment and make key maintenance decisions.

Research Objectives

The objectives of this research study were to evaluate the current CM techniques available in a typical process plant as well as what additional PCM tools could be integrated into the traditional CM toolbox for critical equipment.

The associated research questions were as follows:

- What are the traditional CM tools used on critical equipment in a typical process plant?
- What PCM tools are available to supplement and improve the traditional CM techniques with regards to maintenance decision making on critical equipment for a typical process plant?
- Are these PCM tools recognised by key decision makers in making maintenance decisions?
- What are the costs and benefits of incorporating the PCM tools into the traditional condition monitoring toolbox for critical equipment in a typical process plant?

LITERATURE REVIEW

Traditional maintenance in early history made use of a reactive approach to maintenance equipment. The equipment was operated until it failed and was then repaired (Myhre et al., 2014). This was in line with the view of Tsang (1995) who mentioned that historically, maintenance was viewed as unavoidable in which minimisation of costs were driven by management as a top priority. However, in recent years attitudes have changed to one of viewing maintenance as a strategic function.

Maintenance taxonomy

Kothamasu et al. (2006) developed a taxonomy of maintenance concepts as shown in Figure 1, where they divided maintenance into 2 facets namely planned and unplanned maintenance. Veldman et al. (2011b) described unplanned maintenance as taking place after the failure has occurred while planned maintenance being proactive in nature was initiated prior to equipment failure through a planned set of actions.

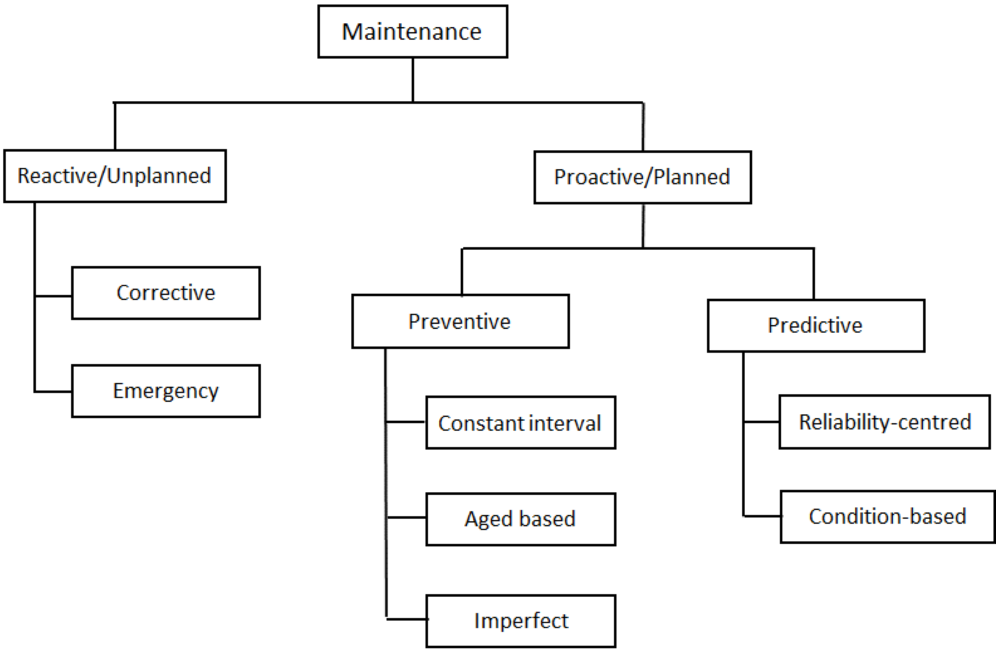

Figure 1: Taxonomy of maintenance concepts (Kothamasu et al., 2006)

Condition monitoring is a large component of predictive maintenance which is a subset of planned maintenance. CM was defined by Bengtsson (2004) as predictive maintenance based on parameter monitoring with the intention of acting. Utne et al. (2012) went on to further deconstruct CM into process and performance monitoring as significant components.

Condition monitoring techniques

The most commonly used CM techniques for mechanical systems are vibration, thermography, tribology, inspection, and process parameter monitoring (Tsang, 1995). Saranga and Knezevic (2000) further listed ultrasonic acoustic emissions and high frequency vibration as additional techniques.

In the survey by Higgs et al. (2004), various industry participants from over 15 different countries were asked some questions on conditioned based maintenance (CBM), ranging from use of the different CM technologies to integration into the business. The results in Figure 2 showed that the main CM techniques that are used in industry are vibration, tribology, thermography, and inspections.

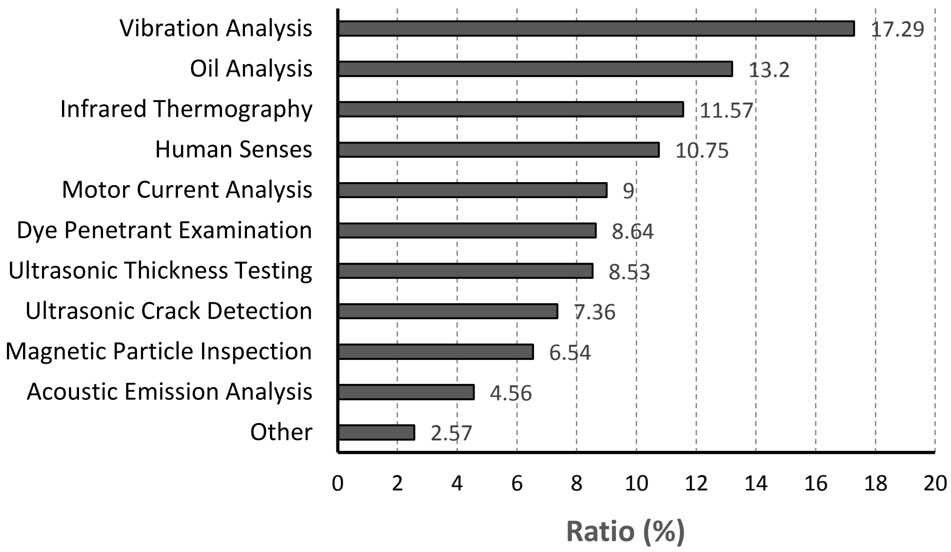

Figure 2: Condition-based maintenance survey results (Higgs et al., 2004)

Vibration analysis

Vibration analysis is the most popular CM method used for condition monitoring of rotating equipment (Higgs et al., 2004). The vibration industry has made great strides in detecting impending bearing failures at their onset, long before loss of function occurs (Water Environment, 2008).

The two types of vibration monitoring included portable measurements where the feedback is periodic and online measurements where the feedback is continuous (Carnero, 2005). Depending on the criticality of the machine, the online versus periodic measurements can be used.

Tribology

Tsang (1995) described tribology as relating to the interface between sliding surfaces. The interface is normally a lubricating agent such as oil. Tribology techniques used in CM includes component analysis of the oil, ferrography and wear particle analysis to ensure safeguarding of oil quality and safeguarding of the components involved (Ahmad and Kamaruddin, 2012).

Thermography

Thermography measures infrared radiation (IR) energy emissions (surface temperatures) to detect anomalies (Water Environment, 2008). Since all equipment emits some level of IR emissions, the warmer the object the more radiation is emitted. Thermography makes use of a rule of thumb where certain machines become very hot before they fail. (Davies and Connolly, 2005).

Process condition monitoring

PCM refers to the use of process variables like temperature, pressure, and flow to make critical maintenance decisions related to degradation and failure of equipment (Water Environment, 2008). Tsang (1995) referred to process parameter monitoring in a slightly wider scope than just pressure, temperature and flow and included measurements like process efficiency and heat loss. He also mentioned that the data from these parameters can be further manipulated to serve as indicators of system health and system condition and that it can be used on process and non-process equipment. Beebe (1998) referred to "performance analysis" as a CM technique which allowed for the ideal time for restorative maintenance to be determined by using fuel consumption or output reduction.

The main process parameters can be used in its raw state or developed into models using physical laws (conservation of mass and energy, thermodynamics etc.) as stated by Berge et al. (2014). Lees (2012) stated that this could be further expanded to measure the following:

- Exchanger efficiency
- Pump efficiency
- Compressor/Turbine characteristics
- Compressor/Turbine efficiency

Process condition monitoring of equipment

PCM is most adept at condition monitoring on process related equipment. In addition to the rotating equipment like pumps, compressors, and turbines it also yielded significant benefit when used on static equipment where the conventional CM toolbox is insufficient.

Turbines & Compressors

Turbines are normally used in industry to convert kinetic energy into electrical energy. It can be used to generate electricity or drive a compressor. The typical fluid used to drive the turbine is either steam or natural gas.

Compressors are used to compress gasses from a low pressure to a higher pressure as required by the process. This compression can take place over multiple stages with the heat of compression being removed by inter-stage coolers.

As described by Beebe (2003) blade damage can be picked up by vibration analysis but problems like scale deposition, blade erosion and general steam leaks required performance monitoring. Compressor efficiency in turn also required pressures and temperatures per stage for machine health to be assessed.

Pumps

A pump is used to move fluids using kinetic energy. It is used throughout the process industry to move fluids like water, slurries, and chemical products. In addition to vibration and tribology there are also the process parameters that can be used to identify failure trends. Bloch and Budris (2004) describe the following PCM techniques for pumps:

- Head flow measures utilised the pressures across the pump as well as the flow which are related via the pump curve. Deterioration can signal a defective pump component and impending failure.
- The temperature increase of the fluid being pumped signified an inefficient pump as well as a component that may be taking strain.

Heat exchangers

A heat exchanger (HEX) is used to transfer energy from a hot fluid to a cold fluid thus ensuring the product stream can reach the specified temperature before moving on to the next section of the process. Like pumps, all process plants utilise heat exchangers to heat or cool down process streams. CM techniques described by Utne et al. (2012) range from:

- Fouling of the HEX tubes which normally required a fouling evaluation using the temperature and flow of the fluids
- Calculating the approach temperature allowed one to determine if bypassing was taking place in the HEX before any outage is required
- Upstream and downstream pressures give an indication of any potential blockages in the exchanger and are most prevalent if the fluids are gasses. This allowed for the correct exchanger to be isolated if required

Decision making regarding condition monitoring

PCM has not been at the forefront of CM for several reasons. Two of the main reasons were the lack of alignment between the process engineering and maintenance engineering disciplines as well as the lack of understanding of how PCM can help in determining the condition of the equipment. Veldman et al. (2011b) put forward a CM black box framework for improved alignment between the disciplines as illustrated in Figure 2. He further emphasized that the lack of integration is disadvantageous to both sides as the process engineer lacks insight into equipment failure and the maintenance engineer does not have the information of the process related factors affecting the equipment. This can lead to incorrect maintenance decisions being made to the detriment of the business.

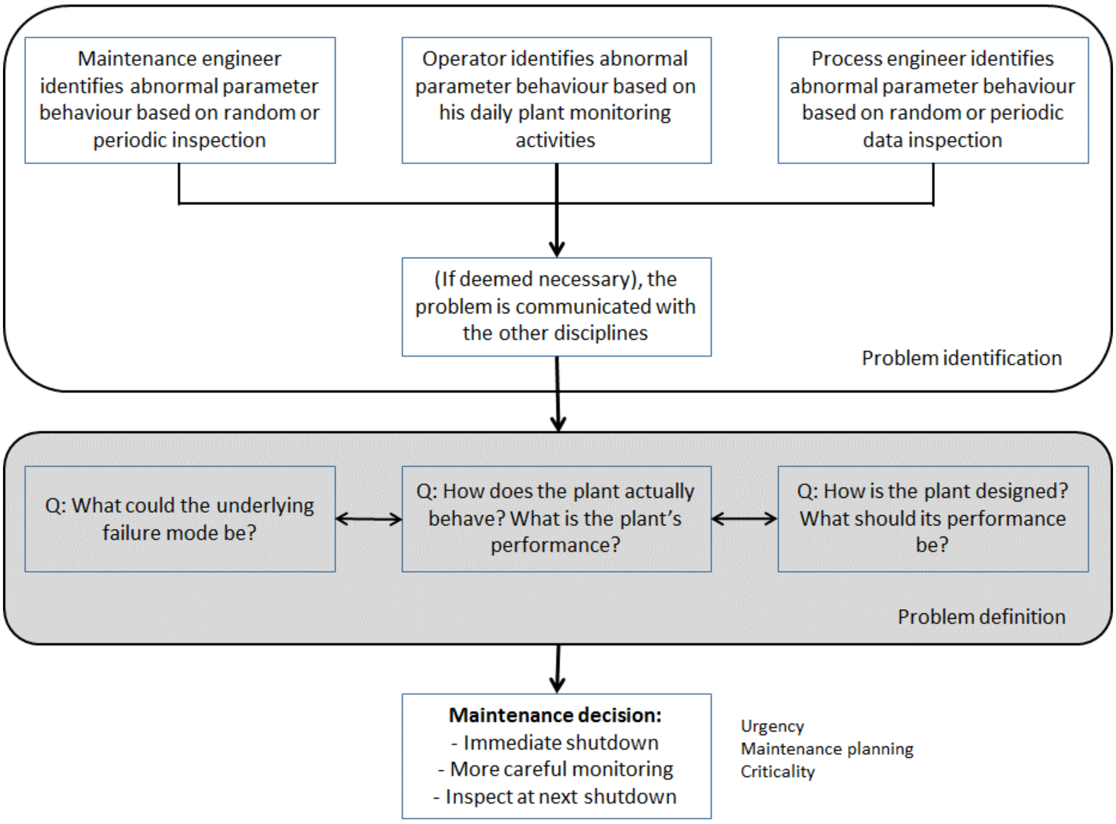

Figure 3: CM black boxes (Veldman et al., 2011b)

The objective of the decision as stated by Christer and Wang (1995) would be to prevent failure, improve uptime, reduce cost, and reduce safety related risk. Other decision-making models posed by Ahmad and Kamaruddin (2012) included the maintenance decision making process as well as the future condition prediction-based method.

Cost and benefits of condition monitoring

CM has often been associated with costly installations that are difficult to sustain and do not necessarily reap the proposed benefits. Ahmad and Kamaruddin (2012) stated that the associated equipment for CM such as sensors, thermography cameras and vibration pens involved high costs which companies were not always willing to invest in. However, although CM instrumentation and analysis is expensive and complex, it is the preferred choice where equipment failures are costly (Jardine et al., 2006).

The methodologies in calculating the costs of CM are comparable in that the costs for the installation and operations of the CM technology of choice must be considered. Hess et al. (2001) expanded on this by incorporating the following costs:

- Technology procurement costs
- Maintenance costs
- Installation and customization costs
- Programmatic costs
- Personnel costs

The benefits of PCM are grounded in the fact that most of the measurements are available as part of the control scheme of the plant and the data is stored continuously on a historian system making it accessible when needed. Schulte's et al. (2007) pointed out that one should take advantage of the existing information already on the machine. This referred to the PCM measurements already installed. Ruiz-Cárcel et al. (2016) made a similar statement and highlighted that most modern installations are heavily automated with much of the process data already available to monitor the condition of systems.

The benefit of CM however does not only lie in the prevention of losses and repair costs but also in the maintenance intervals. These maintenance intervals can be optimized to the point that expensive materials used in PM were not needed based on the condition assessment of the equipment. Prajapati et al. (2012) stated that a PM or corrective maintenance approach lead to manpower wastage, production downtime and financial loss. This was also reiterated by Ahmad and Kamaruddin (2012) and Kareem and Jewo (2015) who clearly stated the optimization possible on maintenance periods when the condition was being monitored as opposed to the maintenance technique prescribed by the original equipment manufacturer.

CONCEPTUAL FRAMEWORK

The addition of PCM to the traditional CM toolbox is an aspect of the literature that is not covered adequately. The industry's reliance on the traditional CM techniques is a possible reason for the lack of content with regards to PCM as a mainstream monitoring technique. To demonstrate the impact that PCM can have on critical equipment in the process industry a conceptual framework, shown in Figure 4, was developed for the study.

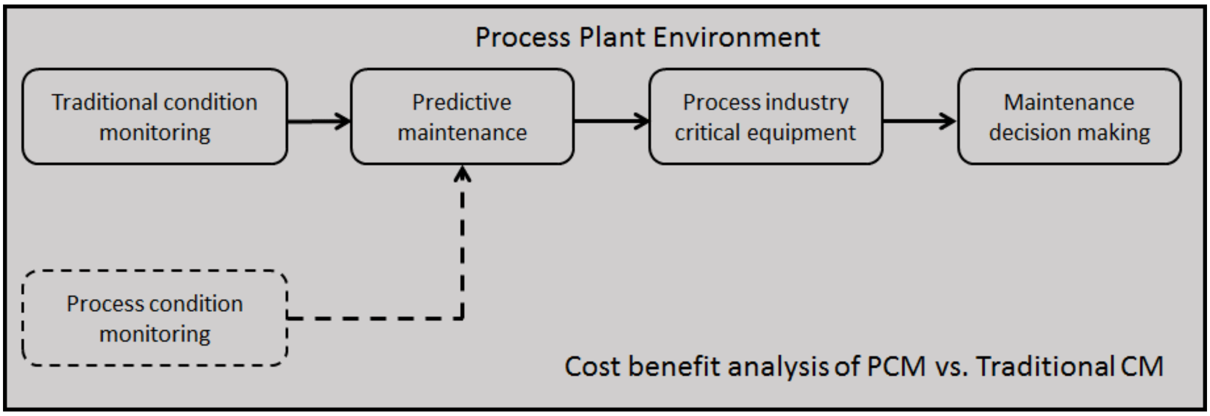

Figure 4: Conceptual framework for research study

The traditional CM techniques of vibration, tribology and thermography was cited by Tsang (1995) and further confirmed by Saranga and Knezevic (2000). The conceptual model included these traditional techniques to highlight the current state of the CM industry. The survey by Higgs et al. (2004) clearly showed the preference for traditional CM techniques as opposed to PCM techniques.

The predictive maintenance component of the conceptual framework encompassed all predictive maintenance tactics available to the maintenance decision maker. It is presented to show that CM is a critical component of the maintenance taxonomy under planned predictive maintenance. Kothamasu et al. (2006) developed a typology of maintenance philosophies where they clearly laid out all maintenance philosophies showing CBM as a subset of predictive maintenance. This was later redrawn by Veldman et al. (2011b) and used to categorise his maintenance concepts. The maintenance typologies show that CM is at the heart of predictive maintenance which pushes the field forward towards improved asset performance, optimised cost, and reduced risk.

The PCM component in the conceptual framework is shown as a dashed block and arrow to emphasise that its inclusion as a mainstream CM technique is the key argument of this study. Frameworks from literature that support this view include the matrix of CBM types by Veldman et al. (2011a), where they specifically refer to process data as a primary input into the execution of CBM. This forms part of the phased approach to CM implementation by Jardine et al. (2006).

The maintenance decision making component of the conceptual framework is the point where the decision is taken to do the following:

- Immediately shutdown and repair equipment
- Continue to monitor and nurse equipment till a planned shutdown date
- Inspect/Repair the equipment at the next available opportunity (e.g. shutdown)

The cost-benefit analysis encompassed all components of the framework and compared the costs and benefits of traditional CM with PCM. Costs incorporated follow from Hess et al. (2001) and included the procurement, installation, and operating costs. The financial benefits were also calculated to evaluate the business case. Financial benefits included the savings in maintenance costs and reduction in production downtime.

RESEARCH METHODOLOGY

The research method for this research was a case study of a typical process plant which contained the critical equipment of turbines, compressors, pumps, and heat exchangers. The process plant selected for this study comprises several plants that all function in an integrated value chain to convert coal into chemical products. The Oxygen plant which forms a vital part of the value chain was selected as the process plant case study.

To establish the existing CM baseline for the Oxygen plant and answer question 1, a quantitative evaluation of secondary data was used. The asset register for the Oxygen plant was used to ascertain all current equipment on the plant. It was decided to focus on the critical equipment of the plant for this study. The company has several departments that provide traditional CM services. The available databases from the CM departments were analysed and cross referenced against the Oxygen asset register to establish which equipment had installed traditional CM technology.

The second question with regards to PCM capability of critical equipment also made use of quantitative evaluation of process databases including reports, drawings, and process tools. These PCM tools were also cross referenced against the critical equipment at Oxygen plant.

The third question was answered qualitatively via interviews with key maintenance decision makers. The Oxygen maintenance department comprised 2 teams. The oxygen compressor maintenance (OCM) team maintained turbines, compressors, and multistage pumps whereas the mechanical maintenance department (MMD) maintained all remaining equipment including single stage pumps and heat exchangers as outlined in Figure 5.

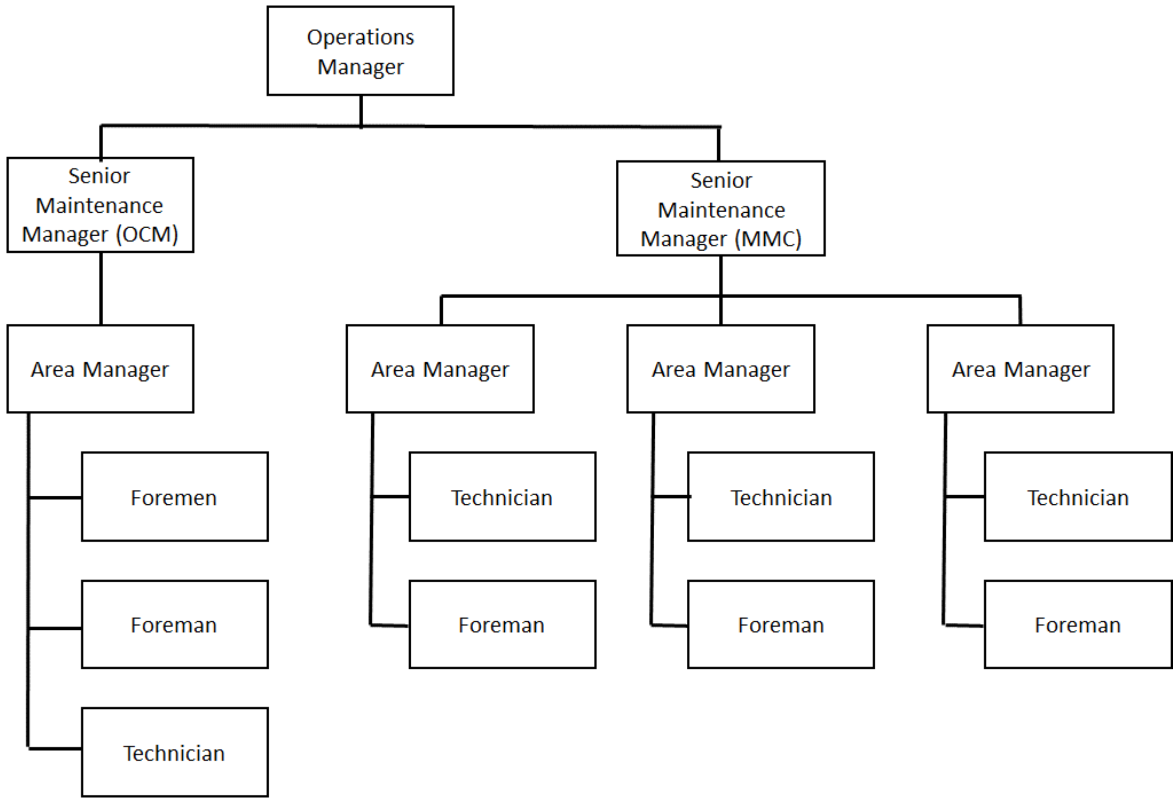

Figure 5. Organisational structure for Oxygen plant maintenance

The fourth question regarding the cost-benefit analysis was analysed quantitatively. Costs were obtained from sources such as official vendor quotations and internet databases. The benefits were calculated from the plant information using costs factors and product prices. Net present values (NPV) were calculated to assess the business cases.

RESULTS

Introduction

The results are discussed in four separate sections that deal with each of the four research questions highlighted in the Introduction. The prevalence of traditional CM techniques is discussed first and then the extent of PCM within the Oxygen plant is analysed. The third section discusses the qualitative results of discussions to determine to what extent condition monitoring influenced maintenance decisions. The last section provides the results of a financial analysis of the profitability of traditional and process monitoring techniques at the Oxygen plant.

Traditional CM Tools

Question 1 was: What are the traditional CM tools used in a typical process plant on critical equipment?

The asset register for the Oxygen plant was used to establish a list of all equipment currently on site. The register consisted of raw data and had to be analysed and filtered meticulously to group equipment together into logical categories. This resulted in a complete list of categorised equipment as well as the quantity of equipment. Table 1 below summarises the critical equipment and associated quantities.

Table 1: Critical equipment at Oxygen plant

Critical Equipment	Quantity
Turbines	48
Compressors	67
Pumps	427
Heat exchangers	944

Each piece of critical equipment was examined to determine what condition monitoring techniques were employed on them. Reports from the databases of the relevant CM departments were analysed and cross referenced against the functional location numbers for each piece of critical equipment to establish which critical equipment had installed traditional CM. Figure 6 shows the critical equipment identified for the Oxygen plant and the number of assets for each category that is monitored using traditional CM techniques.

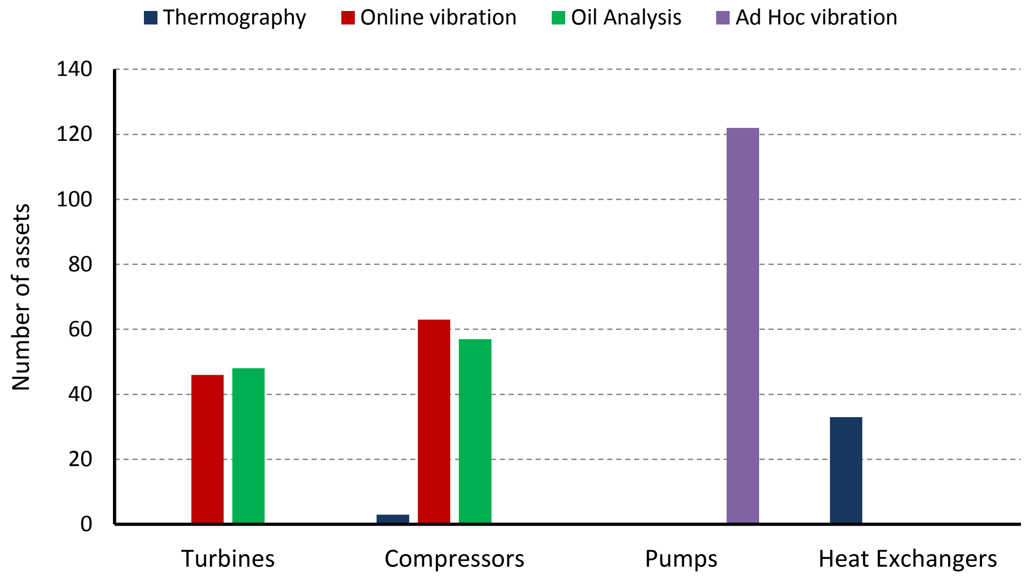

Figure 6: Existing CM techniques on critical equipment at the Oxygen plant

It was evident that the turbines and compressors had the highest quantity of traditional CM employed when compared to pumps and heat exchangers. This was possibly due to the criticality of this equipment in the production process. The two main traditional CM techniques for turbines and compressors were online vibration and oil analysis. Online vibration was employed in over 90% of turbines and compressors at Oxygen plant and tribology in over 80% of turbines and compressors making them the CM techniques of choice for rotating equipment.

Pumps did not have online vibration monitoring or thermographic techniques and were limited to ad-hoc vibration monitoring techniques (29%). Ad-hoc oil analysis was done on pumps when and if required but did not form part of a regimented CM program. The main reason for ad-hoc as opposed to online vibration on the pumps was due to the presence of standby pumps (redundancy) which did not justify online monitoring.

Heat exchangers were the least covered equipment when it came to traditional CM techniques with over 97% of equipment not covered.

Process condition monitoring tools

Question 2 was: What PCM tools are available to supplement and improve the traditional CM techniques with regards to maintenance decision making on critical equipment for a typical process plant?

To assess what PCM tools were available to supplement traditional CM, a similar methodology was used to question 1. Databases containing reports, process tools and MFD's were analysed and cross referenced against the critical equipment per functional location number. Figure 7 shows the number of assets where PCM techniques are used.

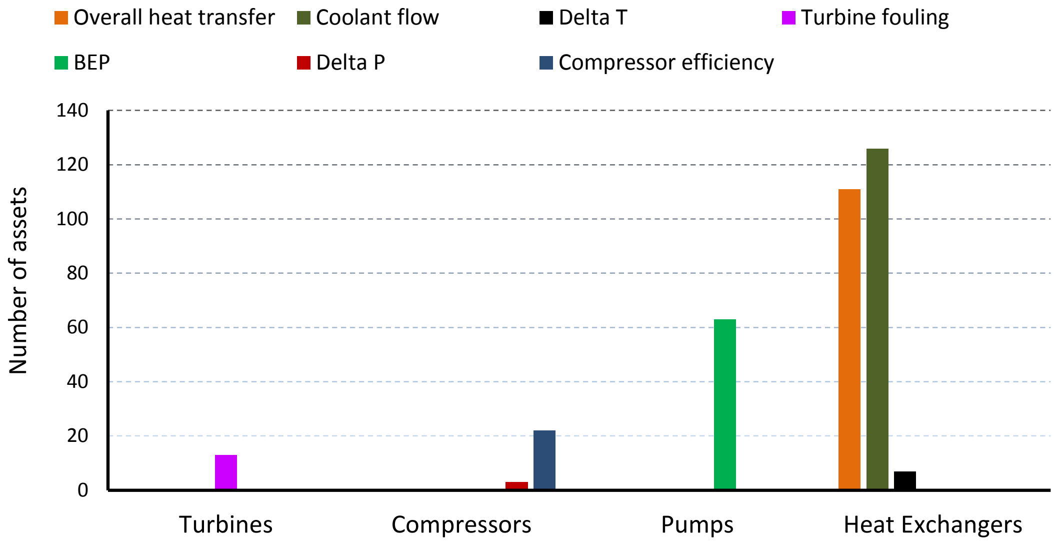

Figure 7: Exisiting PCM techniques for critical equipment at the Oxygen plant

The total number of each of the equipment investigated was given in Table 1. Turbines were dominated by online vibration monitoring (>90%), with the PCM tool of turbine fouling covering about 27% of the equipment. The main reason for the lower coverage was due to the lack of adequate measurements on all turbines and the fact that turbine fouling was geared to monitor steam driven turbines as opposed to expansion turbines.

Compressors followed the same trend with a heavy reliance on online condition monitoring (>85%) as opposed to the PCM tool of compressor efficiency (33%). The reason for the difference was due to the lack of measurements on each stage of the compressor.

Pumps showed 15% coverage of best efficiency point (BEP) PCM tools compared to the 29% coverage of ad-hoc vibration monitoring. Once again, the lack of adequate instrumentation prevented further coverage. Ad-hoc vibration monitoring followed a predetermined frequency based on a route which meant that a pump only got a vibration measurement when the point on the route was passed. BEP on the other hand was based on online measurements with data available as often as required. This increased frequency provided an added advantage for timeous maintenance decision making.

Heat exchangers showed the largest increase in terms of CM and PCM coverage. Where traditional CM covered 3% of heat exchangers with thermography, one found that at least 12% of the heat exchangers were monitored for overall heat transfer coefficient and 13% for cooling water flow. This essentially improved the condition monitoring on a critical piece of equipment by a factor of 4. The remaining PCM tools of delta T and delta P made up 1% and 3% respectively.

PCM tools and maintenance decisions

Question 3 was: Are these PCM tools recognised by key decision makers in making maintenance decisions?

To address this study objective, in-depth face to face interviews were held with the maintenance decision makers on the Oxygen plant. The Oxygen plant had two maintenance divisions. The OCM division maintained the compressors, turbines, and multistage pumps, whereas the MMD division maintained all other equipment. Interviews were conducted at various levels in the maintenance department from senior managers to foremen. The intention was to focus on maintenance decision makers i.e. the individuals that decide on philosophies, work priorities and strategic direction. Table 2 summarises the responses to the main interview questions.

Table 2: Summary of interview responses with maintenance decision makers

Question	Responses
What percentage of work deals with CM of equipment?	The MMD department on senior manager (SM) and area manager (AM) level dealt with CM between 30%-60% of the time, showing that a good amount of traditional CM was used. This dropped to 5%-20% for the foremen level who dealt more with executing work assignments. The OCM department showed a more even spread with 30%-50% from SM level to foremen level. This was due to the greater amount of CM information available for rotating equipment to carry out maintenance actions.
What CM tools are utilised the most?	There was good support for vibration analysis and oil analysis on pumps in the MMD department. Another tool that was used for condition monitoring during outages was ultrasonic wall thickness testing. Routine inspection based CM was also utilised by the foremen and their artisans to assess the daily health of equipment like pumps and heat exchangers. The OCM department clearly favoured vibration as the main CM tool followed by tribology. The possible reason for this is the readily available vibration information and expertise that arose from having dedicated departments for these CM techniques within the SSO facility.
Key decision taken based on CM	The key-decisions taken varied across the board from SM, AM, foremen and technician level. The decisions for the SM and AM centred on whether the equipment being monitored should be replaced or could it run until its next outage. There was also a constant verification process with the maintenance strategies as to whether they were still applicable in view of the CM information. Foremen level focused on whether the equipment in question could be repaired or not. The OCM department took similar decisions in terms of replacement, however the vibration data was actively used to carry out online interventions on the turbine or compressor to extend the operation of the machine until its next outage.
PCM techniques utilised	In the MMD department the process info used was rudimentary and consisted of pressure or flow indications from the plant which had not been converted to any type of PCM tool. The OCM department showed a definite appreciation.

Costs and benefits of using PCM tools

Question 4 was: What are the cost and benefits of incorporating the PCM tools into the traditional condition monitoring toolbox for critical equipment in a typical process plant?

The approach taken to do a cost-benefit analysis was similar to the method that Hess et al. (2001) used. Assessing all 1486 pieces of critical equipment would have been excessive. To perform the cost-benefit analysis it was decided to select specific pieces of critical equipment to represent each critical equipment category.

All cash flows were determined for the CM or PCM technology which included equipment cost, installation costs, operational costs (man-hours and maintenance) as well as anticipated financial benefits from the CM/PCM techniques. These benefits ranged from reduction in production losses to reduction in repair and maintenance costs. The inflows and outflows of the cash flows were accumulated to obtain a net cash flow. The net cash flows were discounted at the weighted average cost of capital (WACC) to arrive at a NPV. Each of the NPV's is shown in Table 3 for CM and PCM techniques. Cash flows were converted from ZAR to USD values.

Table 3: Cost benefit analysis of CM and PCM techniques for different equipment

CM/PCM technique	Turbines (USD million)	Compressors (USD million)	Pumps (USD)	Heat Exchangers (USD)
Online vibration	14.7	19.8		
Oil analysis		5.7		
Ad Hoc vibration			130 000	
Pump Delta P			140 000	350 000
Pump BEP			140 000	
Compressor efficiency		6.1		
Turbine fouling	11.8			
HEX Delta T				
HEX Thermography				410 000
HEX Coolant flow				340 000
HEX Overall heat transfer				340 000

Regarding turbines, it was evident that online condition monitoring provided a significant financial benefit with regards to equipment reliability and production loss prevention. An NPV of more than USD14.7m made it logical to include online vibration monitoring as a CM tool on turbines. The PCM tool of turbine fouling was comparable in terms of NPV at about USD11.8m. The PCM tools ensured critical failure to the turbine blades were mitigated by proposing regular turbine washes. A combined NPV of more than USD26.5m is possible by using both CM and PCM techniques and provided a favourable business case for PCM to supplement the existing CM toolbox.

With regards to the compressor it was evident that the online vibration monitoring NPV of USD19.8m was more than twice the calculated NPV of USD5.7m from tribology and compressor efficiency monitoring (USD6.1m). The reason for the significant disparity was due to the lack of impact that the compressor efficiency brought to the compressor reliability as opposed to the online vibration monitoring. There remained however a strong business case for the PCM tool which also brought with it an added benefit of a relatively minimal installation cost since most of the measurements were already incorporated into the control system.

Pumps showed a lower NPV of about USD140000 for both CM and PCM tools. The main reason for these relatively low NPV values was due to the redundancy present in most pumping systems which meant minimal production losses. A second reason was the lower probability of a catastrophic failure with pumps as opposed to compressors and turbines. However, what should be noted was that both the PCM tools (BEP and Delta P) had a higher NPV when compared to the ad-hoc vibration monitoring due to the input costs of the ad-hoc vibration probes and the requirement of skilled vibration analysts.

The business case for PCM outperforming CM was the reason many plants are investing in process instrumentation around pumps rather than more vibration points.

Heat exchangers also had a relatively low NPV (~ USD350 000) for both CM and PCM techniques. From previous discussions the lack of CM tools for static equipment like heat exchangers was juxtaposed to the host of PCM tools available. Overall heat transfer coefficient as well as temperature, pressure and flow tools provided financially beneficial PCM techniques to improve equipment reliability.

CONCLUSIONS AND RECOMMENDATIONS

Secondary data was used from the process plant and the study focused on the critical equipment to assess the impact of PCM. Interviews were conducted to assess the link between PCM and maintenance decision making which was qualitatively analysed. Finally, a cost benefit analysis was performed to quantify the financial benefit of using PCM to supplement the traditional CM toolbox.

With regards to assessing the traditional CM tools used, turbines and compressors had the highest quantity of traditional CM employed at over 90% online vibration monitoring. Ad-hoc vibration monitoring covered 29% of all pumps since the presence of redundancy did not justify online vibration monitoring. Heat exchangers were the least covered equipment when it came to traditional CM techniques with over 97% of equipment not covered.

An assessment of the PCM tools available to supplement traditional CM techniques for the critical equipment showed that the PCM tool of turbine fouling covered 27% of the turbines. Compressors had 33% coverage with the PCM tool of compressor efficiency. Pumps showed 15% coverage of the PCM tool for BEP and heat exchangers showed 12% coverage for the PCM tool of overall heat transfer coefficient.

The interviews with the key decision makers at Oxygen plant revealed that the SM and AM levels for the MMD dealt with CM up to 60% of the time while the foremen level showed a lower percentage (up to 20%) of work with CM. The OCM department showed a more even spread with 30-50% from SM level to foremen level utilising CM. In the MMD department the process info used was rudimentary and consisted of pressure or flow indications from the plant which had not been converted into any type of PCM tool. The OCM department showed a definite appreciation for process information in the SM and AM levels. The process information used was once again rudimentary (temperature, flow, and pressure indications) however their usage in combination with traditional CM was inextricably linked to decision making.

A cost benefit analysis of the representative critical equipment showed that with regards to turbines, a combined NPV of over USD26.5m is possible by using both CM and PCM techniques. PCM tools for pumps (BEP and Delta P) had a slightly higher NPV of USD140 000 when compared to the NPV of USD130 000 for ad-hoc vibration monitoring. Heat exchangers showed a NPV of USD340 000 for the PCM tool of overall heat transfer coefficient.

Recommendations for future research include:

- Application of a similar research methodology to international process plants to assess PCM impact under different macro and micro economic conditions.
- Expansion of the critical equipment assessed to a wider array of equipment.
- PCM tools assessed to include energy efficiency techniques.

- Interviews to include production departments as well.

REFERENCES

Ahmad, R. & Kamaruddin, S., (2012), An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering,* 63(1)**,** 135-149.

Beebe, R. Condition monitoring by performance analysis to optimise time for overhaul of centrifugal pumps. Henry C Pusey et al. 52nd Meeting of Society for Machinery Failure Prevention Technology Virginia Beach, USA 30 March-3 April 1998, 357-366.

Beebe, R. (2003), Condition monitoring of steam turbines by performance analysis. *Journal of Quality in Maintenance Engineering,* 9(2), 102-112.

Bengtsson, M., (2004), Condition based maintenance system technology–Where is development heading, *Condition based maintenance systems–an investigation of technical constituents and organizational aspects,* 55.

Berge, S., Lund, B. & Ugarelli, R., (2014), Condition monitoring for early failure detection: Frognerparken pumping station as case study, *Procedia Engineering,* 70, 162-171.

Bloch, H. P. & Budris, A. R., (2004), *Pump user's handbook: Life extension*: The Fairmont Press, Inc.

Carnero, M.C., (2005). Selection of diagnostic techniques and instrumentation in a predictive maintenance program: A case study, *Decision support systems,* 38(4)**,** 539-555.

Christer, A.H. & Wang, W., (1995), OR Models for Maintenance Management and Quality Control: A simple condition monitoring model for a direct monitoring process, *European Journal of Operational Research,* 82(2)**,** 258-269.

Davies, E. & Connolly, C., (2005), The use of infrared imaging in industry. *Assembly Automation,* 25(3)**,** 191-195.

Hess, S.M., Biter, W.J. & Hollingsworth, S.D., (2001), An evaluation method for application of condition-based maintenance technologies. Reliability and Maintainability Symposium, 2001. Proceedings. 240-245.

Higgs, P.A., Parkin, R., Jackson, M., Al-Habaibeh, A., Zorriassatine, F. & Coy, J., (2004), A survey on condition monitoring systems in industry. ASME 7th Biennial Conference on Engineering Systems Design and Analysis, 2004. American Society of Mechanical Engineers, 163-178.

Jardine, A.K., Lin, D. & Banjevic, D., (2006), A review on machinery diagnostics and prognostics implementing condition-based maintenance, *Mechanical Systems and Signal Processing,* 20(7)**,** 1483-1510.

Kareem, B. & Jewo, A.O., (2015), Development of a model for failure prediction on critical equipment in the petrochemical industry, *Engineering Failure Analysis,* 56, 338-347.

Kothamasu, R., Huang, S.H. & VerDuin, W.H., (2006), System health monitoring and prognostics–a review of current paradigms and practices, *Int. J. of Advanced. Manufacturing Technology,* 28(9-10), 1012-1024.

Lees, F., (2012), *Lees' Loss prevention in the process industries: Hazard identification, assessment and control*: Butterworth-Heinemann.

Myhre, B., Petersen, S. & Ugarelli, R., (2014), Using wireless vibration monitoring to enable condition-based maintenance of rotating machinery in the water and wastewater industries. *Procedia Engineering,* 89( ), 1397-1403.

Prajapati, A., Bechtel, J. & Ganesan, S., (2012), Condition based maintenance: a survey. *Journal of Quality in Maintenance Engineering,* 18(4)**,** 384-400.

Ruiz-Cárcel, C., Jaramillo, V.H., Mba, D., Ottewill, J.R. & Cao, Y., (2016), Combination of process and vibration data for improved condition monitoring of industrial systems working under variable operating conditions. *Mechanical Systems and Signal Processing,* 66–67( ) 699-714.

Saranga, H. & Knezevic, J., (2000), Reliability analysis using multiple relevant condition parameters. *Journal of quality in maintenance engineering,* 6(3)**,** 165-176.

Schultheis, S.M., Lickteig, C.A. & Parchewsky, R., (2007), Reciprocating compressor condition monitoring. 36th Turbomachinery Symposium, College Station, TX, September, 2007,. 10-13.

Statistics SA, (2012), *Energy* [Online]. Available: http://www.gcis.gov.za/content/resourcecentre/sa-info/yearbook2012-13. [Accessed 25 March 2016.

Tsang, A.H.C., (1995), Condition-based maintenance: tools and decision making. *Journal of Quality in Maintenance Engineering,* 1(3)**,** 3-17.