AN INVESTIGATION OF DIAGNOSTIC, PROGNOSTIC AND STRUCTURAL HEALTH MONITORING SYSTEMS IN ASSET MANAGEMENT

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ABSTRACT

Increasing competition in a globalised environment makes it difficult for business enterprises to meet customer demands and expectations. To meet these demands companies require high performance assets that can produce quality services and products. All physical assets degrade with usage or time due to aging, abnormal operating conditions and the effect of the environment. The purpose of maintenance interventions is to counter this degradation by selectively replacing or repairing items and components of the asset system. Investigation of literature indicated that diagnostic, prognostic and structural health monitoring (DPS) systems are becoming increasingly valuable to determine the health or condition of asset systems and individual items and components. The main objective of this research was to establish the current usage of DPS systems in industry and to determine to what extent data from DPS systems is used by maintenance managers in decision making.

A study was done to determine the application of other tools than just normal condition monitoring to improve and optimize maintenance performance. The focus of the investigation was on DPS systems as a means to improve operational capability, availability and safety. Data was collected by means of surveys in engineering industries in a number of Southern African countries, i.e. Namibia, South Africa, Botswana, Zambia and Zimbabwe. Questionnaires were distributed to plant managers, supervisors, engineers and technologists in engineering industries.

It was found that most industries and companies make use of methodologies and systems that are part of the damage prognosis (DP) process to satisfy their maintenance requirements. Preventive maintenance is used to a large extent and condition monitoring forms part of predictive maintenance strategies. However, structural health monitoring (SHM) is only used by a small number of companies. It was also found that the majority of respondents did not have a good knowledge of what damage prognosis entails and have not adopted this integrated maintenance method. A case study of a hydro-electric power station revealed that productivity levels increased after the implementation of DPS systems on the plant.

This paper addresses aspects of asset management and in particular one of the 39 subjects defined by the Global Forum on Maintenance and Asset Management (GFMAM), namely '*Asset Performance and Health Monitoring*'. The findings can benefit asset managers in industry by highlighting the aspects of health monitoring of assets that could be improved to increase asset performance and benefit the overall business enterprise.

Key words: Asset condition, Monitoring, Diagnostic, Prognostic

INTRODUCTION

Rationale for asset maintenance

Systems and assets need to be available when required and the performance levels should be high in order to produce the right quantity and quality of products or to ensure the timely provision of quality services. According to Worden & Dulieu-Barton (2004), the performance of engineering systems deteriorates with usage and the required performance is not guaranteed indefinitely. It is however possible to ensure that the performance of assets is maintained at required levels for the design life of the asset. This is achieved through maintenance interventions and activities performed on various equipment and systems. The purpose of maintenance interventions is to counter the degradation of equipment by selectively replacing or repairing items and components of the asset system

Research problem

Increased maintenance activities should result in increased performance levels for the business enterprise. Companies need high performance assets that can produce quality services and products. This however comes at an increased cost as resources are required for effective maintenance strategies to be in place. Campbell & Reyes-Picknell (2006) acknowledge that maintenance costs can be extremely high when compared to the contribution of such costs to the total operational costs. It is therefore important that cost effective maintenance methods and procedures are identified and implemented in order to reduce the maintenance cost ratio without compromising on the system performance.

Traditional maintenance approaches involve corrective, preventive and predictive maintenance. These maintenance methods are cost-intensive because they either involve taking remedial actions which are performed after the equipment has failed or routine tasks that are performed at pre-determined intervals with no regard to equipment status (Kumar, Srivastana & Goel, 2009). The current maintenance methods which are used to determine when equipment should be decommissioned rely on conservative analyses because methods such as non-destructive examination (NDE) cannot reliably detect small defects in the equipment. These methods can also not predict remaining useful life of equipment and as such do not allow for reasonable optimum usage intervals. This means that equipment is not used optimally resulting in the possibility of replacing equipment that could have performed adequately for some time period.

This study was therefore conducted to investigate the application of maintenance tools or methods other than just the normal corrective, preventive and condition monitoring which are required to improve and optimise maintenance performance. Diagnostic, prognostic and structural health monitoring (DPS) systems were studied as maintenance tools, with a focus on the concept of damage prognosis (DP).

Research objectives

The main objective of this research study was to establish the current usage of DPS system in industry and to determine the extent to which data from DPS systems is used by maintenance managers in decision making. The study also investigated whether productivity levels were improved by the implementation and usage of DPS systems.

LITERATURE

Overview

A review of the literature shows an increasing trend in research on structural health monitoring (SHM) systems. Emerging applications in the civil and building structures have also been recorded. Mita (1999) provided examples of increased use of SHM in Japan, especially after the country was hit by the earthquake in Kobe in 1995. References in the use of SHM are also mentioned in the aerospace, as well as in the oil and gas industries (Kumar et al, 2009).

In most cases, only the SHM systems are researched and implemented but little emphasis is placed on the integrated damage prognosis (DP) process. Farrar & Lieven (2007) describe the current status of DP as being elusive to which Kumar et al (2009) also agree and state that the DP process is still in a development phase. A few examples in the nuclear industry and in rotating machinery applications where DP has been applied are listed in Farrar & Lieven (2007).

DPS systems

Diagnostic, prognostic and structural health monitoring systems or DPS systems in short, are important systems in asset management. This section of the paper looks at a description of each of these systems before a conceptual model of the DP process is proposed in the next section.

Diagnostic systems allow for the early detection of damage in equipment. It also indicates early deterioration in performance levels of equipment (Aktan et al, 2001 and Kumar et al, 2010).

SHM is the process that seeks to implement a strategy used for the identification of damage in engineering systems (Farrar & Worden, 2006). Worden & Dulieu-Barton (2004) also testify to these definitions where they list disciplines of damage evaluation as being SHM, condition monitoring (CM), non-destructive evaluation (NDE) and statistical process control (SPC). Both diagnostic systems and SHM systems are required for identifying and detecting damage in equipment.

A prognostic system, also known as damage prognosis (DP), is an extension of diagnostic and SHM systems. It is an integrated process that takes into account equipment condition (as measured by the diagnostic and SHM systems) to determine the remaining equipment life. DP is defined as "the estimation of the remaining useful life of equipment by taking into consideration the information gathered from monitoring systems, design information, past operation experience, the prediction of future operating conditions and operating environment of the system or equipment" (Farrar et al, 2003) as cited in Farrar & Lieven (2007). Key components of a DP process are the SHM system and diagnostic systems. A DP methodology involves a virtual life assessment (physics based) and real life prognostic assessment (data based). Various tools and methods are available to perform a virtual life assessment, e.g. the failure mode, mechanism and effects analysis (FMMEA) and Physics of Failure (PoF) models (Pecht, 2009).

The integrated DP process

In order to adopt DPS systems for any application, it is important to understand their constituent parts. The model in Figure 1 below, adapted from the prognostic and health management (PHM) approach proposed by Pecht (2009), shows the subsystems that are part of the overall DP process.

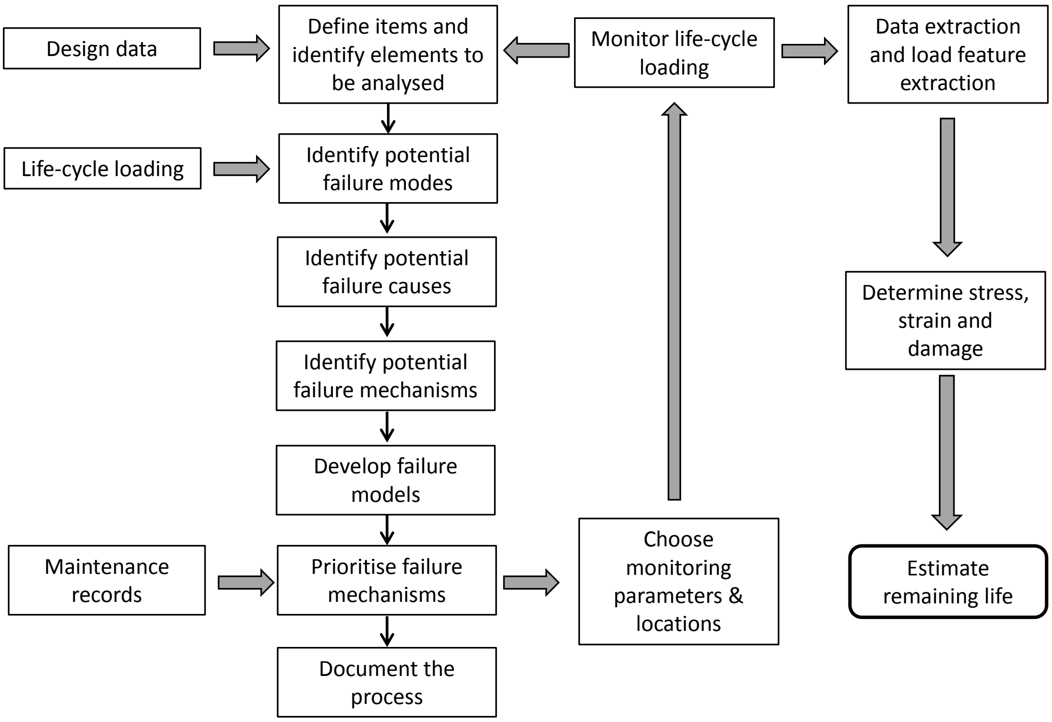

Figure 1: Conceptual model for adopting a comprehensive DP process (Adapted from Pecht, 2009)

Various inputs are required to initiate the DP process, e.g. equipment design data and maintenance records. The next step in the process essentially involves the FMMEA process which also forms part of the reliability-centered maintenance (RCM) approach. This step identifies all the items and components that need to be analysed in terms of their failure modes, failure mechanisms and effects.

RESEARCH METHODOLOGY

Introduction

It is clear from existing literature that the application of SHM and other forms of diagnostic systems bring about safety and economic benefits. The DP process, being an integrated approach, presents more added benefits as far as performance levels are concerned. This means that by applying the DP process, business enterprises have increased potential for satisfying the increasing demands and expectations of customers.

Using the conceptual model shown in Figure 1, a questionnaire was developed on the different systems that make up the DP process. The questionnaire was distributed to plant managers, supervisors, engineers and technologists in engineering industries. They were surveyed on whether their maintenance activities were performed by using a maintenance scheduler (software) and the different maintenance strategies that they used and to what extent these strategies were adopted. The condition of equipment was established by questioning respondents on the maintenance method used, the extent of usage and the method used for monitoring.

This study followed a qualitative approach in investigating the usage of DPS systems in the engineering industry. As qualitative research aims, among other things, to "understand, explain, explore, discover and clarify feelings and experiences of a group of people" (Kumar, 2010), the adoption of this process therefore suit the aims and objectives of this study.

The sample population comprised 72 respondents from the process industries (i.e. food and beverage processing), power utilities, petro-chemicals, transportation and consulting firms which are involved with maintenance activities.

Prior to the distribution of the questionnaire, a pilot survey was distributed to a group of randomly selected personnel. The aim of the pilot survey was to obtain comments on the relevance of the questions and to test the functionality of the electronic process of answering the questionnaire.

In addition to the data obtained through the questionnaires, data was also collected from a power utility's financial statements, supervisory control and data acquisition (SCADA) system as well as from the system application and data processing (SAP) software package. This data was particularly useful for a case study on the performance levels of units of a power station.

RESULTS AND FINDINGS

The questionnaire that was distributed to the sample population comprised 3 main sections, i.e.

- Knowledge of the Structural Health Monitoring (SHM) system and other diagnostic systems
- Knowledge of the Damage Prognosis (DP) methodology
- General information on the use of diagnostic, prognostic and structural health monitoring (DPS) systems

Knowledge of the SHM system and other diagnostic systems

In order to gauge the industry's awareness of the existence of DPS systems, questions were asked on each of the maintenance methods that form part of the DP process as identified in the conceptual model. Respondents were asked to indicate a Yes or No to the question 'Have you heard of the terms 'condition monitoring', 'non-destructive testing' and 'structural health monitoring'? The results are shown graphically in Figure 2.

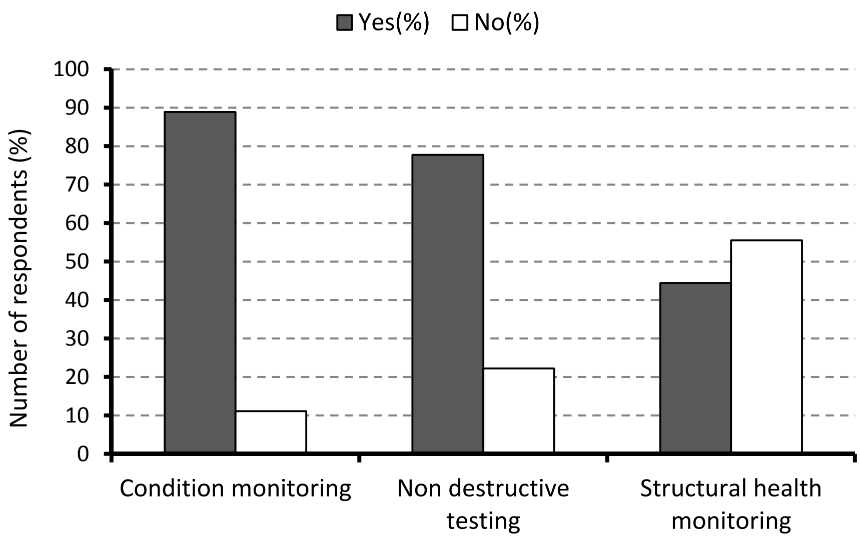

Figure 2: Awareness of the terms CM, NDT and SHM

As indicated in Figure 2 the terms ‘condition monitoring’ and ‘non-destructive’ testing are fairly well known, but only about 44% of the respondents indicated that they know the term ‘structural health monitoring’. There is therefore much room for improvement in this area of monitoring physical assets.

The respondents were also asked to indicate whether they are currently using these 3 systems by indicating Yes or No to the question ‘Which of the following systems do you use in the plant, i.e. ‘condition monitoring’, ‘non-destructive testing’, structural health monitoring?’ The results are shown in Figure 3 below.

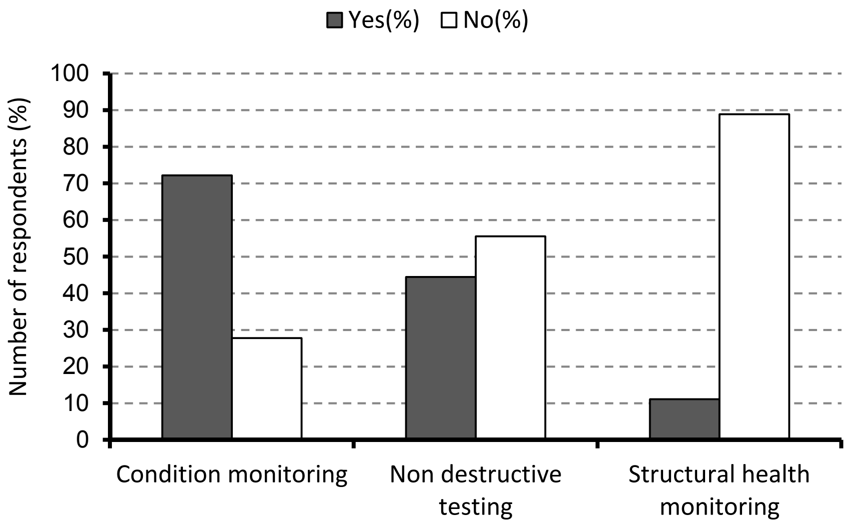

Figure 3: Usage of CM, NDE and SHM in industry

As seen in Figure 3 only about 11% of the respondents indicated that they are currently using SHM in their respective plants. Operations and maintenance managers should first get acquainted with the basic knowledge of SHM and then gradually implement this technique in the workplace.

Respondents were then asked to indicate to what extent they agreed with a number of statements related to their knowledge of a number of diagnostic systems. Respondents were asked to indicate to what extent they agreed with the following statements using a five point scale from ‘Strongly disagree’ to ‘Strongly agree’.

- Condition monitoring strategy is used in the organisation
- The SHM system is applied in the organisation to carry out maintenance activities
- Predictive maintenance strategy is applied in the organisation to carry out maintenance activities

The results of the survey for these statements are shown below in Figure 4 below.

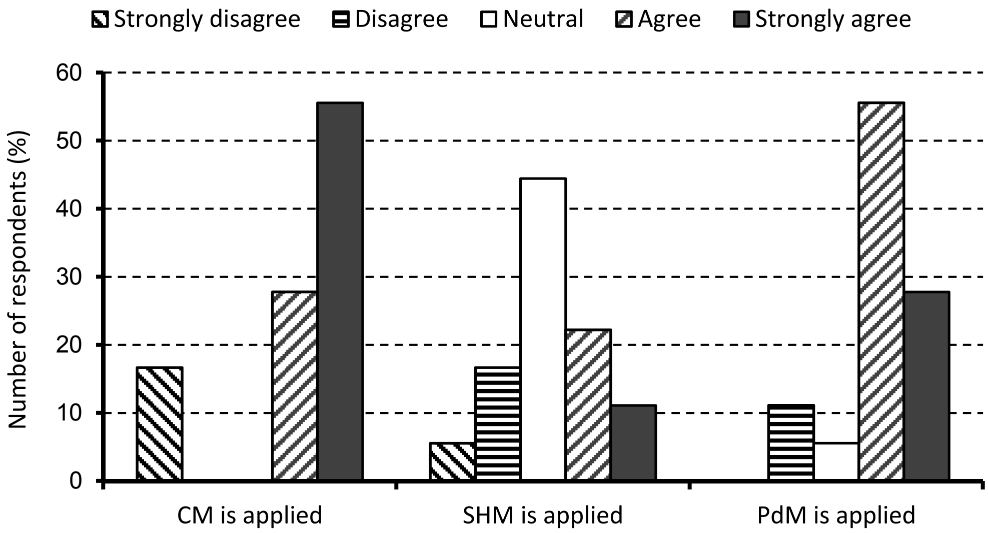

Figure 4: Extent of usage or application of systems

About 83% of the respondents agreed (strongly agreed and agreed) that condition monitoring (CM) is used at their facilities while 17% disagreed. The same number also agreed that predictive maintenance (PdM) is applied. However, only about 33% agreed that structural health monitoring is applied. A large number of respondents (44%) were neutral, probably indicating that they have not heard of the term SHM before as was seen from Figure 2.

Knowledge of damage prognosis

The respondents were also questioned on their awareness of the DP process. In response to the question 'Have you heard of the term or concept of damage prognosis?' about 60% indicated that they have heard of the term or the concept. Respondents that answered 'Yes' to this question were also asked to indicate to what extent damage prognosis is applied in their organisation on a 5-point scale of 'Strongly disagree' to 'Strongly agree'. The results for this question are shown in Figure 5.

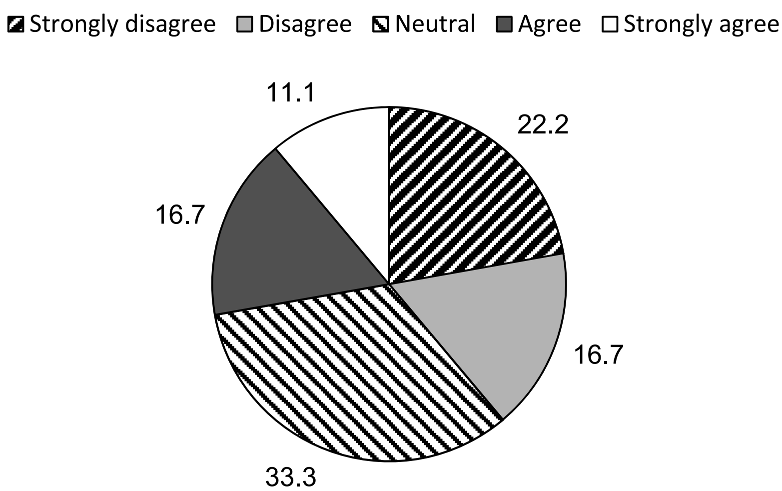

Figure 5: Extent of usage or application of DP systems

It is clear from this result that few respondents (about 28% 'Strongly agreed' or 'Agreed') use DP systems in their plants. This could be due to the lack of knowledge of DP systems.

General information on use of DPS systems

Respondents were asked to rate their agreement on a 5-point scale to the following four statements related to the practical application of DPS systems in the plant.

I. *On-line measurement systems are applied in your plant/processes.*

II. *Operational data captured on-line is analysed by Reliability Engineer's in order to calculate system reliability.*

III. *Maintenance activities are scheduled using an automatic maintenance scheduler or maintenance resource planning tool/software.*

IV. *Data from diagnostic, prognostic and/or structural monitoring system is used to influence decision into new acquisition of equipment.*

The results for these statements are shown in Figure 6 below.

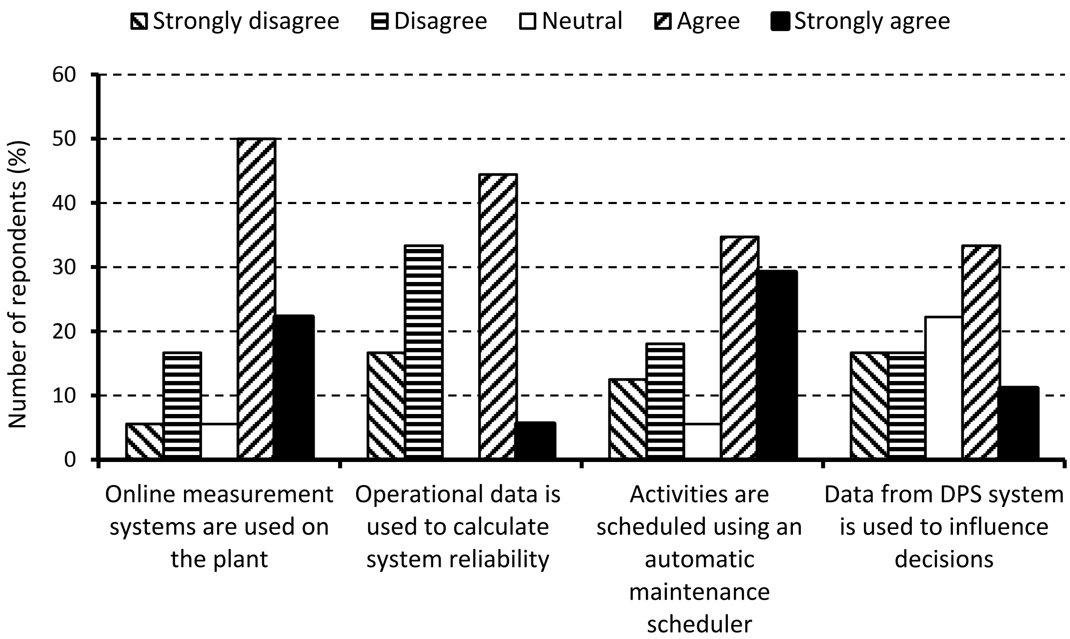

Figure 6: Usage of data on the plant

About 72% of respondents agreed that online measurement systems are used on their plants/systems. This is an indication that operational and asset managers are realising the value of online measurements to manage day-to-say activities on a plant and to obtain real-time data and information related to the performance and health of the assets.

Respondents were divided on the issue of operational data that is used for calculating reliability and availability of the assets. Half of the respondents agreed or strongly agreed but half disagreed or strongly disagreed. There is therefore scope for improvement and operations managers as well as maintenance managers should be encouraged to adapt information systems to provide performance and asset management data on a regular basis for decision making.

About 74% of respondents agreed that maintenance activities are scheduled using an automatic maintenance scheduler. Automated scheduling is mostly provided by asset or maintenance information systems or can be added through a separate module. It appears that most plants make use of this feature of their information system and therefore alleviate the need for a separate information system that has to be maintained and operated.

A very important aspect that the study aimed to establish, among other objectives of the study, was to determine whether data and information obtained through the use of diagnostic (CM, SHM, NDE) and prognostic systems is being used by maintenance managers in the asset acquisition process. The study sought to establish if information on the equipment assist in determining which equipment is to be replaced or to be refurbished and when such replacement or refurbishment should take place. The study also aimed to investigate if equipment information acquired through the various DPS systems assist organisations to budget properly.

It is seen in Figure 6 that about 44% of the respondents agreed that the information from DPS systems influenced decision making in acquiring new equipment or refurbishing the existing ones. However, 32% disagreed or strongly disagreed, indicating that there is scope for improvement in the asset acquisition process for asset managers.

Plant performance

In order to study whether productivity levels were increased for industries that have adopted DPS systems, the Ruacana power station, owned and operated by NamPower (a power utility in Namibia), was used as a case study. Information was collected on the plant using the SAP and SCADA information systems. The amount of generation produced by the power plant was obtained and analysed for the period before the installation of a DPS system and after the DPS system was installed.

To study the productivity levels, the unit availability rate (UAR) was determined for a number of years and for each of the three units installed at the power plant. Only the results of Unit 1 are presented in this paper. The unit availability rates (UAR) were calculated by taking the amount of energy generated by the Unit with respect to the amount of available capacity for that Unit as shown in equation (1):

$$UAR = \frac{actual\ energy\ generated}{available\ energy\ capacity} \quad (1)$$

The availability rate for Unit 1 of the Ruacana power station for the period 2000 – 2003 is shown in Figure 7 below.

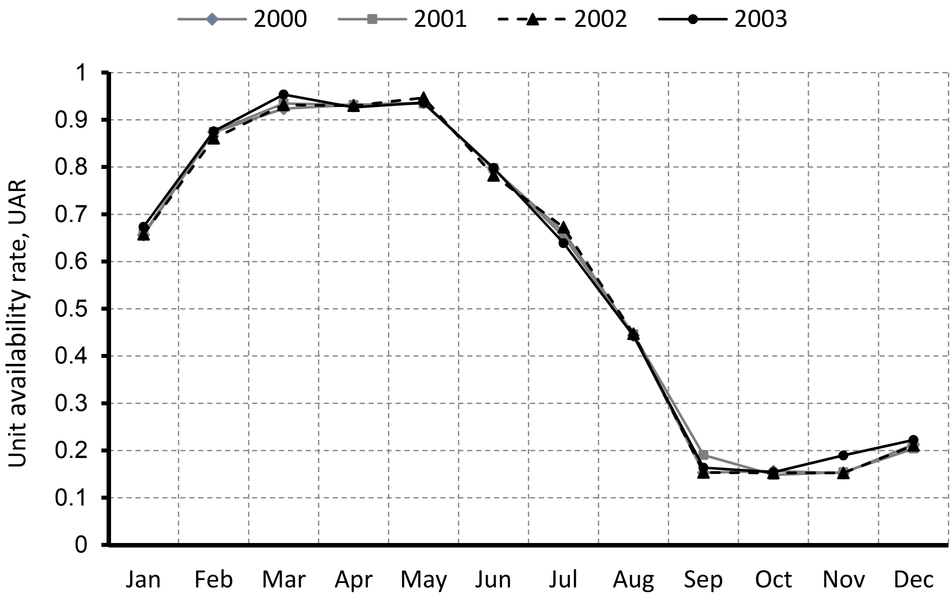

Figure 7: Monthly UAR values for Unit 1 for the period 2000 to 2003

The UAR value increases sharply from January to March as the river flow increases in the rainy season. The maximum value is sustained in March to May after which the UAR decreases gradually until September when the minimum UAR is reached. It can be seen in Figure 7 that the UAR value for the period 2000 - 2003 averaged 65% in January, 84% in February and about 92% in March, April and May before it decreased again to 80% in June.

The unit availability factor for some years after the installation of the DPS process is shown in Figure 8 below.

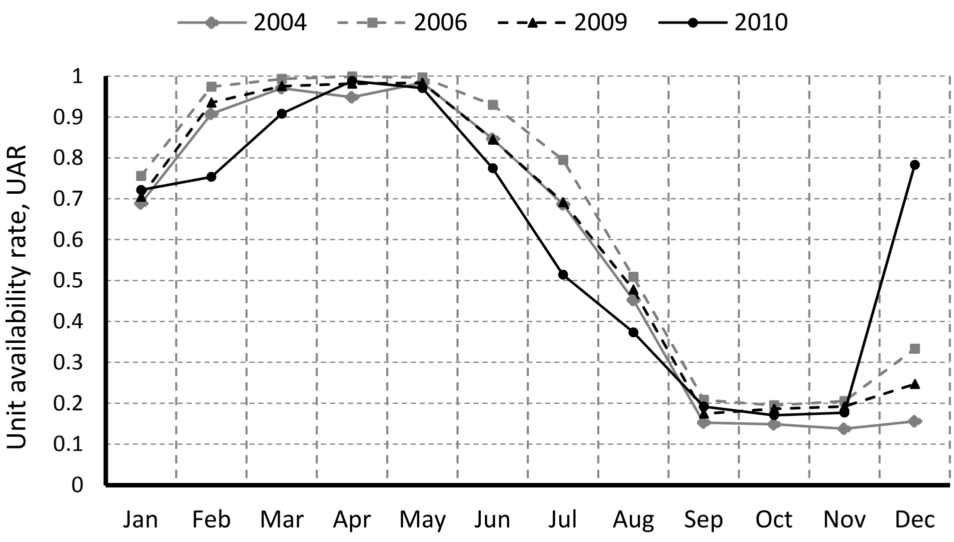

Figure 8: Monthly UAR values for Unit 1 during the period 2004 to 2010

In the year 2003, the plant’s operations were automated to include online monitoring, condition based maintenance and automated trips, the availability of the units have increased notably. The average monthly UAR for the years 2004, 2006, 2009 and 2010 was 72% in January, 89% in February, 97% in March, 98% in April and 98% in May and June respectively. It is clear that, on a month by month comparison, the UAR values in 2004 and onwards are significantly higher than in the years 2000-2003. The UAR values are between 5 and 7% higher after 2004 if compared with the values before 2004.

The Ruacana power plant is situated in the Kunene River and the water flow could therefore influence the unit availability rate (UAR). The river flow rate was therefore analysed for a period of 10 years and the weekly flow rate for a number of years from 2001 to 2010 is shown in Figure 9 below

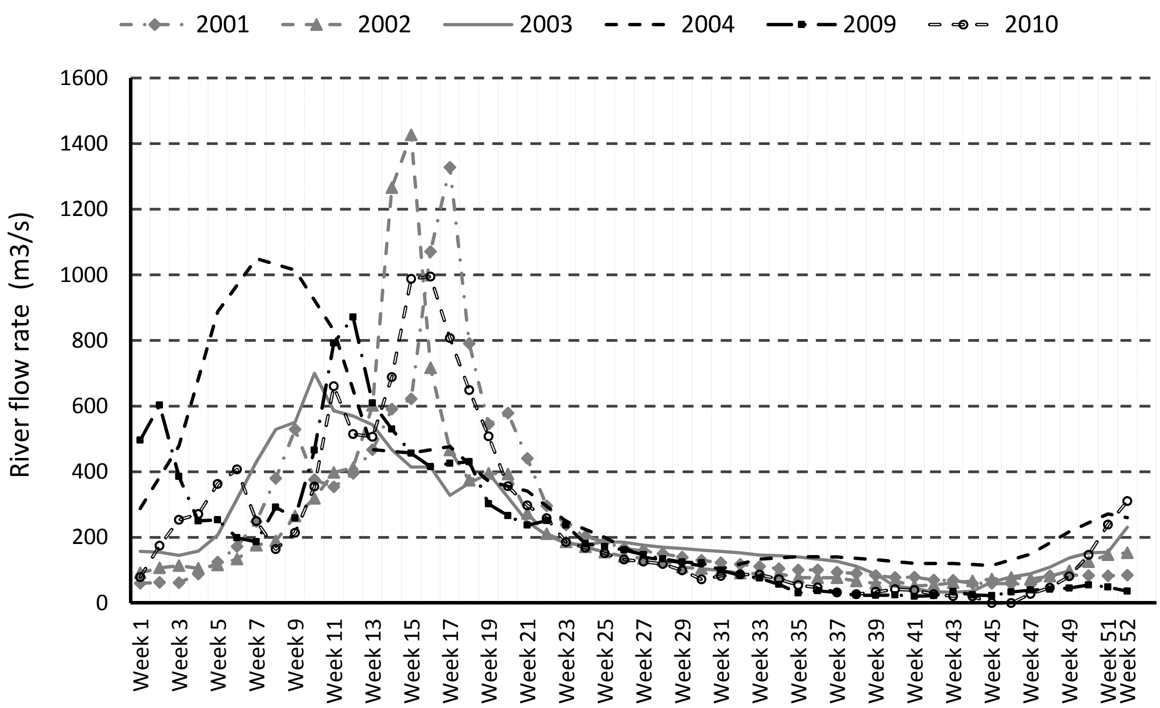

Figure 9: River flow rate in years before and after DPS installation (Extracted from SCAD Archives, Ruacana Power Station)

From Figure 9 it is noticed that the peak and average flow rate in 2009 and 2010 was lower than the peak and average flow rates recorded in 2001 and 2002 respectively However, the UAR value that was calculated from the energy generated versus the units' energy capacity increased from 2004 onwards.

In light of the above findings, it can be argued that there has been an increase in the performance levels in terms of the unit's availability to produce the required energy over the years following the installation of the power station automated monitoring system.

CONCLUSIONS

Industry awareness on the existence of DPS system and their usage

The findings show that most industries make use of maintenance methodologies and systems such as condition monitoring, non-destructive testing and equipment or structural health monitoring systems which are part of the damage prognosis process. These systems are used to varying extent of usage as discussed in the previous section. Adoption of condition monitoring for instance has resulted in many industries, especially in the mining, energy generation and petro-chemical fraternity, indicating extensive usage of preventive maintenance as well as predictive maintenance strategies.

Furthermore, one of the components of a DP process is a data base that is able to archive and retrieve maintenance records on equipment. To this end, the research revealed that various field devices were installed in many industries to retrieve operating data and this information was being stored. What is concerning however is that most of this archived data is not used by maintenance managers in order to make decisions in refurbishing or replacing old equipment. Since the true behaviour of equipment is only determined once that equipment is commissioned and in service, capturing of process parameters as well as keeping records of the maintenance activities is crucial for a functional DP process. The results of this study show positive findings as far as application of on-line measurements and the use of an automatic maintenance activity scheduler is concerned.

However, it was interesting to note that even though the majority of respondents indicated knowledge and to a greater extent application of CM, PM, PdM and SHM systems, many were not aware of what the DP process is, with approximately two-thirds confirming not knowing what this process was about.

Improved plant performance levels

Regarding plant performance, a study on the Ruacana Power Station where CM, PM as well as PdM systems were implemented showed an increase in unit availability and increased production levels. This indicates how effective maintenance can bring about economic benefits to the business enterprise. Downtime, whether planned or unplanned, is unproductive time (Campbell and Reyes-Picknell, 2006). Downtime can be minimised by doing the right maintenance at the right time and this paper demonstrates how doing the right maintenance, through establishment of correct maintenance strategies, can improve productivity and therefore overall performance.

Recommendations and future research

Although there is extensive usage of some of the systems that make up a DP process, many participants indicated that they are not aware of what a DP process entails. Some of the respondents mentioned that a DP process could be very expensive and may not be justifiable for most industries. As such it is recommended that a study needs to be done to determine what resources (funds, material, assets, labour and time) are required to implement a DP process within a plant or facility. Industries such as mining can for instance adopt the DP process in their capital intensive mining vehicles. Other industries or equipment such as turbines, large power motors to mention just a few, can also determine whether adopting a DP process is justifiable. This will entail looking at the cost required to implement the DP process and weighting such a cost (investment) against the benefits that it brings. Good asset management "supports the realisation of value while balancing financial, environmental and social costs, risk, quality of service and performance related to assets" (ISO 55000, 2014).

ACKNOWLEDGEMENT

The authors wish to thank the Department of Engineering Management for administrative and financial support for this project.

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