DEVELOPMENT OF A CONDITION BASED MAINTENANCE SYSTEM FOR A SUGAR PRODUCING COMPANY

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ABSTRACT

With globalisation taking centre stage in almost every market; traditionally monopolistic manufacturing companies in Zimbabwe are struggling to compete with international companies whose operations are optimised. This paper focuses on maintenance practises of a Zimbabwean sugar manufacturer with an aim to improve the company's asset care plans. The company's current maintenance philosophy and its shortcomings on certain equipment in the plant were identified together with the associated annual maintenance costs. A Pareto analysis on the equipment's breakdown history was used to determine the conditions that can be monitored using Condition Based Maintenance (CBM); and experiments to establish the feasibility of monitoring these conditions were done. The paper then recommends and proposes a CBM system replete with its three main elements of data acquisition, data processing and maintenance decision making to reduce breakdowns on the subject equipment by at most 76%.

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1   INTRODUCTION

The manufacturing sector's contribution to the Gross Domestic Product (GDP) of Zimbabwe fell to 12% from a previous 30% and its contribution to exports dropped significantly by 24% to 26% in 2012 [1]. These figures indicate a huge threat to the continued existence of the manufacturing industry. The sugar industry of Zimbabwe represents a subset of the manufacturing sector that has been the latest victim of competition due to globalisation. Competition from international sugar producing companies has intensified; it has not only affected the international market of the local producers, but has also affected the local sales.

The pressure for optimising operations for this industry in order to at least regain the local market is very high. This study is a follow up on prior work that focused on the current maintenance plan being employed on a cane shredding unit by one of the sugar producing companies in Zimbabwe, with a view of optimisation. The initial study outlined the shortcomings of the current maintenance plan in cost terms and recommended that condition based maintenance (CBM) be implemented on the equipment. The paper lays the ground work for the development of a CBM system. A Pareto analysis on the equipment's breakdown history was used to determine the conditions that can be monitored in a Condition Based Maintenance (CBM) system. Experiments to establish the feasibility of monitoring these conditions were done. A CBM system was proposed using the results from experiments and a cost benefit analysis of the company's customary time based and corrective maintenance to the proposed CBM system on the subject equipment was used to show a probable significant reduction in annual maintenance costs should the CBM be implemented.

2   CONDITION BASED MAINTENANCE

Condition based maintenance is a type of maintenance policy that considers the current real state of system degradation [2, 3, 4, 5]. Jardine et al. [6] describe CBM as a maintenance program that recommends maintenance actions based on the information collected through condition monitoring. CBM recommends maintenance actions based on the information collected through condition monitoring and attempts to avoid unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behaviours of a physical asset [7].

2.1   CBM underlying principle

CBM predicts a failure in equipment and optimizes its policy by monitoring the equipment's age and health condition [8]. De Carlo and Arleo [2] indicated that there are many measurable health degradation parameters that can be properly monitored and that different monitoring techniques allow keeping under control the operating parameters that are the most significant for the system degradation, in order to identify the most appropriate time for the execution of maintenance activities dynamically. According to Bengtsson [7] and Mobley [9], condition based maintenance serves the following two functions:

- to determine if a problem exists in the monitored item, how serious it is, and how long the item can be run before failure, and

- To detect and identify specific components in the items that are degrading and diagnose the problem.

Inspection can involve the use of human senses (noise, visual, e.t.c.), monitoring techniques or function techniques [4].

2.2   Condition monitoring

Borresen [10] defines condition monitoring as a technique that uses equipment to monitor other equipment and can be viewed as a highly sensitive version of human senses. Bengtsson, [7] considers condition monitoring as a central part of condition based maintenance and defines it as an activity - performed either manually or automatically - intended to observe the actual state of an item; and is normally performed in an operating state of the item. The purposes of condition monitoring are to collect equipment condition data thus detecting incipient failure so that maintenance tasks can be planned at a proper time and to increase the knowledge of failure cause and effect and deterioration pattern.

2.3   Techniques for condition based maintenance

There are quite a number of monitoring techniques that can be used to measure equipment condition. These techniques are classified according to the symptoms they are designed to detect [7, 10, 11, 12]:

- **Dynamic monitoring** - monitoring condition such as such as vibration and sound. Amplitude sensors are used for the lower range frequencies, velocity sensors are used for middle range frequencies while accelerometers are used for high frequencies.

- **Temperature monitoring** – monitors temperature rises in the equipment. Measurements are done through thermocouples and / or resistance temperature detectors.

- **Chemical monitoring** – monitoring chemicals released into the environment. Detects elements in fluids, usually lubrication oil. Chemical monitoring can detect wear, leaks and corrosion

- **Particle monitoring** - monitoring particles released into the environment. This type of monitoring will be able to detect wear, fatigue, corrosion and contaminants

- **Physical monitoring** – monitors physical effects, such as cracks, fractures, wear, and deformation.

- **Electrical monitoring** – monitors electrical effects, such as resistance, conductivity, dielectric strength, and equipment used etc.

- **Human inspection** – this is the most basic monitoring technique and is based on human senses

2.4   Setting limits in condition monitoring

Limits for conditions being monitored are set by the equipment user, with guidance from the original equipment manufacturer. Numerous standards also exist to guide on limits for condition monitoring – for instance vibration monitoring and analysis has two ISO standards namely [13]:

i.   **ISO/10816 series** – the series consist of six (6) parts on: mechanical vibration – evaluation of machine vibration by measurements on non-rotating parts

ii. **ISO/7919 series** – the series consists of five (5) parts on: mechanical vibration of non reciprocating machines

Where there are no standards or information from the original equipment manufacturer, experiments can be used to determine the limits for condition monitoring.

3   THE CBM SYSTEM

Bengtsson [14] defines a CBM system as an arrangement that uses condition based maintenance to determine and schedule predictive maintenance actions autonomously or in interaction with other systems or humans. Chalwa and Kumar [15], Romesis and Li [3], Zhu

et al [16]and Jardine et al[6] summarize a condition based maintenance system as consisting of three main steps namely data acquisition, data processing and maintenance decision making.

3.1 Benefits of CBM

In their case study for gas turbine plants, Romesis and Li [3]estimated savings of 1–3% of operating costs, due to efficient condition monitoring and CBM; which resulted in an overall cost reduction of up to $1 million per annum. The benefits extended beyond cost-efficient plant operation to increased safety, asset reliability and availability. Based on a case study on HVAC system by De Carlo and Arleo [2], corrective maintenance (CM) was found to be the type with the highest cost because of the times and costs due to unscheduled stops. When Planned maintenance (PM) was a potential choice, it was found important to identify the best PM interval time; otherwise there would be a risk of choosing wrong time intervals for the maintenance activities; which would lead to PM being even worse than CM in terms of costs [2]. De Carlo and Arleo [2]further showed that CBM is associated with the lower average unit cost compared to PM and CM. Chalwa and Kumar [15] reckon that if CBM is properly established and implemented, it can significantly reduce maintenance cost by reducing the number of unnecessary scheduled preventive maintenance operations.

Case studies of the application of CBM resulted in the following benefits to institutions:

- **Reduced maintenance costs** – De Carlo and Arleo [2]give a reduction of between 29 – 75% compared to planned maintenance; Bengtsson [7]gives the reduction as 25 - 30%; Taylor [17]gives the reduction as 7 – 60% compared to planned maintenance;

- **Reduction in production losses** – Bengtsson [7] gives a reduction of 20-25%; Besnard [4]gives a reduction of 50% for wind turbines; Taylor [17]gives an increase in production by 2 - 40% compared to planned maintenance; Romesis and Li [3]give a reduction in production costs of between 1 -3 % for gas turbine plants; Telford et al [18]gives an additional production benefits in the range of 5% for oil and gas industry

- **Breakdown elimination** – Bengtsson [7]gives it as 70 - 75%; Taylor [17] gives it as 33 - 45% compared to planned maintenance;

- **Increase in return on investment** – Taylor [17]gives it as 4 – 30 times compared to planned maintenance; Bengtsson [7] mentions that CBM maximises return on investment

4   CHOOSING THE BEST MAINTENANCE PHILOSOPHY – THE METHOD

Despite the apparent benefits and advantages of CBM compared to other maintenance types as outlined by most authors, the decision to adopt CBM should be based on real cost comparison between CBM and its competing maintenance types. In his thesis, Borresen [10] used a Cost-Benefit Analysis to compare costs of maintenance when using either corrective maintenance, planned maintenance or condition based maintenance.

4.1   Cost Benefit Analysis (CBA)

A cost benefit analysis is done to weigh whether a planned action is profitable or not [10]. A CBA is a conceptual framework for the evaluation of an item which tries to consider all gains and losses from for the item; and it expresses costs and benefits in the common metric of today's money [19]. Costs are subtracted from benefits to obtain the net benefits of the policy, if the net benefits are negative; they are referred to as net costs [20]. The following is the formula for calculating net benefits;

$$Net\ Benefits\ =\ Total\ Benefits\ –\ Total\ Cost \qquad (1)$$

5   CASE STUDY

A feasibility study of implementing a condition based maintenance (CBM) system on certain equipment was done for a sugar factory of one of Zimbabwe's sugar producers. A cane shredder, which is an equipment/unit within the sugar production line of the company, was used in order to simplify the study.

5.1   Background

The CBM feasibility study was a follow up on prior work that focused on the current maintenance plan being employed on the same equipment and its shortcomings. The following were the findings from the initial work;

- Planned maintenance was being employed on the shredder and had cost US$14,676,090 over a period of 4 years

- An equivalent of 13% ($1,932,787.35) of planned maintenance cost was further incurred on corrective maintenance on the same equipment during the same period

Due to these high cost figures of the current maintenance plan and the benefits of CBM in terms of costs reduction; it was recommended that CBM be adopted on the shredder with a view of maintenance optimisation.

5.2   Methodology

A Pareto analysis on the equipment breakdowns was used to determine the most significant breakdowns which would form basis for condition based maintenance. This determined the parameters that needed to be monitored in the CBM system. Experiments to determine the possibility of data acquisition using embedded sensors were carried out while the machine was running. An implementation matrix of the CBM system was developed using experimental results and this was followed by a cost benefit analysis of the CBM system against the existing hybrid of time based and corrective maintenance.

6   THE PARETO ANALYSIS ON SHREDDER BREAKDOWNS DOWNS

A Pareto analysis is a statistical tool in decision making that is used for the selection of a limited number of factors that produce significant overall effect [21]. The purpose of the shredder is to complete the preparation and disintegration of the cane, so as to facilitate the extraction of cane juice by the mills [22]. A total of 80.75 hours were recorded in the period under review. A Pareto analysis of the causes of breakdowns was used to determine the factors or causes that warranted the most attention and those factors which had a relatively smaller effect. The factors were classified into seven major categories according to the part or section on the equipment that is affected whenever the breakdown occurs on the shredder. The diagram below shows the Pareto analysis of the breakdowns;
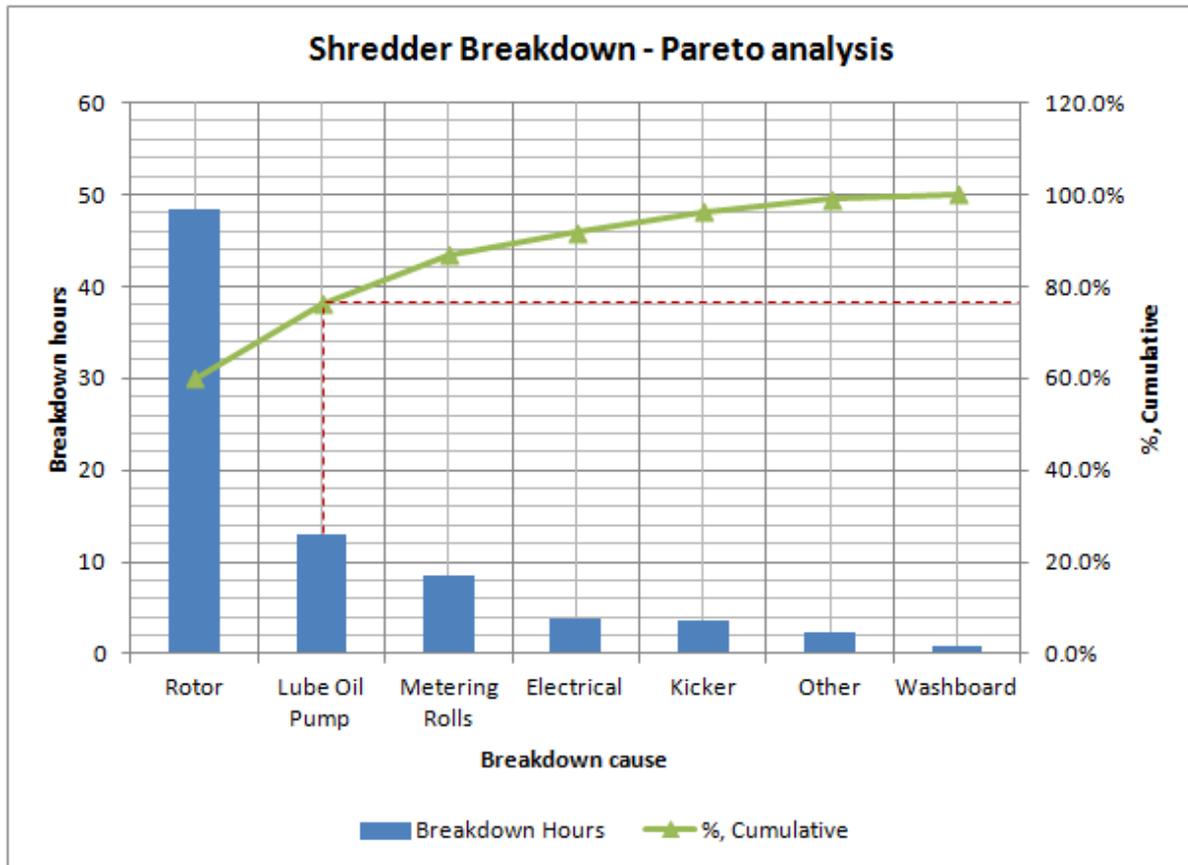
Figure 1: Pareto analysis of shredder breakdowns

6.1 The Pareto analysis summary

The analysis showed that the failures of the shredder rotor and lubrication oil pump accounted for 76% of the breakdowns. The results led to a recommendation to focus condition based maintenance on the two equipment on the shredding unit rather than on low incidence ones.

7 CONDITIONS TO BE MONITORED

The conditions to be used to monitor the rotor and the lube oil pump must be able to detect early forms of degradation or malfunction on the rotor and lubrication oil pump or oil circuit. As noted by Bengtsson [7], the purposes of condition monitoring are:

i.   To collect rotor and lubrication oil pump condition data thus detecting incipient failure so that maintenance tasks can be planned at a proper time.

ii.   To increase the knowledge of failure cause and effect and deterioration pattern.

7.1 Rotor bearing monitoring

To successfully monitor the behaviour of the shredder rotor, the performance of the bearing was considered. Six bearings were replaced during breakdown maintenance in the period under review. Monitoring of the bearing will most likely predict failure or stoppage linked to the rotor

7.1.1 Vibration monitoring for shredder rotor bearing

Vibration measures a rotating shaft's position relative to stationary components in order to guard against changes that would result in catastrophic contact [23]. Vibration is also considered by SKF [23] and Cibulka et al [24] as the best operating parameter to judge

dynamic conditions such as balance, bearing stability, and stress applied to components since many machinery problems manifests as vibration. Vibration monitoring on shredder bearing was thus chosen to monitor the behaviour of the rotor

7.1.2 Temperature monitoring for shredder rotor bearing

According to SKF [23], temperature measurement is a useful indicator of the mechanical condition of a specific component, such as a bearing. The temperature of a bearing will rise due to friction when it starts to fail. Temperature monitoring on shredder bearing was also chosen to monitor the performance of the rotor.

7.2 Lubrication oil circuit monitoring

In order to successfully monitor the behaviour of the lube pump, the oil circuit was considered. Monitoring the oil circuit will most likely predict failure or stoppage linked to the lube oil pump.

7.2.1 Pressure monitoring for lubrication oil circuit

Pressure monitoring of the lube oil circuit by trending the differential pressure across the supply will successfully monitor the lube pump and oil circuit functionality. Pressure monitoring of the oil circuit was chosen to monitor the performance of the lube oil pump.

8 EXPERIMENTS

Experiments were carried out to assess the feasibility of successfully monitoring vibration and temperature on the rotor bearing; and pressure on the lubrication oil circuit. The experiments were based on a temporary periodic monitoring exercise where measurements were taken for the three parameters (vibration, temperature and pressure) at regular time intervals. The overarching objectives of the three experiments were to:

- To determine the normal vibration level for cane shredder bearings
- To determine the normal operating temperature for cane shredder bearings Drive end (DE) and Non – Drive end (NDE)
- To determine the normal operating pressure for lube oil in the bearings of a cane shredder

Figures 2a-c below shows the graphical representation of the experiment results which are further summarised in Table 1. Figures 3 and 4 show the experiments being conducted. Results are for drive end (DE) and non drive end (NDE) rotor bearings and the lubrication oil circuit.
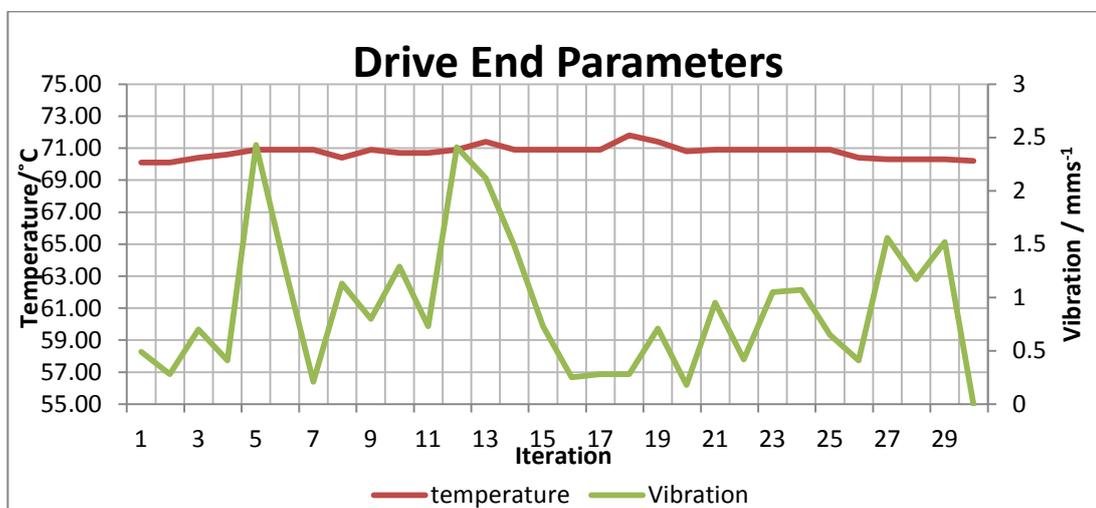

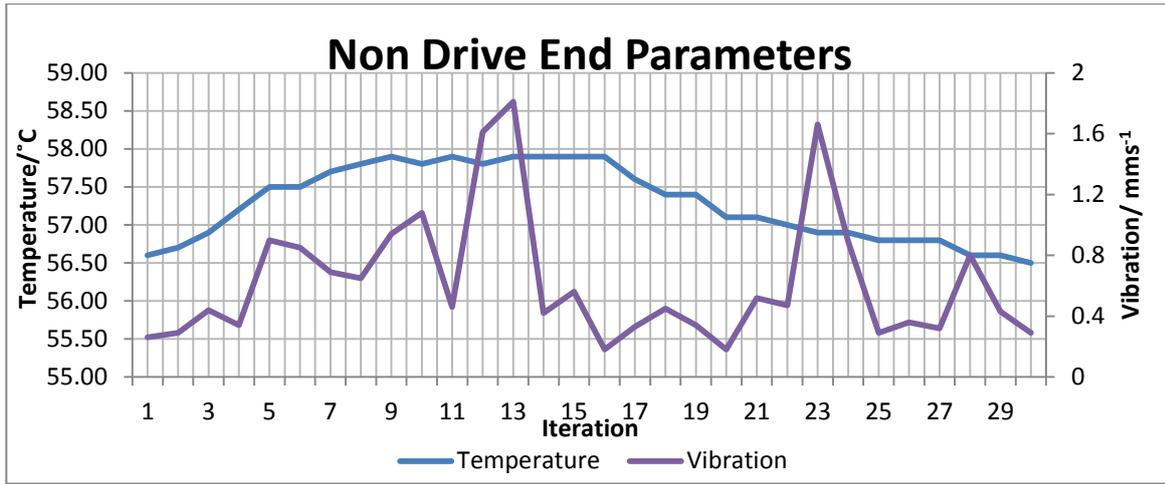**Figure 2a Drive Ends Parameters**

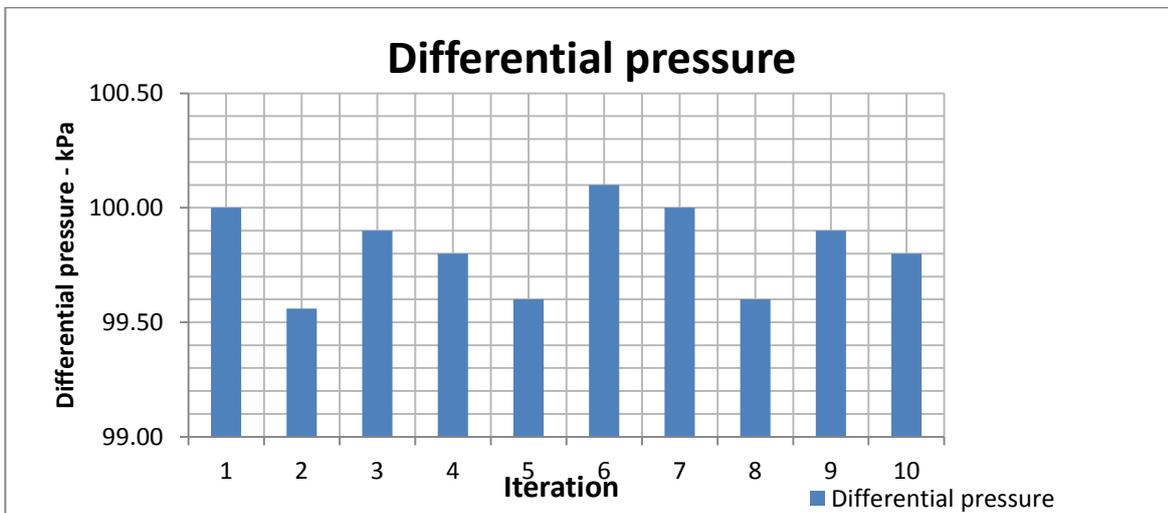Figure 2b Non Drive End Parameters

Figure 2c Differential Pressure

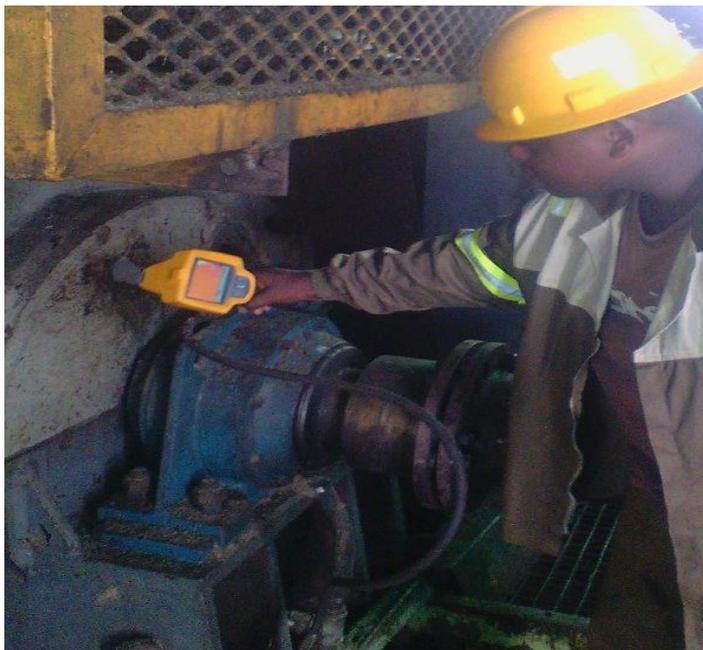Figure 3: Vibration Measurement Using a Handheld Meter

Figure 4: Temperature monitoring using a handheld meter

8.1 Discussion of Results

The normal operating levels for vibration, temperature and pressure for the machine were determined. These values were used for the generation up fuzzy rules for machine health diagnosis in the design stage of the study. Table 1 below is a summary of the three experiments which include apparatus used and the observed results.

Table 1: Experiments results

Experiment	Equipment used	Measurements / intervals	Results		DE	NDE
Vibration in mm/s	Handheld vibration meter (velocitometer)	30	Average		0.931	0.627
			Standard deviation		0.63	0.434
Temperature in °C	Handheld RTD meter (resistance temperature detector)	30	Average		70.75	57.28
			Standard deviation		0.39	0.49
Pressure in kPa gauge	0 -10 bar Differential pressure (DP) cells	10	Average		99.83	
			Standard deviation		0.189	

8.2 Time period for iterations

Temperature and vibration iterations were done over a time period of 15 hours, with thirty (30) minute intervals from 8am to 10pm inclusive on a single day. Pressure measurements were done over a period of 10 hours, with one (1) hour intervals from 8am to 5pm inclusive.

9 PROPOSED CBM SYSTEM

In identifying the major causes of breakdowns and doing experiments to assess feasibility of condition monitoring on the shredder; the ground work for developing a condition based maintenance system was done. The limits on bearing temperature and vibration and lube oil pressure are determined using manufacturer's catalogues, literature and experiments carried on the shredder. Appendix A with fuzzy rules deduced from experiments should be used as the reference in the design of the CBM architecture for the shredder.

9.1 CBM Modules communication

The concept used in designing the CBM system for the cane shredder will be based on the Open System Architecture (OSA-CBM) by the Information Management Open Standards Alliance [25]. Sensors acquire vibration, temperature and oil pressure data from the shredding unit then they pass the data on to the PLC which analyses it for ascertaining the condition of the shredder. Alarms and other diagnostic decisions will be displayed on the HMI. The shredder lubrication oil and bearings useful remaining life (RUL) can be predicted by algorithms programmed in Microsoft Access VBA.

The data acquisition module is linked to the PLC which does diagnosis. Communication between the PLC and the windows application is facilitated by a lean 7 OPC server. To introduce some flexibility, this system will be designed to be accessed online using custom defined web pages crafted using HTML. The inbuilt web server facilitates access of the CPU data on the web. The proposed condition based maintenance system architecture and link between modules is summarized in Figure 5.
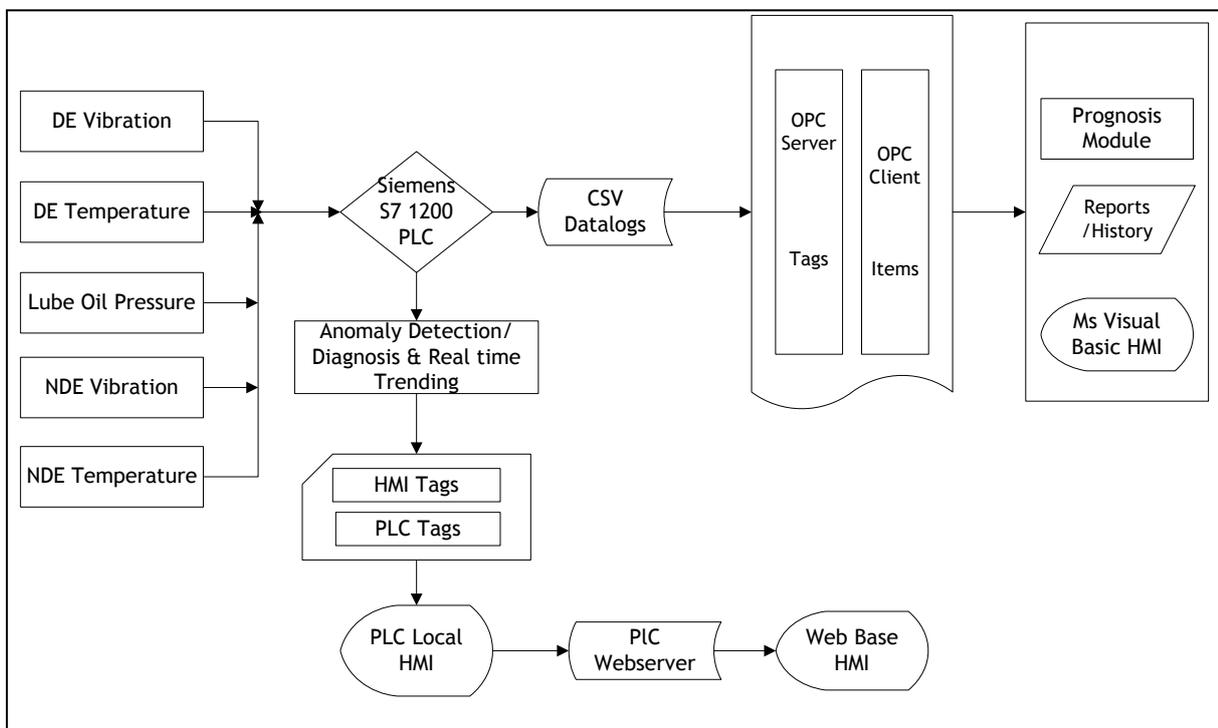

Figure 5: CBM System Architecture for a Cane Shredder

9.2 The anticipated benefits of the CBM system

The anticipated benefits of the proposed CBM system are the difference between the cost of setting up and running the system, to the potential savings realized by adopting the system. Since the CBM system will be in used on the shredder only, with the rest of the production line on planned maintenance; the cost of running the CBM system will be assumed to be equal to that of running the planned maintenance considering overheads such as labour, material and lost productivity due to planned maintenance downtime will still be incurred.

1. **Set up costs of the CBM system**
   Set up costs are those costs associated with purchase of equipment and hardware for the CBM system. Table 2 summarizes the setup costs for the proposed CBM system based on a quotation obtained from an instrumentation equipment supplier.

Table 2: CBM setup costs

Item	Cost in US$
Controller	768.98
Sensors	8,276.65
I/O modules	1,402.88
Total	**10,448.51**

2. **Potential saving – reduction in corrective maintenance costs**
   Given that the proposed CBM will be focusing on 76% of the equipment failures causing breakdowns (i.e. from Pareto analysis); it is assumed that at least half (38%) of the breakdowns will be predicted by the CBM system, thus also reducing corrective maintenance costs by 38%. This gives a reduction in corrective maintence cost over a four year period (CM_{CBM}) of;

$$CM_{CBM} = 38\% \; of \; \$1,932,787.35$$

$$\mathbf{CM_{CBM} = \$734,459.19}$$

9.3 The Net Present value

The net present value (NPV) of implementing CBM is given in table 3. A discount rate of 12.5% per annum reflecting the average lending interest rate charged by local banks in Zimbabwe was used in discounting the potential savings in the four years [26].

Table 3: Net Present Value of CBM implementation

Year	Net Cash flow	Discount factor	PV
0	(USD 10,448.51)	1	(USD 10,448.51)
3	USD 734,459.19	0.702	USD 515,834.16
Net Present Value			**USD505,385.65**

10 CONCLUSION

The study has identified the major causes of breakdowns on the shredder. A breakdown analysis was the basis for recommending the conditions to be monitored. It has also shown - through experiments - the operating levels of three parameters that had been recommended for condition monitoring (vibration, temperature and pressure). Alarm events that warn when defined values of vibration, temperature and pressure have been reached and trips that define thresholds beyond which operation may cause damage to equipment were proposed. The paper has further proposed the implementation of CBM system and summarised how it will work in order to optimize maintenance operations of the sugar producer. The Pareto analysis suggests that the proposed CBM system will be focussing on 76% of the equipment failures resulting in breakdowns. If the CBM system successfully predicts half (38%) of equipment failures, then USD505, 385.65 will likely be saved over a four year period.

Appendix A: Shredder fuzzy rules

SHREDDER STARTING FUZZY RULES	
Situation	**Fuzzy Set**
Oil pressure too low (Below 70kPa)	Prohibit Shredder Start
D.E or N.D.E bearing temperature above 100˚C	Prohibit Shredder Start

SHREDDER CONDITION DIAGNOSIS FUZZY RULES	
D.E Bearing Temperature	**Fuzzy Set**
73˚C	OK
74 - 89˚C	Low level Temperature Alarm
90 - 119˚C	High level Alarm (Shutdown in 10 minutes)
>120˚C	Critical Pressure (Horn + System shutdown)
N.D.E Bearing Temperature	**Fuzzy Set**
59˚C	OK
60 - 89˚C	Low level Temperature Alarm
90 - 119˚C	High level Temperature Alarm (Shutdown in 10 minutes)
>120˚C	Critical Temperature (Horn + System shutdown)
D.E and N.D.E Vibration	**Fuzzy Set**
<1.8 mm/s	OK
1.9 – 4.5 mm/s	Low level Vibration Alarm
4.5 – 8.4 mm/s	High level Vibration Alarm (Shutdown in 10 minutes)
>8.4mm/s	Critical Vibration (Horn + System shutdown)
Oil Pressure	**Fuzzy Set**
98 - 105kPa	OK
81 – 97kPa	Low level Lube Alarm
71 – 80kPa	High level Lube Alarm (Shutdown in 10 minutes)
<70kPa	Critical Pressure (Horn + System shutdown)

SHREDDER FAULT CLASSIFICATION	
Condition	**Fault Class**
D.E and N.D.E vertical, axial and horizontal vibration below 1mm/s	Shredder OK
D.E or N.D.E Excessive Vertical Vibration ≥ D.E or N.D.E Excessive Horizontal Vibration	Rotor Imbalance
D.E or N.D.E Excessive Axial Vibration > D.E or N.D.E Excessive Horizontal Vibration,	Coupling Misalignment
D.E or N.D.E Excessive Horizontal Vibration > D.E or N.D.E Excessive Axial Vibration	Looseness
If oil lube oil pressure is less than 90kPa	Lube oil system faulty

If D.E and N.D.E temperatures are both above 75˚C and 60˚C respectively	Lube oil system faulty
If D.E or N.D.E temperatures is above 75˚C and 60˚C respectively while lube pressure is above 90kPa	Excessive Vibration Wear

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