Improvement of process machinery availability and reliability: A case study of the production line in a sugar processing plant.

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Abstract

Process based industry firms, work with high capital investments and large expenses for downtime, availability and reliability. This in turn puts pressure on the maintenance function and causes the need for advanced maintenance technology and practice (Arts et al., 1998; Ketokivi and Jokinen, 2006; Tan and Kramer, 1997). The performance and competitiveness of these industries is dependent on the reliability, availability and productivity of their production facilities and yet many of these companies still struggle to provide applicable and effective maintenance to their production facilities.

To understand why, this research study conducted an empirical study of the state of an existing maintenance management system of a sugar production facility in order to identify the contextual plant maintenance issues that affected its production line availability (downtime) and reliability. The results of the study were namely, identification of critical or maintenance significance machinery, selection of the appropriate maintenance strategies and concepts, and determination of an optimal schedule of maintenance activities for the subsystems of the production line. The results also highlighted the need to investigate issues such as, poor or incorrect downtime data, maintenance staff not well trained, logistic and administrative delays, all or combination of which could be the reason for the unreliable downtime duration of maintenance tasks.

This research study demonstrated the use of quantitative approaches in a case study methodology to support maintenance management decisions in industry.

Keywords: Reliability, Maintainability, Availability, Maintenance Management, Decision Mapping Grid (DMG).

INTRODUCTION

Many critical assets in the operations of process industries such as manufacturing and mining operations lack cost effective maintenance and operation strategies and practices to meet their production demands and the required level of service. The question is, given the maintenance management information systems (MMIS) that manufacturing companies have in place, a few companies are able to utilise effectively the operations and maintenance data in their databases to support maintenance management decisions. Possible reason could be insufficient knowledge of the maintenance engineering techniques and/or lack of technological capabilities for data management, processing and analysis. The aim of this research study is to illustrate the application of maintenance and reliability analysis techniques in the improvement of process machinery reliability and availability.

LITERATURE REVIEW

Maintenance strategies

The growing importance of maintenance has generated an increasing interest in the development and implementation of optimal maintenance strategies for improving system reliability, preventing the occurrence of system failures, and reducing maintenance costs of deteriorating systems. Maintenance defined as a combination of all technical and associated administrative activities required to keep equipment, installations and other physical assets in the desired operating condition or restore them to this condition (BSI, 1984; Pintelon et al., 1997; Pintelon and VanPuyvelde, 2006).

According to Duffuaa, Ben-Daya, Al-Sultan, and Andijani, (2001), maintenance strategies fall into the broad classifications defined as Corrective Maintenance (CM) and Preventive Maintenance (PM) strategies.

Corrective maintenance (CM) also known as run-to-failure or reactive maintenance, is a strategy that is used to restore (repair or replace) the function of an asset after a failure has occurred. This strategy leads to high levels of machine downtime (production loss) and maintenance (repair or replacement) costs due to sudden failure (Tsang, 1995). Asset managers adopt a preventive maintenance (PM) approach to avoid the problems associated with CM, in order to eliminate waste and reduce asset life cycle costs.

The preventive maintenance (PM) strategy requires the performance of maintenance activities prior to the failure of equipment (Gertsbakh, 1997; Lofsten, 1999). This strategy contributes to minimising failure costs and machine downtime (production loss), and increasing product quality (Usher, Kamal, and Syed, 1998). In industry, application of the PM strategy is either through experience or on recommendations of original equipment manufacturer (OEM), and based on a scientific approach. Moreover, according to Tam, Chan, and Price (2006), PM intervals based on OEM recommendations may not be optimal because actual operating conditions may be very different from those considered by the OEM.

The scientific approach involves specific processes and principles that make use of various analytical techniques, such as statistics, mathematical programming, artificial intelligence, etc. The main advantage of PM based on scientific approach, is that decision-making depends on facts obtained through real data analysis. In the literature, they classify PM based on scientific approach, into two techniques that is the comprehensive-based and specific-based techniques.

The comprehensive-based technique also known as maintenance concept development is defined as a set of various maintenance interventions (experience-based, time-based, condition-based, etc.) and the general structure in which these interventions are foreseen (Pintelon & Waeyenbergh, 2002). Furthermore, according to the authors, a maintenance concept forms the frameworks from which maintenance strategies are developed and is an embodiment of the way a company thinks about the role of maintenance as an operation function. Some of the common maintenance concepts found in the literature are; reliability centred maintenance (RCM), total productive maintenance (TPM), business centred maintenance (BCM), terotechnology, capital asset management, integrated logistics support (ILS) and life cycle cost/profit (LCC/LCP). On the other hand, the specific-based technique, as its name implies, is a specific maintenance technique that has unique principles for solving maintenance problems. Examples of specific-based techniques are time-based maintenance (TBM) and condition-based maintenance (CBM).

This study investigated the effectiveness of the existing time-based maintenance policy on the reliability and availability of a sugar production line through the statistical analysis/modelling of its historical in-house maintenance data.

Maintenance performance measurement

Performance measurement is an important instrument of maintenance management and a powerful methodology, which allows engineers and managers to plan, monitor and control their operations. According to Parida and Kumar (2006), maintenance performance measurement enables companies to understand the value created by maintenance, to re-evaluate and revise their maintenance policies and techniques, justify investment in new trends and techniques, revise resource allocations, and to understand the effects of maintenance on other functions and stakeholders as well as on health and safety. Literature on maintenance performance shows that different authors have different ways of classifying maintenance measures or indicators. Nevertheless, some indicators and categories of indicators generally recognised by all authors as indispensable in the management of the maintenance function are;

- Measures of equipment performance (in terms of number/frequency of breakdowns, MTBF, availability and OEE),
- Maintenance cost related measures, such as labour and material costs of maintenance, and
- Measures of maintenance efforts, such as ratio of planned and unplanned work, schedule compliance, described in different ways by authors e.g. maintenance productivity and operational purposefulness (Coetzee 1997), maintenance efforts (Campbell 1995), maintenance work management (Weber and Thomas 2006).

Maintenance data management

The success of any measurement system depends on the quality of data collected. Poor or incorrect maintenance data entered into a reporting system affects a company’s ability to accurately, track equipment in such engineering terms as mean time between failures (MTBF) or mean time to repair (MTTR) etc. The following are some of issues of maintenance data management that affect its quality:

- Inaccurate or unreliable operations/maintenance data sources/records
- Inexistence of a proper computerised maintenance management system
- Lack of competences to properly handle operations/maintenance data
- Minimal knowledge in advanced maintenance data processing/analysis techniques

Maintenance information management and decision support systems

Computerised maintenance management systems (CMMS) provide capabilities to store, retrieve and analyse information, and can bring about an effective and efficient management of maintenance information (Dunn, 1996; Coopers & Lybrand, 2001; Ingalls, 2000).

In modern production plants, the number of items to maintain is high and the complexity of the plants is high, which therefore renders the need for the implementation of a computerised maintenance management system considerably much more significant.

The system enables managers, planners, and production and maintenance personnel to have access to all equipment data. It would also transform this data into information used to prioritise actions, and to take superior decisions. CMMS applications provide functionality, normally grouped into modules for specific activity sets. Cato and Mobley (Computer-managed maintenance systems, 2nd ed., Boston, USA: Butterworth Heinemann; 2002.) lists some of these activities which include but are not limited to:

- equipment/asset records creation and maintenance;
- equipment/asset bill of materials creation and maintenance;
- equipment/asset and work order history;
- inventory control;
- work order creation, scheduling, execution and completion;
- PM plan development and scheduling;
- human resources;
- purchasing and receiving;
- invoices matching and accounts payable; and
- Tables and reports.

Maintenance engineering techniques

These involve the use of quantitative and/or qualitative techniques, data processing and analysis techniques to support maintenance management decisions such as the:

- RCM framework that helps design and define maintenance plans that ensure the desired equipment reliability,
- TPM concept, which focuses on organisational efforts at the operational level to improve overall equipment effectiveness,
- Quantitative tools that can be used to optimise maintenance management policies,
- Stochastic tools that model failures, allowing for a further use of quantitative techniques and
- Other techniques that focus on optimising maintenance resources management etc.

Reliability, Maintainability and Availability (RAM)

Plant availability is a function of the reliability and maintainability characteristics of a plant. **Availability** is defined as the ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of a time or over a stated period of time (Rausandan and Hϕland, 2004). Achieving a high level of availability is important to plant operations and profitable for the manufacturing industry. According to Ireson (1996), the three frequently used plant availability measures are: operational, achieved and inherent availability and explained below as follows:

- For a plant, operational availability, as seen by the user, is the most realistic of the three. It reflects system availability, including unplanned and planned maintenance time and time lost to operational logistics and administration, defined as;

  Operational availability, $A_o = \frac{MTBM}{MTBM + MDT}$

  Where *MTBM* is mean time between corrective and preventive maintenance actions and *MDT* is mean downtime.

- Achieved availability, as seen by the maintenance department, reflects availability, including unplanned and planned maintenance time defined as;

  *Achieved availa*bility, $A_a = \frac{MTBM}{MTBM + MAMT}$

  Where *MAMT* is the mean active maintenance time

- Inherent availability, as seen by the maintenance personnel, measures the availability to be expected when only taking into account unscheduled (corrective) maintenance time and is defined as;

  Inherent availability, $A_i = \frac{MTBF}{MTBF + MTTR}$

Where *MTBF* is the mean time between failure and *MTTR* is the mean time to repair.

Reliability is the ability of an item to perform a required function, under given environmental and operational conditions and for stated period of time (BS4778, 1991).

R (t) = 1 – F (t)

Where R (t) is the reliability function evaluated at time t in hours and F (t) is the cumulative failure distribution function.

Reliability is concerned with the probability and frequency of failures (or more correctly, the lack of failures). For **repairable systems**, a commonly used measure of reliability is the mean time between failures (MTBF), and the equivalent measure for **non-repairable systems** is the mean time to failure (MTTF). Reliability more accurately expressed as a probability of success over a given duration of time, cycles, etc.

Maintainability is a measure of how to effectively and economically prevent failures through preventive maintenance, and how quickly system operation following a failure, can be restored through corrective maintenance. Personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair, should perform maintenance. There are several measures of maintainability, but the most commonly used measure in terms of corrective maintenance is the mean time to repair (MTTR). In addition other measures such as the median time to repair, the mode, or most likely repair time, the time in which a specified percentage of the failures must be repaired, the mean repair time plus the mean preventive maintenance downtime, and the number of maintenance hours per operating hours. The last measure quantifies the total maintenance workload, whereas the rest focus strictly on downtime. Maintainability is not the same as maintenance, it is a design parameter (i.e. a function of design features, such as access, interchangeability, standardisation, and modularity), while maintenance consists of actions to correct or prevent failure.

The most frequently used characteristics of the duration of a maintenance task (Knezevic, 1993) are:

- Maintainability function;
- Percent duration of maintenance task; and
- Expected or mean duration of maintenance task.

The maintainability function denoted as M (t), represents the probability that the maintenance task considered, will be successfully complete before or at the specified moment of maintenance elapsed time t.

The maintainability measure denoted as F (t) represents the duration of maintenance task by which a given percentage of maintenance tasks considered successfully completed.

The most frequently used value for the maintainability measure is TTR_{90}, which represents the duration of restoration time by which 90% of all executions of the maintenance task considered are complete.

The expected duration of maintenance task also known as mean time to repair (denoted as MTTR), is the mean time required to carry out repair work on assumption that spare parts and skilled personnel are available.

Some important factors for maintainability are:

- Design and use of equipment should be such that failure is immediately noticed and quickly localised;
- Easy accessibility of vulnerable components;
- Maintenance personnel should be competent, well trained and have necessary tools and test equipment;
- Access to adequate spare parts.

Reliability and maintainability analysis methodology

To analyse effectively the operations and maintenance data of a sugar production line, two approaches considered, were namely:

- *The basic maintenance approach***,** which utilises graphical methods to analyse failure trends in equipment. Even in situations of limited data, such as absence of machine operating hours, this type of analysis can still provide indications of excessive repair times or repair frequency (Runciman et al., 1995). Other parameters such as Availability, Mean Time between Failures (MTBF) and Mean Time to Repair (MTTR) can be determined.
- *A reliability based maintenance approach***,** which is a more rigorous procedure using graphical and statistical methodology to fit theoretical probability distributions to the collected maintenance data for prediction of future failure trends.

For the reliability *modelling of repairable systems*, the basic methodology presented below in Figure 2.3. The figure shows a detailed flowchart for the model identification and is used here as a framework for the analysis of failure data (TBF) and repair data (TTR) of a sugar production line equipment.

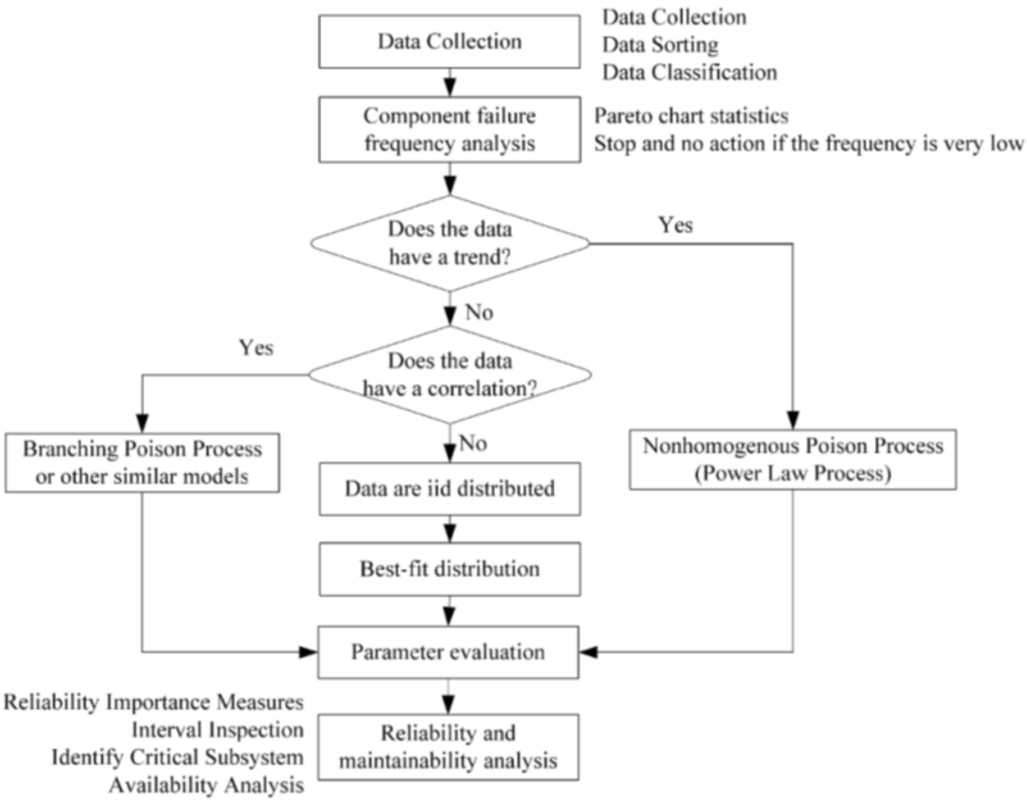

Figure 1: Reliability analysis process of a repairable system

Source: J. Barabady, U. Kumar/Reliability Engineering and System Safety 93 (2008) 647 - 653

Reliability and maintainability analysis techniques

Basic maintenance and reliability analysis techniques involve the use of graphical, analytical and statistical techniques to conduct maintenance analysis as follows:

The basic maintenance analysis approach **i**s a graphical based approach, and provides an effective way to display and analyse data, and is used to evaluate parameters such as; failure frequency, total number of repairs, downtime or repair hours, total downtime or repair time, and availability. The approach is broken down into four general steps as follows:

- Determine the number of breakdowns (failures) of subsystems within each unit of the sugar production line
- Determine the total breakdown duration (downtime) of each subsystem and the total operating time of each subsystem.
- Create graphs which assess failure trends of equipment
- Estimate the mechanical availability of equipment

The reliability based maintenance analysis approach is a probabilistic approach that utilises statistical methods to fit theoretical probability distributions to failure data. The identified probability distribution model used to predict the failure behaviour of components or equipment and to calculate the reliability.

For the reliability based maintenance analysis, the steps followed are as follows:

- Determine the time between failures (TBF), and time to repair (TTR) for each subsystem.
- Verify the assumption of independent and identically distributed (IID) failure data, using the following two common graphical methods;
    - *A trend test* involving the plot of cumulative time between failures or time to repair versus the cumulative failure numbers. Moreover, if the trend test shows a straight line, then the data is trend free, and therefore the first criterion for IID data will be satisfied. A convex or concave curve will indicate a system with a decreasing (improving) or increasing (deteriorating) failure rate respectively.
    - *A serial correlation test*, which is a graphical plot of the i^{th} TBF or TTR against $(i - 1)^{th}$ TBF or TTR, and if the data appears to be randomly scattered with no evident patterns, then it is said to have no serial correlation.
- If both tests indicate no trend and no serial correlation, then the TBF and TTR data is independent and identically distributed (IID), and can be fitted to a theoretical probability distribution,
- If trends and serial correlations exist in the data, then non-parametric models are applied e.g. the non-homogeneous Poisson model indicated in the figure 1 above
- Assess the goodness-of-fit of a theoretical probability distribution to the data. A goodness-of-fit test indicates whether it is reasonable to assume that a random variable comes from a specific distribution. Goodness-of-Fit tests include (Donadio et al., 2006):
    - Chi-square test: for continuous and discrete distributions
    - Barlett's test: a specific test for fitting exponential distributions
    - Mann's test: a specific test for the Weibull failure distributions

- Kolmogorov-Smirnov test: for normal and lognormal distributions when estimated parameters are used. It compares the empirical cumulative distribution function with the normal cumulative distribution function
- Tests for the Power-Law Process Model, such as the Cramer-von Mises test; for symmetric and right-skewed distributions
- Anderson-Darling test: for any data set with any skewness (symmetric distributions, left or right skewed)
- R-square test

- Estimate the reliability of the identified critical subsystems, in each of the units, and then the entire sugar production line

Methodology

The methodology followed in the conduct of maintenance analysis in this case study, starts from the basic study of failure trends in equipment to a reliability-based evaluation and this required the:

- understanding of the sugar production line system and the identification and coding of the subsystems and the faults therein,
- collection, sorting and classification of the time between failure (TBF) and time to repair (TTR) data for each subsystem and fault, and
- data analysis which involves:

  Conducting a *basic maintenance analysis* based on equipment failure and downtime data analysis criteria that involves,

  – Pareto analysis of downtime and frequency of failure to identify critical machinery in the production process, and

  – Mapping the identified critical machinery to a decision mapping grid (DMG) to select appropriate maintenance strategies and concepts (RCM or TPM) based on frequency of failure and downtime duration criteria,

Furthermore, a *reliability-based evaluation* requires failure and repair data of the sugar production line equipment to be organised in a format that supports a reliability study. The objective of reliability and maintainability (R&M) analysis of critical machinery is to improve availability and thus reduce downtime. The analysis uses downtime and maintainability measures to analyse the maintenance and logistic support system of the sugar factory in relation to maintenance policy, inspection intervals and availability prediction

To determine the operating characteristics and failure trend patterns of the sugar production line equipment, a classification system assigned to it, is as shown in the **Table 1** below.

Table 1: Classification system for the sugar production line

Production Line System Processes	Machinery or Subsystems	Codes
Cane Handling, Feeding and Conveying	Cane Handling, Feeding and Conveying	CHFCS
Cane Preparation	Cane Preparation Cutter Knives	CPCKS
	Cane Preparation Shredder	CPSS
Cane Juice Extraction	Cane Juice Extraction Diffuser Cane Juice Extraction Mills	CJEDS CJEMS
Bagasse Handling and Conveying	Bagasse Conveying	BCS

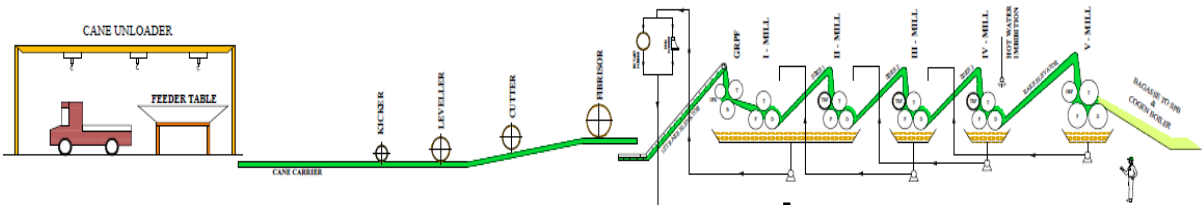

Figure 2: Sugar Cane Production Line Process Flow Diagram (Front End)

Source: http://www.ponnisugars.com/attachments/pfd.pdf;

RESULTS

In this study, in-house plant maintenance data collected for the four year period (2010 – 2013) was considered, sorted and classified in the form required to perform the:

- Basic maintenance analysis; and
- Reliability-based analysis (CM Events Frequency; TBCM Events or TBF; CM Downtime or TTR; Cumulative TBCM Events; Cumulative CM Downtime).

CM = Corrective Maintenance, TBCM = Time between Corrective Maintenance.
The data is categorised for the six subsystems described in Table 3.1 above.

Basic maintenance analysis

For the basic maintenance analysis, corrective maintenance downtime data statistics for the six categorised subsystems over the four-year period (2010 – 2013) presented in excel spreadsheets.

Pareto Analysis

Identification of the worst or critical machines of the production line based on both downtime and breakdown frequency criteria:

- **Downtime** considered low if less than 15 hours, high if more than 30 hours and medium if between 16 – 29 hours.
- **Frequency** is low if less than 20, high if more than 50 and medium if in the range of 21 – 49.

Decision rules

The next step is to place the identified critical or worst machines in the decision-making grid shown in Figures 3 and 4 below in order to determine the appropriate maintenance decisions for them. The identified critical machinery or subassemblies in terms of downtime and frequency in each of the six subsystems of the production line (highlighted in red) are categorised in order of criticality as follows:

- The *first most critical machinery or subassemblies* are found in the CPSS, CJEDS and CJEMS systems and require a reliability centred maintenance (RCM) approach in regard to the identified design out maintenance strategy (DOM) for these systems.

- The *second critical machinery or sub-assemblies* are found in the CPCKS, CJEDS, CJEMS and MCCA systems and require a total productive maintenance (TPM) approach in regard to the identified fixed time maintenance strategy (FTM) for these systems.

- The *third critical machinery or sub-assemblies* are found in the BCS and the CJEDS systems and require a reliability centred maintenance (RCM) approach in regard to the identified fixed time maintenance strategy (FTM) for these systems.

The CJEDS is the most maintenance significant equipment of the production line as it has critical machinery in all the three categories of criticality.

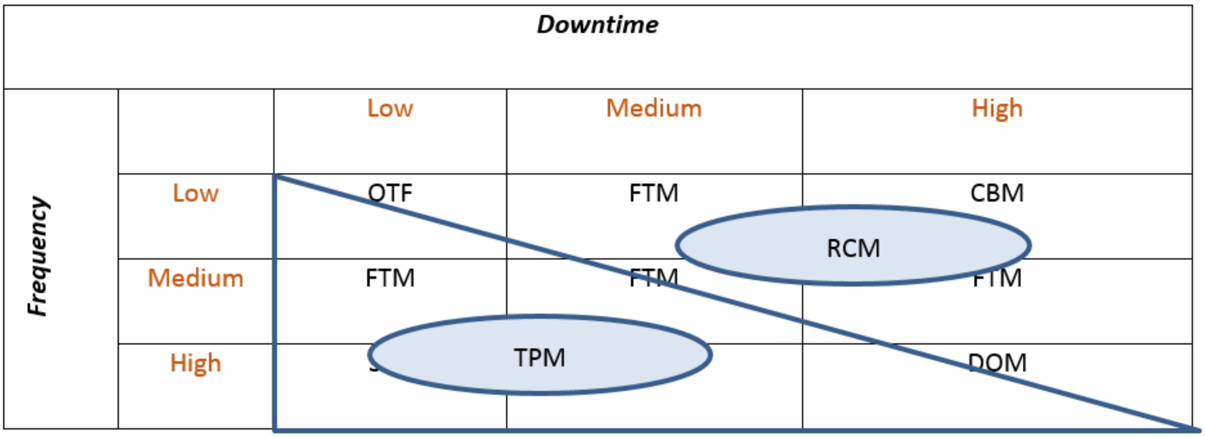

Figure 3: Schematic classification diagram of management approaches to maintenance for a system of interest based on multiple decision criteria, here downtime and frequency of failure.

TPM – Total Productive Maintenance, RCM – Reliability Centred Maintenance

According to Labib (1998), the TPM approach is applicable in the lower triangle and the RCM approach in the upper triangle of the DMG matrix.

		Downtime		
Frequency		Low	Medium	High
	Low	**OTF** BCB4; BCB7; BR BCAB6; BCB2CK	**FTM** DIFOCA3; DIFICA2; BCB2'A'; BCAB5; BCB2	**CBM**
	Medium	**FTM** M2DGBC; BCB1	**FTM** SFBM; CLK; MCCA; CKHRA; M1DWMA.	**FTM** DIFDA
	High	**SLU**	**FTM** CKD; DIFIC1; M1ST	**DOM** SHHRA; SD; M2ST M2DWMA; M2C; DIFBCLS

Figure 4: Decision making grid (DMG)

Reliability-based analysis

The categorised data for the reliability-based analysis of the six subsystems of the production line over the four-year period (2010 – 2013) is as follows:

CM Events Frequency; TBCM Events or TBF; CM Downtime or TTR; Cumulative TBCM Events; Cumulative CM Downtime.

Whereby CM = corrective maintenance and TBCM = time between corrective maintenance. The data used for the following analyses.

Trend test and Serial Correlation test

The first step in this analysis is to test the subsystems' TTR (CM Downtime) and TBF (TBCM Events) data for trends and serial correlation. The purpose of these tests is to verify the assumption that the data is 'independent and identically distributed' (IID) and in the event that the data exhibits the presence of trends or serial correlation, then it is considered non-independent and non-identically distributed.

Application of Parametric and Nonparametric methods to the TTR and TBF data
Following the reliability and maintainability analysis framework, it follows that for the IID data, parametric methods of analysis are applied. For non-IID data nonparametric methods, the power law process, NHPP model is used.

Parametric methods involve the,

- identification of candidate theoretical probability distributions (Exponential, Weibull and Lognormal distributions) that fit the data,
- estimation of the parameter(s) of distribution (MLE)
- application of the goodness-of-fit test (Anderson-Darling test) to the IID TTR and TBF data

Nonparametric methods involve the;

- application of the power law process NHPP model to the data,
- estimation of the parameters of model

- performing the goodness-of-fit test for this model (i.e. Cramer-von Mises test) under the following hypotheses:
  - H_o: A nonhomogeneous Poisson process with intensity abt^{b-1} describes the data and
  - H_1: The process does not describe the data

  If the Cramer-von Mises test statistic, Cm < Critical value, CV, H_o is accepted

Using Matlab software, the results of the above analysis shown in the table below.

Table 2: Summary table of the best-fit distributions for TTR and TBF data

Production Line System Processes	Machinery or Subsystem		Best-fit Distribution	Parameters
Cane Handling, Conveying and Feeding	Cane Handling, Conveying and Feeding System (CHCFS)	CM Downtime (TTR)	Lognormal	-0.9680 1.2562
		TBCM Events (TBF)	Weibull	237.1663 1.0597
Cane Preparation	Cane Knives System (CPCKS)	CM Downtime (TTR)	Lognormal	-1.7377 1.0620
		TBCM Events (TBF)	Weibull	207.3196 0.8201
	Shredder System (CPSS)	CM Downtime (TTR)	Lognormal	-1.5756 0.9808
		TBCM Events (TBF)	NHPP	0.2286 0.6758
Cane Juice Extraction	Diffuser System (CJEDS)	CM Downtime (TTR)	Lognormal	-1.2780 1.2748
		TBCM Events (TBF)	NHPP	0.0055 1.1004
	Milling System (CJEMS)	CM Downtime (TTR)	Lognormal	-1.7995 0.9560
		TBCM Events (TBF)	NHPP	0.5352 0.6022
Bagasse Conveying	Bagasse Conveying System (BCS)	CM Downtime (TTR)	Lognormal	-1.0399 1.0749
		TBCM Events (TBF)	Weibull	210.8981 0.8666

Estimation of production line systems reliability

The production line in the case study is of continuous process type, and considered to be of a series system configuration. The reliability of a series system defined as:

$$R_s(t) = \prod_{i=1}^{n} R_i(t)$$

Where $R_s(t)$ is the reliability of the system in series at a time t (in hours), *n* is the number of components or subsystems, and $R_i(t)$ is the reliability of ith component or subsystem at time t (in hours). This implies that all components or subsystems of the system must all work in order for the system to operate.

The production line has a planned/scheduled maintenance downtime of **twenty one hours every 4th week** (10 times) and **three hours every other week** (33 times) during the forty three weeks (43), twenty four hours operating period in a year.

Table 3 below shows the reliability estimates of the production line subsystems for the next 168 hours (equivalent to a week). The results show that apart from the CHCFS subsystem with a 50% chance of not failing within a week of 168 hours of operation, the other four subsystems have about a 40% chance of not failing (implying there is almost 60% chance of failing).
Moreover, for the CJEDS subsystem, it is almost certain that it will fail within a week. Based on the reliability estimates or predictions, there is conclusion that the planned or scheduled maintenance downtime of three hours every other week in addition to the twenty-one hours during every fourth week has not been effective in improving the reliability of all but one subsystem.

Table 3: Reliability estimations of the subsystems for the next 168 hrs (week)

Subsystem	Best Fit for MTBF (h)	MTBF (h)	Reliability estimate R(168 hrs)
CHCFS	Weibull	231.82	0.50
CPCKS	Weibull	230.87	0.43
CPSS	NHPP	206.64	0.44
CJEDS	NHPP	52.21	0.04
CJEMS	NHPP	217.76	0.46
BCS	Weibull	226.75	0.44

The reliability estimates of the subsystems in the Table 4 below indicate that the production line and subsystems reliability decreases as the operating time increases, and the CJEDS subsystem is the most unreliable compared to the rest. In addition, we also observe that the production line has a 0.62 probability or chance of not failing during the 10hrs of operation. This data provides information for the improvement of the subsystems reliability and hence the overall production line reliability.

Table 4: Reliability estimations of the subsystems at the end of different time intervals

Time (hrs)	CHCFS (Weibull)	CPCKS (Weibull)	CPSS (NHPP)	CJEDS (NHPP)	CJEMS (NHPP)	BCS (Weibull)	Production Line
0	1	1	1	1	1	1	1
10	0.97	0.92	0.95	0.83	0.96	0.93	0.62
20	0.93	0.86	0.91	0.68	0.91	0.88	0.40
30	0.89	0.81	0.86	0.56	0.87	0.83	0.25
40	0.86	0.77	0.82	0.46	0.83	0.79	0.16
50	0.83	0.73	0.79	0.38	0.79	0.75	0.11
60	0.79	0.70	0.75	0.32	0.76	0.71	0.07
70	0.76	0.66	0.71	0.26	0.73	0.68	0.05
80	0.73	0.63	0.68	0.22	0.69	0.65	0.03

A plot of the reliability estimates (from Table 3 above) of the subsystems and the corresponding overall reliability of production line shown in Figure 4 below.

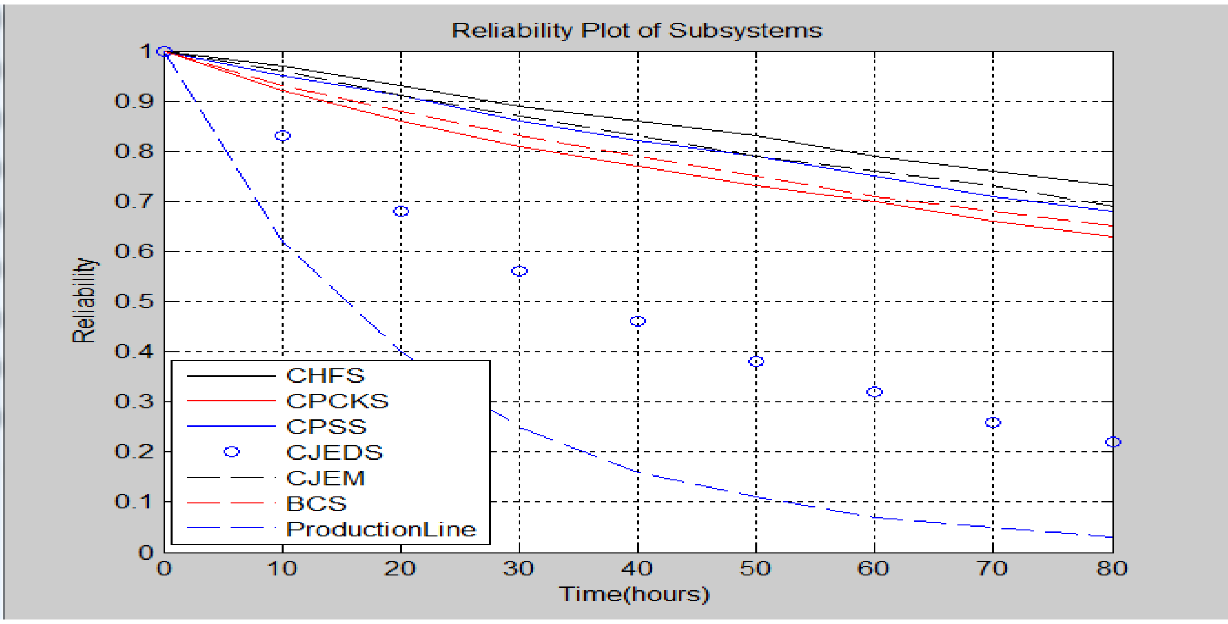

Figure 5: Reliability plot of the subsystems

Results in **Table 5** below, provide for the adjustment of the **preventive maintenance time intervals** of subsystems to a realistic reliability level of 0.75. This results in a **preventive maintenance time interval of fifteen hours for CJEDS subsystem.** This being the most critical unit which impacts most on the overall reliability of the production line, it can be seen from the reliability plot (Figure 5 above) that at fifteen hours of operation, the overall reliability of the production line will be at 0.5. The goal of the determined preventive maintenance time intervals is to optimise the scheduling of inspection and/or maintenance activities of the subsystems.

Therefore, by identifying the most critical or maintenance significant equipment, which significantly contributes to downtime in the production process, and attending to its maintenance, can lead to a reduction in downtime and hence improve availability and productivity of the entire production line. In this study, it is the CJEDS subsystem, and based on a predetermined reliability, able to determine realistic preventive maintenance time intervals for all the subsystems.

Table 5: Reliability-based preventive maintenance time intervals for the subsystems

Subsystem	**Reliability-based maintenance intervals for different reliability levels (hrs)**		
	0.9	**0.75**	**0.5**
CHCFS (Weibull)	28	72	168
CPCKS (Weibull)	13	45	133
CPSS (NHPP)	22	60	144
CJEDS (NHPP)	23	15	36
CJEMS (NHPP)	24	63	151
BCS (Weibull)	16	50	138

Production line subsystems maintainability measures

Maintainability measures represent the duration of a maintenance task by which a given percentage of maintenance tasks are complete. In the **Table 6** below, the corrective maintenance events mean downtime (MTTR), the standard deviation and predicted corrective maintenance events downtime (TTR) durations for the subsystems given maintenance tasks completion rates of 95, 90, 75, 50 and 25 percent have been calculated and tabulated.

The poor quality time to repair (TTR) data of subsystems i.e. CPCKS, CJEDS, CJEMS, CPSS and BCS failed to fit the known theoretical distributions that model repair times (TTR) and as such has been assumed to fit the lognormal distribution which is commonly used to model repair times. On the hand, the goodness of fit test for the subsystem CHCFS time to repair (TTR) data identified the best-fit distribution to be Lognormal.

The most frequently used value for maintenance tasks completion rate is TTR_{90}, which represents the duration of the restoration time by which 90% of all executions of the maintenance task considered are complete. Besides this value, the key figure of merit for maintainability is often the **mean time to repair** (MTTR) and a limit for the **maximum repair time** (TTR_{95}), which represents the maximum allowable duration of restoration time by which 95% of all repairs are complete. This maximum repair time is very beneficial for **maintenance planning** purposes and requires control of three main items of downtime:

- active repair time (a function of system design i.e. its inherent maintainability characteristics, training and skill of maintenance personnel),
- logistic time (time lost for supplying the replacement parts),
- administrative time (a function of the operational structure of the organisation)

Table 6: Maintainability measures

Subsystems	**Best fit theoretical distribution**	**MTTR (h) (CMEMDT)**	**Standard deviation, (h)**	**TTR_{95} (CMEDT)**	**TTR_{90} (CMEDT)**	**TTR_{75} (CMEDT)**	**TTR_{50} (CMEDT)**	**TTR_{25} (CMEDT)**
CHCFS	Lognormal μ = - 0.9680 σ = 1.2562	0.836	1.64	2.999	1.896	0.881	0.375	0.164
CPCKS	Lognormal μ = - 1.7377 σ = 1.0620	0.309	0.45	1.009	0.678	0.358	0.174	0.086
CPSS	Lognormal μ = -1.5756 σ = 0.9808	0.33	0.43	1.038	0.727	0.400	0.207	0.107
CJEDS	Lognormal μ = - 1.2780 σ = 1.2748	0.628	1.27	2.268	1.424	0.654	0.275	0.033
CJEMS	Lognormal μ = - 1.7995 σ = 0.9560	0.261	0.32	0.797	0.562	0.314	0.164	0.087
BCS	Lognormal μ = -1.0399 σ = 1.0749	0.630	0.93	2.071	1.401	0.730	0.353	0.171

CMEMDT = Corrective Maintenance Events Mean Downtime; CMEDT = Corrective Maintenance Events Downtime

CONCLUSIONS AND RECOMMENDATIONS

The aim of the research study was to investigate the effectiveness of the existing time-based maintenance policy on the reliability and availability of a sugar production line through the statistical analysis/modelling of its historical maintenance data.

Findings of the basic maintenance evaluation, reliability and maintainability analysis were as follows:

Critical or worst performing machinery or subsystems

- **Basic maintenance analysis** identified all the worst performing machines (critical machinery) of the production line based on the multi decision criteria, in this case frequency of failure and downtime duration. **Reliability analysis** identified CJEDS as the most critical or maintenance significant subsystem or machinery amongst all the worst performing based on their predicted reliabilities.

Equipment maintenance strategies

- **Basic maintenance analysis** recommended fixed time maintenance and design out maintenance strategies or system modifications as the appropriate equipment maintenance strategies (policies) for the identified critical machinery based on downtime duration and frequency of failure. **Reliability analysis** exposed the ineffectiveness of the existing preventive maintenance strategy of the production line based on the predicted reliabilities of subsystems or machinery; in addition to enabling the determination of an optimal schedule of maintenance activities for the subsystems

Maintenance concepts

- **Basic maintenance analysis** identified the applicable management approaches to maintenance as either TPM or RCM for the critical machinery based on downtime and frequency of failure.

Maintainability measures

- Results of the **maintainability analysis** highlighted the need to investigate issues such as, poor or incorrect downtime data; maintenance staff not well trained; logistic and administrative delays, all or any of which could be the reason for the unreliable downtime duration of maintenance tasks.

Overall, it is evident from the findings of the analysis that maintenance management decisions concerning maintenance policy and techniques employed by this company, were devoid of or not informed by the reliability analysis of in-house plant maintenance data. Just like many industries in our context, preventive maintenance decisions are normally based on either experience or original equipment manufacturer (OEM) recommendations.

Through experience, rarely followed are standard procedures, and as such, knowledge from technicians and engineers for maintenance purposes is a valuable asset to the company. The main drawback of preventive maintenance through experience, however, is that the company may face difficulties when the experienced personnel leave the company. Moreover, such persons may not be always present in production lines round-the-clock to solve maintenance problems.

Through OEM recommendations, preventive maintenance is carried out at a fixed time, for example every 1500h, based on recommendations. Nevertheless, according to Tam, Chan, and Price (2006), preventive maintenance intervals based on OEM recommendations may not be optimal because actual operating conditions may be very different from those considered by the OEM.

With the advances in computing software, data processing and analysis/modelling techniques should be an integral part of maintenance management systems in industry. This study has demonstrated that the implementation of reliability analysis techniques will assist in ensuring the accuracy of data collected, will result in better maintenance practices and equipment designs, lead to improved equipment availability, reduced maintenance and production costs and thus to enhanced competitiveness.

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Appendices

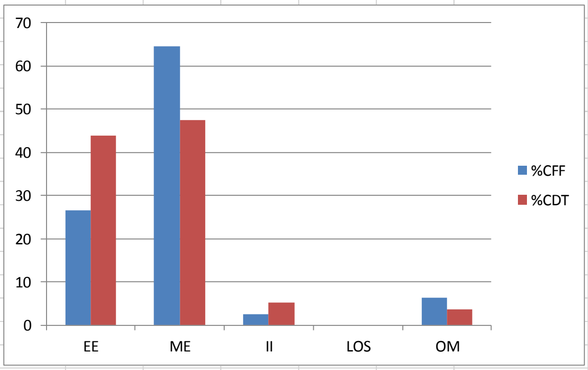
Machinery Name	Machine ID
Cane Handling, Conveying and Feeding System	
Wolf Crane	WC
Hilo Crane	HC
Spiller Table	ST
Cross Conveyor	CC
Old Feeder Table	OFT
Main Cane Carrier Assembly	MCCA
Cane Levelling Knives Assembly	CLK
Anvil Drum Assembly	ADA
Cane Knives System	
Cane Knives Housing & Rotor Assembly	CKHRA
Cane Knives steam turbine & transmission	CKD
Shredder System	
Shredder Feed belt & Magnet	SFBM
Shredder Housing & Rotor Assembly	SHHRA
Shredder steam turbine & transmission	SD
Diffuser System	
Diffuser Inlet Conveyor No. 1	DIFFIC1
Diffuser Inlet Carrier No. 2	DIFFICA2
Diff. Body Cells & Lifting Screws	DIFBCLS
Diff. Drive Assembly	DIFDA
Diff. Press Water Pumps (1&2)	DIFPWP: 1 & 2
Diff. Stage Pumps (1 - 12)	DIFSP: 1 - 12
Draft Juice Pumps (1 & 2)	DJP: 1 & 2
Diff. Outlet Carrier No. 1	DIFOCA1
Diff. Outlet Conveyor No. 2	DIFOC2
Diff. Outlet Carrier No. 3	DIFOCA3
Milling System	
No. 1 Mill Carrier	M1C
Mill No. 1 Dewatering Mills Assembly	M1DWMA
Press Water Trays, Tank, Pumps, Pipes & Valves	M1PWU
Mill No. 1 Steam Turbine	M1ST
Mill No. 1 Drive Gearboxes & Couplings	M1DGBC
No. 2 Mill Carrier	M2C
Mill No. 2 Donnely Cute	M2DC
Mill No. 2 Dewatering Mills Assembly	M2DWMA
Press Water Tray, Tank, Pumps, Pipes & Valves	M2PWU
Mill No. 2 Steam Turbine	M2ST
Mill No. 2 Drive Gearboxes & Couplings	M2DGBC

Bagasse Conveying System	
Bagasse Conveyor B1	BCB1
Bagasse Conveyor B2	BCB2
B2 Conveyor Kicker	BCB2CK
Bagasse Conveyor B2'A'	BCB2'A'
Bagasse Conveyor B3	BCB3
Bagasse Conveyor B4	BCB4
Bagasse (Slat Chain) Carrier B5	BCAB5
Bagasse (Slat Chain) Carrier B6	BCAB6
Bagasse Conveyor B7	BCB7

Types of Downtime Faults in Cane Handling, Feeding and Conveying System

Period 2010 - 2013

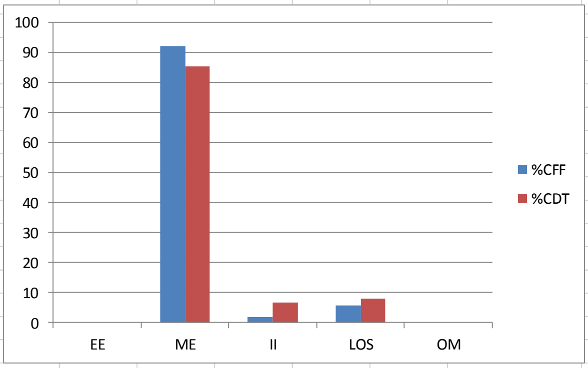
CUM	EE	ME	II	LOS	OM	
CFF	21	51	2	0	5	79
CDT	23.72	25.61	2.83	0	1.94	54.1
%CFF	26.58	64.56	2.53	0	6.33	
%CDT	43.84	47.34	5.23	0	3.59	



CUM – Cumulative, CFF – Cumulative Frequency, CDT – Cumulative Downtime, EE – Electrical /Electronic Faults, ME – Mechanical Faults, II – Instrumentation Faults, Lube Oil System Faults, OM – Other Machinery Problems

Types of Downtime Faults in Cane Knives System

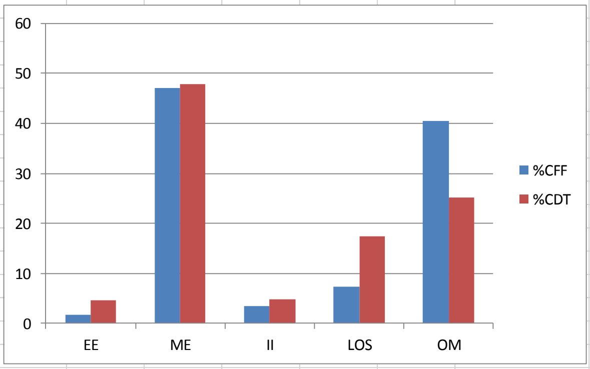
Period 2010 - 2013						
CUM	EE	ME	II	LOS	OM	
CFF	0	95	2	6	0	103
CDT	0	30.06	2.42	2.79	0	35.27
%CFF	0	92.16	1.96	5.88	0	
%CDT	0	85.23	6.86	7.91	0	



CUM – Cumulative, CFF – Cumulative Frequency, CDT – Cumulative Downtime, EE – Electrical /Electronic Faults, ME – Mechanical Faults, II – Instrumentation Faults, Lube Oil System Faults, OM – Other Machinery Problems

Types of Downtime Faults in Shredder System

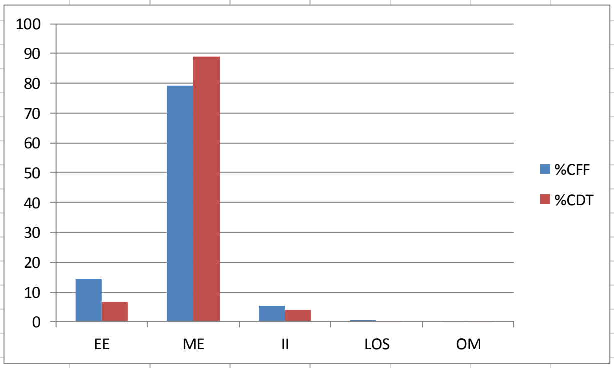
Period 2010 - 2013						
CUM	**EE**	**ME**	**II**	**LOS**	**OM**	
CFF	8	187	14	29	160	398
CDT	6	60.82	5.96	21.85	31.5	126.13
%CFF	1.77	46.97	3.54	7.32	40.4	
%CDT	4.67	47.87	4.77	17.49	25.21	



CUM – Cumulative, CFF – Cumulative Frequency, CDT – Cumulative Downtime, EE – Electrical /Electronic Faults, ME – Mechanical Faults, II – Instrumentation Faults, Lube Oil System Faults, OM – Other Machinery Problems

Types of Downtime Faults in Diffuser System

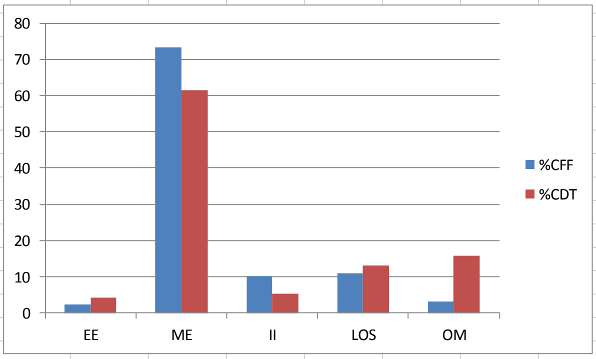
Period 2010 - 2013						
CUM	EE	ME	II	LOS	OM	
CFF	40	226	15	2	1	284
CDT	15.25	200.69	9.3	0.34	0.42	226
%CFF	14.34	79.21	5.38	0.72	0.36	
%CDT	6.75	88.8	4.12	0.15	0.19	



CUM – Cumulative, CFF – Cumulative Frequency, CDT – Cumulative Downtime, EE – Electrical /Electronic Faults, ME – Mechanical Faults, II – Instrumentation Faults, Lube Oil System Faults, OM – Other Machinery Problems

Types of Downtime Faults in Mill No. 1 System

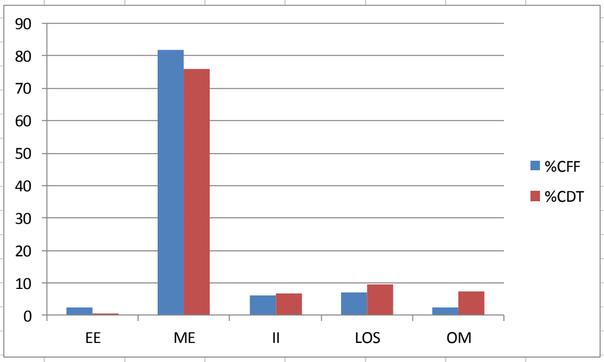
Period 2010 - 2013						
CUM	EE	ME	II	LOS	OM	
CFF	3	92	13	17	4	129
CDT	1.92	27.25	2.39	6.6	7	45.16
%CFF	2.36	73.23	10.24	11.02	3.15	
%CDT	4.3	61.56	5.35	13.12	15.67	



CUM – Cumulative, CFF – Cumulative Frequency, CDT – Cumulative Downtime, EE – Electrical /Electronic Faults, ME – Mechanical Faults, II – Instrumentation Faults, Lube Oil System Faults, OM – Other Machinery Problems

Types of Downtime Faults in Mill No. 2 System

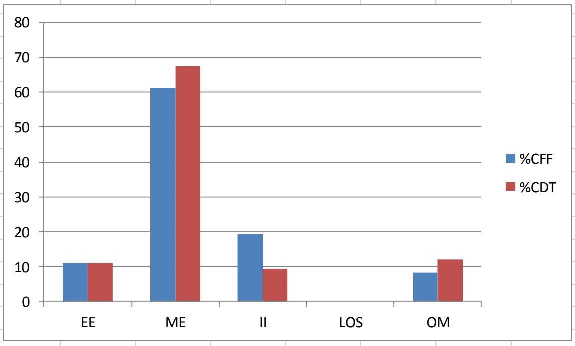
Period 2010 - 2013						
CUM	EE	ME	II	LOS	OM	
CFF	10	353	26	30	10	429
CDT	1.06	124.41	10.98	15.7	11.92	164.07
%CFF	2.39	81.86	6.21	7.16	2.39	
%CDT	0.65	75.83	6.69	9.57	7.27	



CUM – Cumulative, CFF – Cumulative Frequency, CDT – Cumulative Downtime, EE – Electrical /Electronic Faults, ME – Mechanical Faults, II – Instrumentation Faults, Lube Oil System Faults, OM – Other Machinery Problems

Types of Downtime Faults in Bagasse Conveying System

Period 2010 - 2013						
CUM	EE	ME	II	LOS	OM	
CFF	13	74	21	0	8	116
CDT	11.92	72.38	9.78	0	11.07	105.15
%CFF	10.92	61.34	19.33	0	8.4	
%CDT	11.11	67.47	9.35	0	12.07	



CUM – Cumulative, CFF – Cumulative Frequency, CDT – Cumulative Downtime, EE – Electrical /Electronic Faults, ME – Mechanical Faults, II – Instrumentation Faults, Lube Oil System Faults, OM – Other Machinery Problems

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