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How to cite this thesis
A review on effective maintenance strategies and management for optimising equipment systems

by

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A minor dissertation

Submitted in partial fulfilment of the requirements for the degree of

MAGISTER INGENIERIAE

in

ENGINEERING MANAGEMENT

at the

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

of the

UNIVERSITY OF JOHANNESBURG

2017

SUPERVISOR:

Prof Arnesh Telukdarie
I would like to give thanks to God for giving me the opportunity and knowledge in developing this research and preparation of this dissertation.

- I want to express my gratitude to my supervisor Dr Arnesh for his guidance, support and trust in me.

- And thank Mr Pieter Nienaber from Glencore’ Lion Ferrochrome smelter in Steelpoort for giving permission to use real system and operational logbook data for development of reliability analysis.
Abstract

The theory on maintenance in engineering organisations has become more applicable and acknowledged in modern industries. The correct strategies and plans for maintenance in the mining, process and manufacturing organisations have produced profitable results when applied effectively. Minimised costs, standard safety compliance, and integrity of production processes influence industrial and commercial entities to employ improved measures.

The current research reviews various maintenance strategies pertaining optimisation and improved reliability of engineering systems. Industrial operations now require a high degree of availability for production and high profit margins. Maintenance strategies application differs according to the type of industry. Corrective and preventive maintenance strategies have great similarities with different outcomes, economic and operational implications. Preventive maintenance requires tools and resources for good long-term rewards for organisations, while generally corrective maintenance strategies have high cost implications. Organisations with long-term goals to realise an operation process with high reliability and availability for production choose preventive methods. While some operations interchange between the two methods due to time constraints and cost mitigations. Overall maintenance structures apply according to the level of intensity and complexity of the system, plant and equipment. Larger operations select strategies to employ for specific systems and equipment. Main driver to select between strategies is to focus on the criticality of equipment and impact severity to overall system or plant.

This research presents a review of maintenance strategies and analysis of failure data. The study researches corrective and preventive maintenance strategies with supporting policies such as the Reliability-Centred Maintenance (RCM), Condition-Based Maintenance (CBM), and Time-Based Maintenance (TBM). Condition monitoring and reliability based modelling quantifies failure behaviour outcomes and provides both scientific and theoretic interpretations. Focus is on the methods applied to optimise performance of equipment and systems by increasing equipment availability. The study further develops quantitative and qualitative analysis using mathematical and statistical modelling tools for failure data. Qualitative analysis seeks to understand the core factors resulting to failure. Quantitative analysis develops the interpretation of failure from data. Results obtained indicate reliability parameters with an increasing failure rate over the recorded period. Probability functions depict varying
average time between failures on monthly intervals. Weibull functions provide graphical representation of the failure distributions and failure rate. The functions also depict the wear out and constant regions of the distribution.
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Abbreviations

RCM – Reliability-Centred Maintenance
TPM – Total Productive Maintenance
WBS – Work Breakdown Structure
CBM – Condition-Based Maintenance
AR – Auto Regression
CBR – Case-Based Reasoning
MCDM – Multi-Criteria Decision Making
CMMS – Computerised Maintenance Management System
FMECA – Failure Mode Effect Cause Analysis
FTA – Fault Tree Analysis
RFCA – Root Failure Cause Analysis
AHP – Analytical Hierarchy Process
OEM – Original Equipment Manufacturer
KPI – Key Performance Indicator
OEE – Overall Equipment Effectiveness
TEEP – Total Effective Equipment Performance
PM – Preventive Maintenance
CARCMS – Computer Aided Reliability-Centred Maintenance Systems
MSG-1 – Maintenance Steering Group 1
FAA – Federal Aviation Administration
MSI – Maintenance Significant Item
MTTF – Mean-time-to-failure
MTTR – Mean-time-to-repair
ARM – Age replacement model
RPN – Risk Priority Number
NUREG – Nuclear Regulatory Commission
MLE – Maximum Likelihood Estimation
1. Introduction

1.1. Background

A review of maintenance strategies is influenced by the need to focus on minimising costs incurred due to maintenance for plant operation. Maintenance strategies in organisations are essentially derived from achieving desired reliability and availability of plant equipment and effective use of maintenance resources [1]. Large-scaled plant operations maintenance costs account a significant amount of operational expenditure [2], hence an increased improvement in maintenance efficiency is an advantage to reduction of costs. The reciprocal approach of minimising cost of maintaining equipment requires reliability to be high in order to have the reduced cost of breakdowns. This approach demands monitoring of equipment owing to preventive maintenance, hence the introduction of reliability-centred maintenance is highly favoured. Reliability-Centred Maintenance (RCM) is a maintenance plan that involves determining the requirements for ensuring that system components or equipment operate according to the expected levels [3].

Research indicates that the application of maintenance theory is vastly relevant in the field on maintenance engineering. The need for high production levels of performance in manufacturing and process industrial environments is of utmost importance, thus maintenance of process equipment and machines remain vital [4]. Maintenance is defined as a system of activities carried out with the aim to keep a component or integrated components in an operating state [5]. Maintenance is thence performed to achieve optimum performance of equipment and plants, increasing reliability and life span of equipment [6]. Maintenance application activities are classified in two streams; the preventive and corrective maintenance structures [7], corrective maintenance is required for breakdown scenarios of equipment where failure occurs. While preventive maintenance is applied on operating equipment to mitigate the probability or failure severity resulting to long-standing periods or downtime [8]. Corrective maintenance applications take place unplanned as breakdown cases or planned where the system or equipment is ‘run to failure’ before action can be taken to retain its normal operating state, as illustrated in Figure 1.
1.2. Problem Statement

In the mining and manufacturing industries, maintenance is the driving force of production and keeping equipment operational. Traditionally, production is of high priority and the equipment is expected to be available and reliable. This implies effective maintenance to prevent downtime and production loss.

Artisans, planners, coordinators, and engineers at large are faced with the task of implementing effective strategies to maintain the plant with minimum breakdowns. A process plant is a system with different components and equipment that require maintenance; this involves breakdowns or failures within the system where technical input is useful. Developing strategies for obtaining an efficiently functioning system that aids to optimise the operation of the plant is hence essential.

Poor maintenance and lack or resources, insufficient measuring and monitoring systems result in improper maintenance.

1.3. Research Purpose

The purpose of the current research is to perform an analysis on maintenance strategies applied in maintenance plant operations to maximise availability and deliver a reliable system. Focus will be on aspects surrounding engineering maintenance; the management of maintenance strategies, planning structures, performance measurement, people management, cost of maintenance, resource management, etc. In addition, the impact of different approaches for delivering improved results in optimising plant operation.
1.4. Research Objectives
The current research aims to address fundamental aspects in maintenance engineering owing to interdisciplinary engineering organisations.

1.4.1. Primary Objectives
- Define various strategies implemented in maintenance and sustainability of organisations.
- Evaluate essential characteristics influencing maintenance profitability.
- Implement maintenance functions with the impact on availability of equipment and plant production.
- Identify decision-making processes in maintenance for plant reliability and sustainability of production process.
- Identify cases and environments where certain maintenance strategies are ineffective or effective and investigate conditions where different approaches have profitable results.

1.5. Research Scope
The current research aims to investigate the theoretical and practical aspects of maintenance practices and strategies applicable in engineering organisations. The scope vastly covers the following:

- Maintenance engineering strategies
- System characteristics and failure modes analysis
- Management of maintenance systems
- Reliability-Centred Maintenance (RCM)
- Costs and benefits of Total Productive Management (TPM)
- Resource management

1.6. Research Questions
The current research aims to address the following questions about maintenance and the evolution of maintenance in modern engineering industry:

- What is the impact of maintenance management and strategies in today’s engineering organisations?
- How total systems yield due to preventive maintenance activities on equipment and optimisation?
- What data interpretation techniques reflect using quantitative analytical methods regarding causes of component failure?
1.7. Research Document Structure

- Research topic: A review on effective maintenance strategies and management for optimising equipment system.

- Literature review: This chapter lays out the body of literature where previous research and findings is illustrated. Literature on maintenance engineering strategies; the impact, models, economic benefits, life cycle, applications and theory is discussed together with the shortcomings that exist.

- Conceptual Analysis: A methodology and analysis on maintenance and systems engineering, design and implementation pertaining to maintenance of equipment, evaluation amid different approaches for profitability.

- Case study: Shows application of theoretical concepts and derivation of results. The chapter basis analysis on real system events and recordings, data obtained from the scenario is utilised for computations.

- Conclusion and Discussion: Summarises the critical points, highlight differences in the results obtained, interpretation of the literature and evaluation.

- Appendix: This part of the dissertation consists of supplementary material collected and appended.
1.8. Work Breakdown Structure (WBS)

![Work Breakdown Structure Diagram]

*Figure 2: Work Breakdown Structure*
2. Literature Study

2.1. Introduction

The literature study in the current research mainly covers reviews postulated theories about the maintenance engineering management, it acknowledges different theories and applications about maintenance engineering and strategies implemented in various operational structures. Maintenance is defined as an combination of all procedures and activities carried to preserve a system or equipment in a desired state of operation [10]. Developing and executing a maintenance strategy consist of the following steps [2]:

- Identify the activity that needs to be done and formulate a task plan
- Obtain all necessary resources for execution of tasks
- Implementation.

2.2. History of Maintenance

Maintenance became significant because of equipment failure, components required maintenance for continuous production. Inevitably, process operation causes wear and stress on machine components and results to failure [11]. During industrial revolution, managing failure of components was growing and the philosophy of maintaining equipment evolved. The idea of maintaining equipment brought about the concept of the bathtub, which stated that the system/equipment is likely to fail in the early stages of operation and then operate at low risk of failure until it reaches a point of increased rapid failure due to wear and degradation. The bathtub is based on the research done on failure patterns of electronics components [12] during the 1940’s and 1950’s, thus replacing system components before reaching point of wear-out increases system reliability and availability.

Similar approach was followed in the commercial aviation industry; the successful passenger aircraft McDonnell Douglas DC-3 in the 1930’s had little information on the failure patterns of its components which created safety concerns [13], introducing the condition monitoring approach that involved regular maintenance and scheduled inspections on aircrafts. In the 1960’s, the Boeing 747 was built in Seattle, its size raised safety concerns leading to the aviation industry reassessing the structure of daily maintenance strategies on aircrafts [12]. After the United Airlines reviewed maintenance strategies employed, investigations proved that the bathtub failure patterns do not coincide completely with the failure of components used on
aircrafts. A Maintenance Steering Group 1 (MSG-1) developed maintenance plans for aircrafts approved by the Federal Aviation Administration (FAA), the success of MSG 1 led to a revised version (MGS 2) for improvement to develop and advance maintenance strategies on similar aircrafts (MC Donnell Douglas DC-10 and Lockheed L-1011). In 1980 MGS-2 was updated and incorporated in MSG-3 used for maintenance programs developments on aircrafts such as Boeing 757 and 767.

2.3. Framework of Maintenance Strategies

Maintenance consists of two main streams; corrective maintenance which in some work is referred to as breakdown maintenance and preventive maintenance [14]. Corrective maintenance is aimed at equipment that has to be restored after it has failed to function, while preventive maintenance is actioned before failure occurs and to prevent its likelihood. Thus the strategies for maintenance are mainly aimed at the factors associated with occurrence of failure on plant equipment. Within the factors; reliability of components and systems is ensured to maintain operations, equipment prognostics which require data and nature of systems failure to predict time based failure occurrences, systems diagnostics which classifies failures and aids with remedial actions required to prevent long standing durations of components or plant equipment, the concept of configurability or redundancy involves configuration management of subsystems according to severity of their failure to the overall system thus making priority on equipment for maintenance [15] [16].

Literature indicates the changing of focus on maintenance from a ‘fail and fix’ philosophy to a more attractive approach of ‘predict and prevent’ with the aim of improving reliability of equipment [17]. Table 1 lists maintenance strategies with brief descriptions.
Table 1: Maintenance Strategy Alternatives

<table>
<thead>
<tr>
<th>Maintenance Strategy</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrective Maintenance [18]</td>
<td>The equipment is restored to a functional state or replaced after it has failed to operate.</td>
</tr>
<tr>
<td>Preventive Maintenance [19]</td>
<td>Maintain equipment at periodic intervals to reduce the possibility of failure given the historic behaviour</td>
</tr>
<tr>
<td>Condition-Based Maintenance [20]</td>
<td>Maintenance done on equipment based on the historic data measured and monitored</td>
</tr>
<tr>
<td>Predictive Maintenance [17]</td>
<td>Predicting risks of components failure in an equipment, given the historical behaviour of the equipment or system</td>
</tr>
<tr>
<td>Reliability-Centred Maintenance [21]</td>
<td>A systematic probabilistic approach of collecting data and analysing its failure mode effects and criticality of the system components then making a decision on its reliability</td>
</tr>
</tbody>
</table>

2.4. Corrective Maintenance

Corrective maintenance (breakdown maintenance) in simple terms is referred to as a repair method or fixing a malfunctioned equipment to operate. The corrective maintenance strategy is often unfavourable for obvious reasons; high costs incurred, long standing time, labour required, fault finding, cumbersome installations, working overtime, etc [22]. The relationship between maintenance and costs in not only in purchasing equipment and service but also on the repairing time taken on an equipment holding production, thus the amount of production loss due to a standing equipment or component of the plant/system.

2.5. Condition-Based Maintenance (CBM)

One of the approaches is CBM, it focuses on the condition of the equipment and monitors its behaviour over time. The criticality of the method is on monitoring and identifying the points that could lead to failure or malfunction beforehand, it reduces the uncertainty of maintenance activities based on equipment condition [10]. The
strategy assumes that failures of a component do not occur instantly, meaning they initially show symptoms of abnormality and degradation leading to anticipation of failure. Thus, maintenance tasks are based on the condition of the components. CBM is distinguished from preventive and corrective maintenance by the aspect of failure prognosis given the condition measured amid normal functioning or operation of the system. Key elements in CBM are:

- Data acquisition, involves obtaining data/information relevant to the operation and condition of the component in order to track the trend behaviour.
- Signal processing, to handle and process the type of data obtained for interpretation of the status and condition of the concerned component.
- Decision-making, for conclusive decision on maintenance plans required given the information received.

Recent studies on the application of CBM indicate that the approach depends largely on data for various systems; mechanical, electrical, and electronic. Reviewed research and techniques include models, algorithms, and technologies for data handling in making informed maintenance decisions. Other proposed mathematical models for determining efficient CBM policies used renewal processes theory, which uses planned inspections and replacements as decision-making variables. A recent suggested framework on CBM based on a Bayesian network model was derived from simulations of various scenarios, integrated analysis to test the develop high-order model for failure prediction.

There are three different methodologies in CBM application, mainly; data-driven, model-based, and the hybrid method. In, it is illustrated that data-driven approach is based on models derived using historical data (artificial neural network, Bayesian network, Gray model etc.) And model driven approach utilizes mathematical techniques that are physics based deducted using multivariate statistical methods with calculus and numerical algorithms.

The standard procedure for implementing CBM method is developed in phases consisting of techniques as follows.

1. Measuring, monitoring and collecting equipment/component data
2. Making diagnosis and prognosis
3. Estimating replacement or repairing cost and time
4. Execution of appropriate required maintenance
Table 2 below summarises the techniques for implementing CBM

<table>
<thead>
<tr>
<th>Phase</th>
<th>Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostics</td>
<td>– Logistic regression&lt;br&gt;– Artificial Neural network&lt;br&gt;– Reliability theory&lt;br&gt;– Statistical analysis (e.g. Regression)&lt;br&gt;– Time series data analysis</td>
</tr>
<tr>
<td>Prognostics</td>
<td>– Case-Based Reasoning(CBR)&lt;br&gt;– Renewal theory&lt;br&gt;– Mathematical programming&lt;br&gt;– Simulation</td>
</tr>
<tr>
<td>Maintenance operation</td>
<td>– Multi-Criteria Decision-Making (MCDM)</td>
</tr>
</tbody>
</table>

Research shows an increase in the usage of CBM by companies due to a need for improving equipment reliability and spares availability, maintenance and logistics costs reduction [31]. Condition Monitoring tools through making use of relevant equipment data for maintenance deteriorating equipment aid in reducing downtime due to process failure and unplanned shutdowns. Determining cost of failure and the cost-benefit of avoiding failure is essential in determining planned maintenance tasks and critical spare equipment, this often requires thorough analyses of current costs and deterioration of equipment with the required steps to achieve the goal of plant or equipment optimisation [32].

Identification of equipment failure patterns requires modelling methods to characterise the conditions and effects, to set systematic failure prevention plans, and maintenance schedules. Theoretically, there are characterised failure patterns [33]:

The Bath Tub curve: Infant mortality, followed first by a constant or gradually increasing failure probability and then by a pronounced wear out region.

Figure 3: Bathtub curve: Infant mortality - useful - rapid wear out.

Constant or gradually increasing failure probability, followed by a pronounced wear out region.

Figure 4: Rapid wear out after long useful life.

Gradually increasing failure probability, but with no identifiable wear out age.

Figure 5: Gradual wear

Low failure probability when the equipment is next followed by a quick increase to a constant level.

Figure 6: No infant mortality followed by indefinite useful life.
Bloch and Geitner (1983) indicated that symptoms of equipment failure can be identified through condition monitoring techniques such as:

- Vibration monitoring
- Oil analysis
- Acoustic monitoring
- Thermography
- Electromagnetic testing
- Physical conditions
- Non-destructive testing

2.6. Reliability-Centred Maintenance (RCM)

RCM is an integration of corrective, condition-based, and proactive maintenance for identifying applicable preventive maintenance actions [34]. The correct application of RCM requires the following two steps (1) to ascertain that maintenance personnel are educated and acquainted with fundamental principles of RCM; (2) to develop a computer aided RCM system (CARCMS) as a control and monitoring system [35]. F Stanley Nowlan and Howard F. Heap originally interpreted the logic of RCM implementation on following functions:

- The way failure occurs
- Its impact considering safety, economics or operability
- Making decision on the applicable maintenance actions.

RCM implementation process mainly consists of systematic phases namely [36]:

**Preparation:** The initial step is to gather relevant information about the system or equipment; that is historic data values, component set points, rated output parameters, etc.

**System analysis:** Criticality of the components is analysed according to dominant failure modes. Associated risks involved require failure modes, effect, and criticality analysis (FMECA) – adopted from reliability and risk analysis and tools such as fault tree analysis (FTA) and root cause failure analysis (RFCA)

**Decision-making:** The selection of appropriate maintenance approach focusing on the significant consequences; thus looking at how component or subsystem failure affect the entire system, economic implication of corrective and preventive maintenance, maintainability of the system, and trend of rate of failure.

The application of maintenance strategies in different organisation vary according to processes applied and structures employed. Reliability and productivity integrates all maintenance management concepts such as; total productive maintenance (TPM), reliability-centred maintenance (RCM), condition based maintenance (CBM), preventive maintenance (PM), and other approaches with the objective to optimise and manage operation of equipment [37]. Cumulative approach of Figure 9 shows a detailed process flow for implementation of the methodology.


2.6.1. System Selection and Data Collection

Data collected indicating failure (breakdowns) of equipment is used to measure maintenance results and analyse the impact each significant item carries on the entire plant’s reliability, availability and operability. The main indicator for evaluating maintenance performance and if maintenance strategy requires improvement or change are [11]:

- **Availability (Av)**
  Availability is the ratio of time a component or system is available for production use.

  \[
  A_v = \frac{T_{tot} - D}{T_{tot}} \times 100 \, (\%) \tag{1}
  \]

  \( A_v \) = Availability  
  \( T_{tot} \) = Total production time for period (hours)  
  \( D \) = Downtime for period (hours)
- **Mean time to failure (MTTF)**
  MTTF is the period equipment takes before failure occurs (average up time).

\[
MTTF = \frac{T_{tot} - D - T_{nu}}{N}
\]  

MTTF = Mean Time to Failure (hours) 
T\(_{tot}\) = Total production time for period (hours) 
N = Number of breakdowns during interval (0, T\(_{tot}\)] 
D = Downtime for period (hours) 
T\(_{nu}\) = Time machine not utilised (hours)

- **Breakdown frequency**
  Breakdown is the reciprocal of MTTF

\[
B_D = \frac{N}{T_{tot} - D - T_{nu}}
\]  

B\(_D\) = Breakdown frequency

- **Mean time to repair (MTTR)**
  MTTR is the duration of the breakdown

\[
MTTR = \frac{D}{N}
\]  

- **Production rate**
  Production rate shows the impact maintenance has on operability and plant production

\[
P_R = \frac{P}{T_{tot} - D - T_{nu}}
\]  

P = Production for period (production units)

### 2.6.2. FMEA and FMECA
Failure modes and effects analysis technique is used within the RCM methodology for evaluating maintenance plans to employ based on analysis [38]. Development of failure modes and their effect on Maintenance Significant Items (MSI) assists to classify each potential failure with its severity. FMEA follows the following criteria:

- Item description
- Function
- Functional failure
- Failure mode.

FMECA distinguishes the criticality of failures from less to more critical and the severity level.

Methodology of FMEAs is recommended and recognised international, and follows the following process; identification of potential failures pertaining to a function, identifying possible causes, and impact to mitigate the effect [39]. FMEA process involves system or product analysis with potential effect of failures. Risk evaluation of potential failures is essential to identify and locate system aspects that require control plans and corrective actions. RPN is used to assess risk in Occurrence (O), the frequency of possible failure to occur, Severity (S), the extent to which the effect is serious, and Detectability (D). The probability that the failure mode can be detected prior system failure.

Risk Priority Number (RPN), is calculated as a product the three ratings:

\[
RPN = O \times S \times D \tag{6}
\]

<table>
<thead>
<tr>
<th>Rating</th>
<th>Probability of occurrence failure rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Very high: failure is almost inevitable</td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>High: repeated failures</td>
</tr>
<tr>
<td>7</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Moderate: occasional failures</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Low: relatively few failures</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Remote: failure is unlikely</td>
</tr>
</tbody>
</table>
### Table 4: Ratings for severity of a failure

<table>
<thead>
<tr>
<th>Rating</th>
<th>Effects</th>
<th>Severity of Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Hazardous without warning</td>
<td>System failure resulting in hazardous effects almost certain.</td>
</tr>
<tr>
<td>9</td>
<td>Hazardous with warning</td>
<td>System failure resulting in hazardous effects highly probable.</td>
</tr>
<tr>
<td>8</td>
<td>Very high</td>
<td>System inoperable but safe</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>System performance severely affected</td>
</tr>
<tr>
<td>6</td>
<td>Moderate</td>
<td>System operable and safe but performance degraded.</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>Reduced performance with gradual performance degradation.</td>
</tr>
<tr>
<td>4</td>
<td>Very Low</td>
<td>Minor effect on system performance</td>
</tr>
<tr>
<td>3</td>
<td>Minor</td>
<td>Slight effect on system performance Non-vital faults will be noticed most of the time.</td>
</tr>
<tr>
<td>2</td>
<td>Very Minor</td>
<td>Negligible effect on system performance</td>
</tr>
<tr>
<td>1</td>
<td>None</td>
<td>No effect</td>
</tr>
</tbody>
</table>

### Table 5: Ratings for detectability

<table>
<thead>
<tr>
<th>Rating</th>
<th>Detection</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Absolutely impossible</td>
<td>Controls will not and/or cannot detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>9</td>
<td>Very remote</td>
<td>Very remote change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>8</td>
<td>Remote</td>
<td>Remote change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>7</td>
<td>Very low</td>
<td>Very low change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>Low change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>5</td>
<td>Moderate</td>
<td>Moderate change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>4</td>
<td>Moderately high</td>
<td>Moderately high change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>3</td>
<td>High</td>
<td>High change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>2</td>
<td>Very high</td>
<td>Very high change: the controls will detect a potential cause and subsequent failure mode</td>
</tr>
<tr>
<td>1</td>
<td>Almost certain</td>
<td>Controls will almost certainly detect a potential cause and subsequent failure mode</td>
</tr>
</tbody>
</table>
2.6.3. Failure Cause Analysis

Failure causes consist of dependent events contributing to failure of a component or equipment in a system. Common cause failure is defined as an event consisting of component failures with the following characteristics [40]:

- Individual components that have failed or degraded its functional capacity
- Components failing within period of operation resulting into system uncertainty
- Failures resulting from a shared fault
- Component failure resulting within equipment.

The main objective of conducting and performing failure cause analysis on systems inclined to failure is to assess their impact and severity to the system. Identification and analysis of the causes aid in developing design strategies and improve system reliability and availability.

Root cause and coupling factors are classified as core attributes to causes of failure [41]. Roof cause is fundamentally considered a main contribution to causing failure. Examples of root causes involve faults in engineering and design, manufacturing, maintenance, installation, commissioning, operational, production, and execution. Including other external contributors such as thermal stress, natural disasters, and fire. Coupling factors are referred to as elements linked with components associated with a single root cause. Typical factors include components enclosed in same area or environment, same maintenance procedure, same installation equipment, same faulty components used.

The procedural failure cause analysis was arranged in three phases by NUREG-CR-5485 [40]:

- Screening analysis
- Detailed qualitative analysis
- And detailed quantitative analysis

Screening analysis identifies all possible chances posing risk to failure occurrence within the system. This includes subsystems with significant impact on reliability of the whole system.
Qualitative analysis desires to consolidate the systems’ components detailing its susceptibility to cause failure. Detailed analysis allows identification of root causes and coupling factors. Resulting analysis provides information on points to correct when improving the system and for future design methods. Quality methods used, improve reliability as well as reducing possibility of failure occurrence.

Quantitative analysis involves the introduction of data analysis, mathematical models using algorithms, parameter estimation for variable functions, results interpretation, and system quantification.

2.6.4. Task Selection

Task selection process is carried based on failure modes, the feasibility and practicality of the task for the equipment. Selection for all failure modes within the system forms a truncated decision tree with consequence decisions. Figure 10 shows the decision tree with selection of tasks based on the technical and economic factors. Similarly, tasks can be selected based on safety, health, or environmental factors.

![Task decision tree](image)

*Figure 10: Task decision tree [11]*
2.6.5. Decision-Making

In reviewing various applicable maintenance strategies, the argument becomes wide as to which strategy is more suitable in certain industries and which factors support such a decision. As evident from the discussed strategies with different techniques, there is a trend of similarities among them. Failure is stochastic in nature and hence adoption of maintenance strategies should differ according to industrial application and organisational objectives. In [42], two determining factors for selection of effective maintenance approach were compared between;

i. Production loss and
ii. Cost of maintenance incurred in each maintenance strategy.

These factors largely contribute towards decision making of a suitable strategy, however there are tools available to aid making informed decisions. The well-known Analytical Hierarchy Process (AHP) [43] methodology provides flexibility in making decisions based on both qualitative and quantitative aspects. Thus not only is a maintenance strategy selected based on the two mentioned factors above but also on other influential factors such as judgements and vendor or Original Equipment Manufacturer (OEM) recommendation [44].

2.7. Maintenance Management

Preventive maintenance reduces the amount of times it takes for maintaining equipment after it has failed; this integrates the CBM and RCM structures. The impact of information systems through computerized tools for data collection, processing and analysis provides support for managing maintenance systems.

2.7.1. Equipment Maintenance and Repair

Standard of maintenance and repair of equipment provides efficiency and improves running and operation of the plant or equipment. Effective management of maintenance systems comprises various tools equipped to provide organised timely and safe maintenance approach [45]. Specialised systematic tools include; CMMS (Computerised Maintenance Management System) tools used for resource planning, inventory and procurement control, work flows tracing, planned maintenance scheduling, and equipment cost management in organisations that are software applications available for supporting maintenance management.
2.7.2. Systematic Approach Application

Efficient maintenance and repair systems improve availability of equipment and effectively increase production of the organisation [46]. Current research focuses on factors influencing challenges encountered within the maintenance field. Main problems involve preventative actions to prevent reoccurrence of failures and improve reliability of equipment (effective management of systems), rational maintenance and repair strategies (planning and execution of tasks), key performance indicators (service evaluation and trend performance), profitability of implemented maintenance strategies (impact on downtime, production and equipment performance). According to research, improving plant/equipment performance and reliability requires application of science-based Maintenance and Repair Organisations (MRO) [47].

Techniques for measurement and management of maintenance activities include using performance measurement tools for effective monitoring. Such instruments require set goals for achieving efficient maintenance plans, analysis of current maintenance level and the required level for improvement. Key performance indicator (KPI) is a system for indicating goals hierarchy to identify the level of status and objectives, the results for improving the system require monitoring and measuring the performance of a system. A balanced scorecard can be used to test validity for decision strategists, Kaplan and Norton introduced this tool to measure the performance of strategies presented for key objectives in organisations [48]. KPI models process data collected from maintained equipment/systems to evaluate performance and operation effectiveness, different approaches for data processing include; regression analysis, decision tree analysis, data classification, etc. Key indicating factors used commonly measure the overall equipment effectiveness (OEE) and total effective equipment performance (TEEP) to distinguish between the current state and desired level of performance. Performance indicators mainly aim for the following points:

- Continuously improve standard or level of maintenance.
- Maintain enterprise competitiveness.
- Identify discrete key areas to increase maintenance efficiency.
- Gathering information obtained from the analysis and implements necessary changes required and monitor the results.
2.7.3. Total Productive Maintenance (TPM)

Lezlo [49] indicated that one of the key aspects of management is the ability to manage people, and this is defined by the leadership styles implemented in an organisation. A leadership that promotes learning for its employees, encouraging innovation and emphasis on continual improvement brings about total quality management (TQM).

TPM constitutes the following strategic aspects in management of maintenance productivity in maintenance organisations [50]:

- Training and skills development: Increase knowledge of personnel about equipment and systems within the organisation to improve maintenance effectively. Equip personnel with necessary skills and knowledge to manage and maintain equipment.
- Ownership: Permeate the mind-set of equipment ownership where maintenance team has control over their equipment and its operation. Artisans and technicians then carry the responsibility of their equipment to ensure its well condition.
- Cross-functional team work: Promote the culture of involvement from top to bottom management and allowing input from individuals about methods to improve systems and optimise uptime.
- Stability: Process and maintenance teams must work as a team in unity to maximise the overall plant/equipment effectiveness.

2.7.4. Replacement Study

Decision making to replace or retain equipment in a system has economic and non-economic effects, where total annual expenses and the initial equipment cost breakeven yields the minimum cost life [51].

Equipment replacement decision is based on several sources namely:

**Improved requirements.** System improvement on speed, accuracy, recently introduced technology, or change in specifications. Improving a system require change of an equipment with installing a new or refurbished one.

**Reduced performance.** Equipment failure and the impact on production as a result affect the level of reliability in terms of the plant availability and the costs of operation, rework and large maintenance costs.
Figure 11 depicts the relation of economic replacement study and total cost of maintenance where at the optimal point, the current cost estimates over all possible years the equipment may provide service is minimal. The graphical representation on maintenance cost versus level of maintenance to prevent failure.
2.8. Theoretical Analysis

2.8.1. Probabilistic Analysis of Failure Data

Probabilistic analysis of time failure data is a process for characterising failure data and statistical interpretation [52]. Series failure data set is analysed through distribution model and decisions made according to costs for selected maintenance plan. Table 6 shows the systematic modelling approach.

Table 6: Modelling structure

<table>
<thead>
<tr>
<th>Format</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data set</td>
<td>– Failure time series</td>
</tr>
<tr>
<td>Reliability modelling</td>
<td>– Weibull distribution model</td>
</tr>
<tr>
<td></td>
<td>– Normal distribution model</td>
</tr>
<tr>
<td></td>
<td>– Lognormal distribution model</td>
</tr>
<tr>
<td>Model outputs</td>
<td>– Mean-time-to-failure (MTTF)</td>
</tr>
<tr>
<td></td>
<td>– Failure rate “λ”</td>
</tr>
<tr>
<td>Decision-making</td>
<td>– Failure cost</td>
</tr>
<tr>
<td></td>
<td>– Maintenance cost</td>
</tr>
<tr>
<td></td>
<td>– Maintenance strategy</td>
</tr>
</tbody>
</table>

2.8.2. Statistical Modelling

*Method for estimating reliability parameters* [53]

Weibull distribution is a technique used for accurate failure analysis and life distribution modelling. Failure distributions can be characterised as in Figure 3 of the Bathtub curve. Distributions shapes such as exponential, Rayleigh and normal distributions are characterised with different shape factors. Two parameters representing the model is the shape parameter, $\beta$, and the scale parameter, $\eta$. Both parameters show the component characteristics, age and different failure rate trends. Based on the Weibull distribution model, the shape and scale parameters change as indicated below:
\( \beta < 1 \), indicates a decreasing failure rate

\( \beta = 1 \), indicates a constant failure rate

\( \beta > 1 \), indicates an increasing failure rate

\( \eta < 1 \), hazard function decreases

\( \eta = 1 \), constant hazard function

\( \eta > 1 \), hazard function increases

Data collected for analysis is ranked according to the order of failure events. \( F_i \), the median rank of failure event “i” is calculated as follow:

\[
F_i = \frac{i - 0.3}{N + 0.4}
\] ...

(7)

Where \( N \) is the total ranking number of a component. Parameters for Weibull distribution can be determined using straight line formula:

\[
y_i = mx_i + c
\] ...

(8)

\[
x_i = ln(t_i)
\] ...

(9)

Where \( t_i \) is the period of the failed component in the ith rank, and \( y_i \) is determined by:

\[
y_i = ln ln \frac{1}{1 - F_i}
\] ...

(10)

The Weibull probability distribution is plotted on a logarithmic scale axis for large range variable quantities.
\( \beta \), the shape parameter is calculated as:

\[
\beta = m = \frac{\sum_{i=1}^{N} x_i y_i - \frac{\sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N}}{\sum_{i=1}^{N} x_i^2 - \frac{[\sum_{i=1}^{N} x_i]^2}{N}}
\]

\[
\ldots (11)
\]

and

\[
c = \frac{\sum_{i=1}^{N} y_i}{N} - m \frac{\sum_{i=1}^{N} x_i}{N}
\]

\[
\ldots (12)
\]

\( \eta \), the scale parameter calculated as:

\[
\eta = e^{-\left(\frac{c}{m}\right)}
\]

\[
(13)
\]

The value of MTTF can be determined the scale and shape parameters as:

\[
MTTF = \eta \Gamma \left( 1 + \frac{1}{\beta} \right)
\]

\[
(14)
\]

Where \( \Gamma \left( 1 + \frac{1}{\beta} \right) \) is the gamma function evaluated at \( 1 + \frac{1}{\beta} \).

Weibull distribution function \( f(t) \) represents the probability of failure at a specific period \( t \).

\[
f(t) = \left( \frac{\beta}{\eta} \right) \left( \frac{t}{\eta} \right)^{\beta - 1} e^{-\left( \frac{t}{\eta} \right)^{\beta}}
\]

\[
\ldots (15)
\]
Weibull cumulative distribution function $F(t)$ represents the probability of failure at a specific time “$t$”. Reliability function $R(t)$ and Hazard rate $\lambda(t)$ are expressed as follow:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (16)$$

$$R(t) = 1 - F(t) = e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (17)$$

$$\lambda(t) = \frac{f(t)}{R(t)} = \left(\frac{\beta}{\eta}\right) \left(\frac{t}{\eta}\right)^{\beta-1} \quad (18)$$

Failure of components in a system result to failure of the system to function. Each component forms part of a series connection for functioning system, the total failure rate measures reliability

$$\lambda_{total}(t) = \sum_{i=1}^{n} \lambda_i(t) \quad \ldots (19)$$

$\lambda_i(t)$ is the failure rate of component $i$ and $n$ is total number of sub-components.

Total failure rate consists of the sum of failure rate for each sub-component within a system. Newly replaced components have low failure rate as a result the change affects the overall system failure rate. Equation 20 shows the total system failure rate where “$m$” denotes total number of components replaced in period $t$.

$$\lambda_{sys}(t) = \lambda_{total}(t) - \sum_{i=1}^{m} \lambda_i(t) \quad \ldots (20)$$
The Weibull Distribution Theory \cite{54} \cite{55}

There are three Weibull parameters:

- The threshold parameter, $\tau$
- Characteristics life or scale parameter, $\eta$
- Shape parameter, $\beta$

According to the extreme value theorem, from equation 16:

$$F(T \leq t) \approx 1 - e^{-\left(\frac{t-\tau}{\eta}\right)^\beta} \quad \text{for} \quad t \leq \tau, \; \eta > 0, \beta > 0$$

For the probability at time $T$.

$$F(T \leq \tau + \eta) = 1 - e^{-\left(\frac{\tau + \eta - \tau}{\eta}\right)^\beta}$$

$$F(T \leq \tau + \eta) = 1 - e^{-\left(\frac{\eta}{\eta}\right)^\beta}$$

\therefore \quad F(T \leq \tau + \eta) = 1 - e^{-1} = 0.632$$

That is, at time equal to the characteristic life, there is a 0.632 or 63.2\% probability of failure. Which is referred to as the quantile of the distribution for any shape parameter value, $\beta$.

Figures 12 and 13 below show the variability of the Weibull normal distribution function when the scale parameter and shape parameter is varied. Figure 14 shows how the hazard function changes with scale parameter values.
Figure 12: Probability function for different characteristic life

Figure 13: Probability function with different shape parameters
Maintenance decision-making process [52]

Process for making decision is essentially based on minimising costs, operational and maintenance, and optimising system reliability and availability. Two main aspects account for assessment, failure cost and preventive maintenance cost. Equation 21 and 22 show how costs can be calculated:

\[ TC_{fc} = C_m + C_r + C_{dt} \]  
(21)

\[ TC_{pm} = C_m + C_{dt} \]  
(22)

\( TC_{fc} \) is the total failure cost, \( TC_{pm} \) the total PM cost, \( C_m \) the maintenance cost, \( C_r \) the product reject, and \( C_{dt} \) is the downtime cost.
Replacement models aid in decision-making for components of equipment replaced or repaired. According to the Age Replacement Model (ARM), a component has an optimum replacement time $T$ before or at failure with the replaced component assumed ‘as-good-as-new’. 

\[
C(T) = \frac{C_f F(T) + C_p R(T)}{\int_0^T R(t)dt}
\]

\[\text{.... (23)}\]

$C(T)$ is the cost function of time for the optimum replacement age $T$, $C_f$ the cost of failure replacement, and $C_p$ the cost of preventive replacement, $F(T)$ the cumulative distribution function, and $R(T)$ is the reliability function.

Repairable equipment policy aid to make informed decisions for repair or replacement under the assumption that equipment be replaced after time $t$ and any failure that occurs before time $t$ is restored with minimal repairs. Equation 24 shows $g_m(t)$, the long-run expected cost per unit time.

\[
g_m(t) = C_m N(T) + C_p t
\]

\[\text{.... (24)}\]

$C_m$ is the cost of minimal repair. Minimal repair function $N(T)$ is the expected number of failures at time $t$.

2.8.3. Probability Plotting

The Weibull graph in Figure 15 is widely used to plot Weibull cumulative distribution functions [56]. The $y$-axis scale is ruled proportionally to the values of $\ln\ln(1/R(t))$ and a logarithmic $x$-axis scale is represented by $\ln t$. Equations 16.1 – 16.3 shows the derivation of abscissa and ordinate formulas. The purpose of the Weibull graphical method is to develop estimates for the $F(t)$ function using sample points on a linear grid.
From Equation 16, the cumulative failure distribution function is given by:

\[ F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \]  

(16)

\[ \frac{1}{1 - F(t)} = e^{-\left(\frac{t}{\eta}\right)^\beta} \]  

(16.1)

Introducing natural logarithms

\[ \ln\left(\frac{1}{1 - F(t)}\right) = \beta \frac{\ln t}{\ln \eta} \]  

(16.2)

\[ \ln \ln\left(\frac{1}{1 - F(t)}\right) = \beta (\ln t - \ln \eta) \]

\[ \ln \ln\left(\frac{1}{1 - F(t)}\right) = \beta (\ln t) - \beta (\ln \eta) \]  

(16.3)

The linear form \( Y = \beta X + C \) is expressed where:

\[ X = \ln t \]

\[ Y = \ln \ln \frac{1}{1 - F(t)} \]

\[ C = -\beta \ln \eta \]
Figure 15: Weibull Probability Paper [56]
Rank regression

Regression analysis uses Equation (8) to fit a straight line through the \( n \) points as plotted in Figure 16. The straight line is used to estimate the parameter values, characteristic life and shape parameter. Fitting the straight line requires a mathematical method for accuracy given how the data points are randomly positioned. Least squares method is used to perform such line fitting, which minimises the squares of the distances between the sample point and the line \([58]\). Random sample points drawn in Figure 17 on x- and y-axis illustrate the application on least squares method. The derivation of linear regression equations is indicated in Appendix A1 \([59]\).

\[ \text{Figure 16: Minimising distances in x- and y- directions} \]
Another method for parameter estimation is the maximum likelihood; the method computes parameters that maximise the probability (likelihood) of sample data fitting the distribution [60]. The method considers a time, \( t \) as a random continuous variable with a probability density function [38]:

**Maximum Likelihood Estimation (MLE)**
\[ f(t; \alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_k) \quad (25) \]

Where \( \alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_k \) are estimate parameters and sample times, \( t_1, t_2, t_3, \ldots, t_n \) are failure data.

The likelihood function is given by:

\[ L(t_1, t_2, \ldots, t_n | \alpha_1, \alpha_2, \ldots, \alpha_k) = \prod_{i=1}^{n} f(t_i; \alpha_1, \alpha_2, \ldots, \alpha_k) \quad \ldots(26) \]

The likelihood function is:

\[ \Lambda = \ln L = \sum_{i=1}^{n} \ln f(t; \alpha_1, \alpha_2, \ldots, \alpha_k) \quad \ldots(27) \]

Partial derivative of the function with respect to each estimate is given by:

\[ \frac{\partial (\Lambda)}{\partial \alpha_j} = 0, \quad j = 1, 2, \ldots, k \quad (28) \]

2.8.4. Maintenance Optimisation Models

Optimising maintenance through preventive maintenance actions involves performing maintenance to improve system reliability to a certain degree. Lifetime of a randomly distributed system has a corresponding failure (hazard) rate. System lifetime distributed Weibull with parameters as illustrated in Equation 15 can be used to model maintenance repairs and periods. Maintenance modelling for optimising system availability and reliability requires finding the optimum number of cycles (N) to perform maintenance and period interval, T [61].

Modelling Preventive Maintenance performed considers a degrading system with a failure rate function \( \lambda(t) \). Assuming maintenance activities performed at time intervals \( kT \), where \( k \) refers to the \( kth \) action. System reliability is improved to a certain degree \( p \), where \( p \) is between 0 and 100 % (0 \( \leq p \leq 100\% \) [59]. Post the \( kth \) maintenance activity, the failure rate \( \lambda_k(t) \) of the system is defined such that:
\[
\lambda_k(t) = p[\lambda_{k-1}(t-T)] + (1-p)[\lambda_{k-1}(t)]
\]

From Eq. (28), if \( p = 0 \), \( \lambda_k(t) = \lambda_{k-1}(t) \) meaning there is no degree of improvement on the system. And for \( p = 1 \), \( \lambda_k(t) = \lambda_{k-1}(t-T) \). The relationship between the hazard rate \( \tilde{\lambda}(kT + t) \) of the system after the \( k \)th maintenance and the first system failure rate \( \lambda(t) \) is given by:

\[
\tilde{\lambda}(kT + t) = \sum_{i=0}^{k} \binom{k}{i} p^{k-i} q^i \lambda h(kT + t)
\]

Equation (29) drawn in Figure 18 indicates the failure rate reduced with a factor at different maintenance intervals. The figure clearly shows an indication of the impact performing five \((T = 5)\) maintenance cycles carries. Figure 18 corresponds to a Weibull distributed lifetime for \( k = 5 \) and \( p = 0.45 \), with shape and scale parameters set at 2.35 and 250, respectively.

Figure 18: System hazard rate with degrees of improvement [63]
Replacement intervals for maintenance occur in preventive replacement or failure replacement cases. The replacement cost per unit time can be expressed as [61]:

\[
C(t_p) = \frac{\text{Total expected cost in interval } (0, t_p]}{\text{Expected length of the interval}}
\]

\[\text{... (30)}\]

hence,

\[
C(t_p) = \frac{C_p + C_f N(t_p)}{t_p}
\]

\[\text{... (31)}\]

where \(C_p\) = cost of one preventive replacement, \(C_f\) = cost of one failure replacement, and \(N(t_f)\) = expected number of replacements during interval \((0, t_p]\).

Age preventive replacement maintenance considers system replacement at age \(t_p\) or replaced when the system failed prior planned age. Equation (32) show the expected maintenance cost per unit time as:

\[
C(t_p) = \frac{\text{Total expected replacement cost per cycle}}{\text{Expected length of cycle}}
\]

\[\text{... (32)}\]

Where total expected replacement cost per cycle = (cost of preventive maintenance) (probability the system survives to the planned replacement age) + (cost of failure replacement)*(probability of equipment failure before \(C\)):

\[
C_p R(t_p) + C_f [1 - R(t_p)]
\]

\[\text{(33)}\]

And the expected cycle length = (length of preventive cycle) (probability of a preventive cycle) + (expected length of a failure cycle)*(probability of a failure cycle):

\[
t_p R(t_p) + \int_0^{t_p} t f(t) dt
\]

\[\text{... (34)}\]
Hence, the expected maintenance cost per unit time is:

\[
C(t_p) = \frac{C_p R(t_p) + C_f [1 - R(t_p)]}{t_p R(t_p) + \int_0^{t_p} t f(t) \, dt}
\]

.... (35)

2.8.5. Pareto Principle

Pareto’s principle was derived from a theory by an economist Vilfredo Pareto who developed a formula describing the unequal distribution of wealth in his country [65]. Observation of the principle is based on the phenomenon that the vital few contributions are responsible for the main problem, interpreting the rule as the 80/20 rule.

Four steps for constructing the Pareto chart:

- Identify contributions to failure.
- Express the failure contributions in a number of occurrences per individual contribution converting the figures into percentages of the total.
- Create a bar chart of the results, the highest bars ordered in a descending order to the right. The Y-axis on the right hand side indicates the contribution figures, and cumulative percentages on the left hand side.
- Draw a cumulative percentage line showing accumulation of contributing factors to the problem.
3. Methodology and Analysis

3.1. Introduction

Chapter 3 proposes a methodological structure on analysis of performed maintenance. The structure is developed through a thought process for designing a preventive maintenance program for systems and equipment. This chapter focuses and analyses a subsystem of a process plant with a goal of analysing the application of maintenance on a specific machine in the operational unit.

South African process plants producing ferrochrome use the Outokumpu FeCr process which started in 1968 in Finland [66]. Figure 19 shows the process where the molten metal undergoes a crushing after cooling and screened in different range of sizes for shipping.

![Diagram of Ferrochromium process](image-url)

*Figure 19: Ferrochromium process [67]*
3.2. Research Methodology

Methodology structure outlines criteria of data collection and selection of sample. Process for data analysis through investigation of the considered equipment is stated under the case study. Research process is summarised below:

- Gathering set of failure time data
- Analyse data through statistical and reliability modelling
- Identify characteristics of equipment failure; MTTF estimation and failure rate
- Model aging periods using the Weibull distribution.

3.3. Case Study

Step 1: System/equipment selection and data collection

Selected system for case analysis is sub-section of a Ferrochrome smelter process plant. Final product crushing plant is a subsystem for preparing the metal product in different sizes and shipping to a designated customer. Final product plant consists of the crushing and the screening sections, cooled ingots from furnaces is fed into a primary crusher and conveyed to the secondary crusher and transferred to the screening plant for metal sorting. Figure 20 shows the block diagram of the plant.

Scheduled preventive maintenance at crushing plants involves a number of tasks, including:

- Crusher wear parts
- Screen decks
- Feeder wear parts
- Conveyor skirting and adjustment
- Oil and lubrication
- Conveyor belt repair
- Visual inspections
- Electrical and instrumentation.
Step 2: Functional Block Diagram (FBD)

Step 3: Failure data analysis

Extracted data for analysis is recorded from the daily logbook of the plant operator. Information recorded consists of any breakdown and stoppages that occurred during the shift with supporting reasons for occurrences and tasks performed to resolve the problems.
Step 4 and 5: Failure Modes and Effects Analysis (FMEA) and Criticality Analysis
- Investigate potential failure modes for each component and subsystem
- List potential effects of each failure mode
- Identify failure causes
- Perform severity ranking for each mode
- Assign occurrence ranking for each effect or mode
- Assign a detectability ranking for each mode
- Calculate the risk priority for each failure mode.

Step 6 and 7: Task selection and decision tree
Task selection process is carried based on failure modes, the feasibility and practicality of the task for the equipment. Selection for all failure modes within the system forms a truncated decision tree with consequence decisions. Figure 10 showed the decision tree with selection of tasks based on the technical and economic factors. Similarly, tasks can be selected based on safety, health, or environmental factors.

Step 8: Maintenance plan
Maintenance plan and strategies for these tasks can be compiled categorically with the type of tasks selected:
- Tasks can be performed during normal plant operation
- Tasks placed on the opportunistic list for times during short plant stoppages
- Scheduled shutdown periods for major tasks.
4. Detailed Analysis and Results

4.1. Case Study: Ferrochrome Crushing Plant

Process operations producing ferrochrome use crushing plants to prepare the final product for exports. A smelter in Steelpoort, South Africa processing ferrochrome has a crushing plant with a throughput of 190t/hour. The process starts with larger ingots fed into the crusher, processed through different stages and stored in varying stockpile sizes. The crushing plant consists of crushing equipment, material conveyors and screening equipment, Figure 19 and 20 shows the process flow diagram in detail.

The objective of this case study is to perform an analysis on the downtime of various engineering equipment. Analyse the plant downtime data and estimate failure parameters for different equipment. In addition, investigate the impact maintenance carries for reliability and availability of the plant.

The trend in Figure 21 below indicates cumulative maintenance and downtime data. Information log was obtained through the company as recorded by plant operators for months between January 2016 and July 2016.

![Cumulative failure duration](image)

*Figure 21: Failure duration trend*
4.2. Data Analysis

Table 7 shows the recorded data from operators’ log sheet of plant breakdowns and stoppages from engineering equipment. Downtime summary recorded in hours and minutes expands from January to July, listed is the most common components with breakdowns. Cumulative duration due to failure and planned maintenance is further analysed using statistical methods.

Table 7: Seven month down time summary

<table>
<thead>
<tr>
<th>Engineering</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Year to date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumps</td>
<td>2:45:00</td>
<td>0:00:00</td>
<td>0:00:00</td>
<td>3:40:00</td>
<td>0:00:00</td>
<td>0:00:00</td>
<td>0:00:00</td>
<td>6:25:00</td>
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<td>Scales</td>
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<tr>
<td>Grizzly</td>
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<td>0:00:00</td>
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<td>149:16:00</td>
<td>1091:12:00</td>
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Figure 22 represents the cumulative probability plot using the Weibull distribution for its flexibility in accurately fitting large scaled ranging data. The probability plot corresponds with the scale parameter ($\eta$) at approximately 63% probability with a value of 24 hours. The plot indicates a relationship between the cumulative failure probability and time to failure in hours. The graph also indicates the scale parameter value which can be used to calculate the shape parameter value. The x- and y-axis values are indicated in Table 10 of failure data in Appendix A1. Using the probability plotting paper created using ReliaSoft Weibull++ software allows to manually measure the estimation parameters.
4.3. Reliability Parameters Estimation

Table 10 in Appendix A1 shows the failure data in a chronological order with a total of 42 recorded failures. The first column shows the failure number time between failures $t_i$ and time to failure $T_i$. The first column is in the order of failure occurrences, second column shows the time to failure, and the third column calculates the cumulative failure time. Cumulative failure probability is calculated as the ratio of failure number and total number of recorded failures. Median rank is calculated according to equation 7.
4.3.1. Maximum Likelihood Estimation (MLE)
Since the Weibull Distribution Function \( f(t) \) from equation (15) is given by:

\[
f(t) = \frac{\beta}{\eta} \left( \frac{t}{\eta} \right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}
\]

Using the maximum likelihood method, the following two equations are derived to simultaneously solve for the shape and scale parameters:

\[
\frac{1}{n} \sum_{i=1}^{n} \ln t_i = \frac{\sum_{i=1}^{n} (t_i^{\beta} \ln t_i)}{\sum_{i=1}^{n} t_i^{\beta}} - \frac{1}{\beta}
\]  
(15.1)

and

\[
\eta = \left( \frac{\sum_{i=1}^{n} t_i^{\beta}}{n} \right)^{\frac{1}{\beta}}
\]  
(15.2)

Calculation for characteristic parameters in Table 8 are based on formula described in Equations (14) to (18). Shape and scale parameters are calculated from the Weibull distribution. The scale parameter corresponds with 63% cumulative probability of failure at 24 hours. Shape parameter, \( \beta > 1 \), indicates an increasing failure rate at 1.045.

*Table 8: Reliability parameter calculations*

<table>
<thead>
<tr>
<th>Shape parameter ( \beta )</th>
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<td>MTTF (hours)</td>
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4.4. Weibull Distribution
Reliability functions defined in Equations (15) to (18) represent the cumulative distribution, probability of failure, reliability and hazard functions. Appendix A1 shows the spreadsheet of fitted data and Weibull distributions.

4.4.1. Cumulative Distribution Function
Cumulative probability function shown in Figure 23 indicates that the probability that a system fails at a specific age. Early stages of a system have less probability of failure given that the component is new. Aging components within a system increase certainty of failure cumulatively until it reaches 100% probability. Figure 23 shows that after 20 hours of operation, there is 54% certainty of failure.

Figure 23: Cumulative Probability Function
4.4.2. Probability Density Function

Probability density function of a system failure at a specific time is shown in Figure 24. Discrete probability values represented by the function cumulatively sum up to 100%. Area under the function is equal to one, equivalent to 100% total probability. The area of the probability density function is calculated through integration of the function $f(t)$. Failure probability of the system at precisely 5 hours of operation is approximately 0.0342 or 3.4%.

4.4.3. Reliability Function

Failure probability of the system at precisely 5 hours of operation is approximately 0.0342 or 3.4%.

Figure 24: Failure Probability Function

Figure 25: Reliability Distribution Function
Reliability function gives the probability of failure before or at a certain time. Reliability at time zero is 100% but as time progresses, the reliability decreases indicating degradation of the system. Equations (16) and (17) illustrate the relationship between reliability function and cumulative probability distribution. Figure 25 indicates that up to 46% of the system has a survival probability of 20 hours of operation without failure. The relation shows that Figure 23 reciprocates Figure 25. System components at a later stage show a rapid decrease in probability of surviving, up to only 24% of the system survives at least 35 hours.

4.4.4. Hazard Function

In Figure 26, the failure rate indicates a gradual but constant increase of failure rate between 3% and 4.5% preceded with a rapid rate in the early stages. The right side skewed Weibull probability density function is as a result of the shape parameter value ($\beta\approx1$). The function indicates the increase of failure probability as time progresses.
4.5. Pareto Analysis

Figure 27 shows the downtime analysis using the Pareto principle. Analysis indicates that approximately 20% of the downtime factors contribute 80% of total downtime. Crushing and planned shutdowns contributed 83% of downtime during January month. First and the second highest contributing factors to overall downtime amount to at least 80% of the total downtime. Figures below show the Pareto analysis for different months and the significant variances each element contributed to failure of equipment.
February had a major planned shutdown contributing to longer standing period. Significant impact of stoppages of conveyors introduced a direct impact on crushing equipment as indicated in Table 7. Month March had least planned shutdowns due to pressure from production following February’s production loss, indirectly affecting maintenance on crushing equipment.

Planned shutdown increased due to high amount of breakdowns on crushers and interconnected conveyors. At least 76% of downtime caused by the planned shutdowns and conveyor failures. Limited maintenance activities had an impact on the routine scheduled inspections and condition monitoring.

Month May had the highest number of failures on conveyor belts; skirting, pulley bearings, chute liners and motor trips causing stoppages. Figure 30 shows high amount of failures on conveyors with less breakdowns on primary and secondary crusher.
Year to date data shows the top three most affecting and contributing downtimes. Planned shutdowns that normally take place on weekly basis are longer depending on the amount of work required for specific plant components. Crushing equipment is the second highest contributing factor; the primary crusher consists of V-belts failing due to slacking tension, wearing liners, loose bolts due to high vibration. Conveyor failures resulting from tail pulleys, drive pulleys, worn pulley lagging, worn belts, skirting, and gear drive lubrication.

4.6. Failure Analysis

4.6.1. FMEA/FMECA
Appendix A2 shows the FMEA analysis worksheet consisting of top six downtime-contributing elements. Respective failure modes and causes for each component with list of failure effects. Rating scores corresponding to each component measures the Risk Priority Number for criticality.

4.6.2. Criticality Analysis
FMECA Identifies the criticality scale of failure through the Risk Priority Number (RPN) order. Three elements ranking the occurrence, severity, and detectability produce a qualitative approach for establishing criticality of failure. RPN values show the highest critical component as the crushers at 1427, followed by the conveyors at 629. Criticality of components indicates areas where failure is most concentrated and various causes.
4.6.3. Root Cause Failure Analysis (RCFA)

Fundamental objective of RCFA is to find the aspects and sources causing a system to fail or be dysfunctional. There are various standardised methods, procedures to investigate, and system analysis for equipment failures. Depending on the nature of the system and its characteristics, failure analysis methods apply differently.

The following failure analysis procedure is employed when identifying the root cause for specific equipment identified to have an impact on the system.

- Information gathering: This requires detailed information regarding the component; this includes inspection reports, OEM manual documents, research on the application, interviewing operators and servicemen.
- Problem definition: Description and listing of core symptoms regarded identifies as main causes to the problem.
- Investigation: Amongst others identifying the magnitude of the problem, previous similarly known problems, the actual cause, event trend prior to the occurrence, location of the problem, changes before the failure, and early symptoms of failure.
- Cause analysis: conduct a standard failure mode effect and cause analysis (FMECA), and cause effect diagram.
4.7. Discussion of Results

The primary and secondary crushers used at the final product plant have a throughput of approximately 140 tons per hour. Figure 31 shows the double toggle jaw crusher used as a primary crusher for large abrasive lump material. The secondary crusher for smaller product size conveyed for screening is a single toggle. Both Jaw Crushers function with 75kW motors coupled with v−belts drive system.

Failure and breakdowns recorded for the crusher on each of the components are listed in Table 9 with their failure modes. Figure 32 shows the RCM logic for a degrading system aiding with decision making for replacement of components. Figure 33 indicates a systematic development proposed for maintenance strategies depending of the type of failure that occurred.
Table 9: Crusher failure modes

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<td>Loose toggle block bolts</td>
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<tr>
<td>Worn Jaw liner bolts</td>
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<tr>
<td>Tension rod</td>
</tr>
<tr>
<td>Broken springs</td>
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<td>Worn tension rod</td>
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<tr>
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<td>Worn toggle plate edges</td>
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<tr>
<td>Jaw liners</td>
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<td>Wear</td>
</tr>
<tr>
<td>Loose liners</td>
</tr>
<tr>
<td>Vibration</td>
</tr>
<tr>
<td>V-Belts</td>
</tr>
<tr>
<td>Low tension</td>
</tr>
<tr>
<td>Worn belts</td>
</tr>
<tr>
<td>Motor</td>
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<td>Overload</td>
</tr>
<tr>
<td>Misalignment</td>
</tr>
<tr>
<td>Voltage imbalance</td>
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<tr>
<td>Lubrication</td>
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</table>

Figure 32: RCM logic [11]
Figure 33: Proposed Maintenance System
Maintenance system proposed in Figure 33 carries the core of procedural structure for maintaining equipment. System failure results from one of the subcomponents listed on the system. The success on maintenance requires a team of managers, engineers, technicians, operators, planners and artisans working closely with OEMs and other external support structures to realise plant availability and optimise production.

Closed loop control management system in Figure 34 shows the flow of input objectives for plant optimisation and output results. The objectives are the inputs; the iterative inner cycle with feedback controls the management system and the output results.

KPIs constitute the objectives for plant and equipment sustainability. The inner cycle consists of planning, communication, action, monitoring, and feedback sessions.

**Planning** – First step is to establish a plan for equipment and tasks for the objectives. Strategies for maintenance form fundamentals of achieving the results. The planning phase requires participation of organisational personnel from management to lower level employees to give input.

**Communication and action** – Individual opinions are essential in developing the right strategies for critical tasks and processes involved. Both lower level employees and middle management must constantly be part of the communication process for the decisions taken and implementation plans. Execution of discussed plans and strategies is critical for obtaining expected results. Teams executing the plans also need maintain the correct communication channels with managers and engineers.

**Monitoring and feedback** – Post completion of implementing necessary changes and installations where required, all involved must revisit the plan and simultaneously monitor the improvement. Comparing the obtained results with the initial plan structure allocates opportunity to revise and adjust the implementation processes. Monitoring and revising the scope is an iterative process for continuous improvement with set objectives. Similar to control system in robotics and electronic engineering, the feedback provides adjustable variables.

*Figure 34: Closed Loop Control System*
5. Conclusion and Evaluation

Literature shows that maintenance is mainly classified in two types; Preventive and corrective. Additional to the classified types, each type consists of divisions based on the operational structure and strategies. Preventive maintenance entails time based maintenance, condition-based maintenance, and predictive maintenance structures. Each maintenance strategy within the preventive maintenance is applied according to various requirements regarding the system and equipment maintained. Contributing factors for selecting maintenance strategy for specific system or equipment include; reliability and availability requirements, consequence of failure, health and safety requirements, and cost effect. Corrective or breakdown maintenance approach results after system failure, traditionally applied when profit margins are high. The most suitable combination of maintenance strategies can be applied for a system to satisfy the contributing factors. For some equipment, a corrective time-based maintenance can be more cost-effective than a condition-based predictive maintenance strategy.

Decision making for selecting a maintenance strategy is a challenging task for maintenance engineers and practitioners. The first challenge is to decide which maintenance strategy or a combination of strategies to implement for specific equipment. Secondly, how to justify the decision. Decisions have to be made with knowledge that failure of equipment is stochastic in nature. Implementation of various strategies can only mitigate the impact failure has on equipment.

Main decision making elements include the impact and improvement realised from a maintenance strategy, feasibility of the proposed decision, costs incurred, and other intangible factors. Determining maintenance strategies require knowledge on the amount of impact failure carries; the safety aspect to personnel in the plant, the environmental effect posed by such failure, the health hazards resulting from such failure, and the product or process quality according to international organisational standards. Maintenance personnel need approve feasibility of proposed decision for assessment of its feasibility and application. Capital required to implement the decision, level of skills required performing the tasks, logistics for implementation, stock levels, procurement, service providers, and the value for money also play a role in decision making.

Costs required to sustain maintenance is essential when making decisions. Main objectives for deriving maintenance plans and systems are to minimize maintenance
costs and improve production. Two variables, cost and production, need be maintained at optimum level to achieve a balanced operation. Equivalently, the amount invested in improving system/equipment reliability must be economically viable.

Other influential factors resulting from downtime and longer standing time of equipment include:

- Ineffective use of CMMS (Computerised Maintenance Management System): The less effective use of inventory control applications for spares, work orders and maintenance-planning tools create data inconsistency in management of equipment monitoring.
- Lack of correct tools: Availability of correct tool for performing tasks quicker and effectively decreases duration of repair and overall downtime. Some tasks require specialised tools for artisans to work safely and effectively, increasing the safety of the environment.
- Poor maintenance policy and process: Critical tasks require clearly set work instruction plans to provide sufficient knowledge about the equipment and necessary important information for maintenance.
- Lack of interest and motivation: The culture of the environment can negatively influence employees. Leadership styles employed by management and supervisors are critical in cultivating a healthy environment.
- Insufficient resources: Limited resources negatively affect execution of maintenance activities. This includes shortage of manpower and tools, or delayed delivery of equipment.

Statistical analysis characterises failure data to enable interpretation of historical events for a system. From the results, certain parameters indicate the trend followed and components with highest amount of failures.

For future research, data analysis can be further extended to analyse the characteristics of each components and sub-component within the plant system. This must involve the discrete analysis of time, cost and resources to perform maintenance tasks on the respective sub-components. A thorough study of the components’ fault trend and activities performed. Data derived from such a system will assist with precision in modelling the characteristics of each sub-component and holistically form
the entire plant system. The improvement cycle requires significant focus on the best Key Performance Indicators (KPI) such as:

- Reliability
- Availability
- Maintenance cost
- Safety and compliance

Processes for extracting data require time and precision in accuracy, periodic records, consistency, and detailed maintenance procedures. The quality and quantity of information is essential for improving overall maintenance of equipment.

In conclusion, with continuous improvement on maintenance strategies to sustain equipment reliability and improved availability, certain organisational aspects must improve. Task planning is essential for an effective maintenance team and inventory control software supports execution when utilised correctly. Training for personnel for required skill levels to be adequate to perform tasks and involvement in decision-making processes.
References


## Table 10: Failure Data

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<tr>
<th>Failure Number</th>
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## Weibull Distribution Fitting Algorithm

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<td>-61.86</td>
<td>290.68</td>
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</table>
Given the set of \( n \) points \((x_i, y_i)\) on a set of axis.

To find the best-fit line, \( \tilde{y}_i = mx_i + c \)

Such that the sum of squared errors in \( y \), \( \Sigma(y_i - \tilde{y}_i)^2 \) is minimised.

Let \( Q \) represent the sum of squares

\[
Q = \sum_{i=1}^{n} (y_i - \tilde{y}_i)^2 = \sum_{i=1}^{n} (y_i - mx_i - c)^2
\]

\( Q \) will be minimised at the values of \( c \) and \( m \) for which

\[
\frac{\partial Q}{\partial c} = 0
\]

And

\[
\frac{\partial Q}{\partial m} = 0
\]

Thus

\[
\frac{\partial Q}{\partial c} = \sum_{i=1}^{n} -2(y_i - mx_i - c) = 2 \left( nc + m \sum_{i=1}^{n} x_i - \sum_{i=1}^{n} y_i \right) = 0
\]

\[
\therefore c = \frac{\sum_{i=1}^{n} y_i}{n} - \frac{m \sum_{i=1}^{n} x_i}{n}
\]

And

\[
\frac{\partial Q}{\partial m} = \sum_{i=1}^{n} -2x_i(y_i - mx_i - c) = \sum_{i=1}^{n} -2(x_i y_i - mx_i^2 - x_i c) = 0
\]

Given the value of \( c \);

\[
\sum_{i=1}^{n} \left[ x_i y_i - mx_i^2 - x_i \frac{\sum_{i=1}^{n} y_i}{n} + x_i \frac{m \sum_{i=1}^{n} x_i}{n} \right] = 0
\]

\[
\equiv \sum_{i=1}^{n} \left[ x_i y_i - x_i \frac{\sum_{i=1}^{n} y_i}{n} \right] - m \sum_{i=1}^{n} \left[ x_i^2 - x_i \frac{\sum_{i=1}^{n} x_i}{n} \right]
\]
Solving for m

\[ m = \frac{\sum_{i=1}^{n} x_i y_i - x_i \sum_{i=1}^{n} \frac{y_i}{n}}{\sum_{i=1}^{n} x_i^2 - x_i \sum_{i=1}^{n} \frac{x_i}{n}} \]

Noting that

\[ \sum_{i=1}^{n} \left( \frac{\sum_{i=1}^{n} x_i}{n} \right)^2 - x_i \frac{\sum_{i=1}^{n} x_i}{n} = 0 \]

And

\[ \sum_{i=1}^{n} \left( \frac{\sum_{i=1}^{n} y_i}{n} \right) \left( \frac{\sum_{i=1}^{n} x_i}{n} \right) - y_i \frac{\sum_{i=1}^{n} x_i}{n} = 0 \]

m can be expressed as a ratio of Cov(x,y) to Var(x):

\[ m = \frac{\text{Cov}(x, y)}{\text{Var}(x)} \]

\[ \therefore m = \frac{\sum_{i=1}^{n} x_i y_i - x_i \sum_{i=1}^{n} \frac{y_i}{n}}{\sum_{i=1}^{n} x_i^2 - x_i \sum_{i=1}^{n} \frac{x_i}{n} + \sum_{i=1}^{n} \left( \frac{\sum_{i=1}^{n} x_i}{n} \right)^2 - x_i \sum_{i=1}^{n} \frac{x_i}{n}} \]

\[ = \frac{\sum_{i=1}^{n} \left( x_i - \frac{\sum_{i=1}^{n} x_i}{n} \right) \left( y_i - \frac{\sum_{i=1}^{n} y_i}{n} \right)}{\sum_{i=1}^{n} \left( x_i - \frac{\sum_{i=1}^{n} x_i}{n} \right)^2} \]

Equivalently

\[ m = \frac{\sum_{i=1}^{n} (x_i y_i) - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n}}{\sum_{i=1}^{n} (x_i)^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n}} \]
M is the slope; the shape parameter, \( \beta \).

\[
\beta = m = \frac{\sum_{i=1}^{N} x_i y_i - \frac{\sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N}}{\sum_{i=1}^{N} x_i^2 - \frac{[\sum_{i=1}^{N} x_i]^2}{N}}
\]
## Appendix A2

### FMEA/FMECA

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure Mode</th>
<th>Failure Causes</th>
<th>Failure Effect</th>
<th>Occurrence</th>
<th>Severity</th>
<th>Detectability</th>
<th>RPN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet separator drum</td>
<td>Failing to rotate</td>
<td>Foreign debris sticking on the magnetic drum</td>
<td>Worn v-belts</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>Water pumps</td>
<td>Inadequate flow</td>
<td>Slurry water at the discharge point</td>
<td>Material spillage</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>168</td>
</tr>
<tr>
<td>Material bins</td>
<td>Ineffective scrubbers</td>
<td>Bin choking at discharge</td>
<td>Material spillage at the discharge point</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>224</td>
</tr>
<tr>
<td>Conveyors</td>
<td>Insufficient lubrication</td>
<td>Material spillage at the discharge point</td>
<td>Material spillage</td>
<td>7</td>
<td>3</td>
<td>5</td>
<td>120</td>
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<td>Abnormal discharge</td>
<td>Worn pulleys</td>
<td>Material spillage at the discharge point</td>
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<td>120</td>
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<td>Spillage of material fines</td>
<td>Material spillage</td>
<td>7</td>
<td>3</td>
<td>5</td>
<td>120</td>
</tr>
<tr>
<td>Drums</td>
<td>Drum motor tripping</td>
<td>Drum motor tripping to convey material</td>
<td>Material spillage</td>
<td>4</td>
<td>5</td>
<td>7</td>
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### Conveyors

<table>
<thead>
<tr>
<th>Component</th>
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<tbody>
<tr>
<td>Abnormal discharge</td>
<td>Drive motor overload</td>
<td>Overload/Material overfeed</td>
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<tr>
<td>Abnormal discharge</td>
<td>High temperature on swingstock shaft</td>
<td>Insufficient lubrication</td>
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<tr>
<td>High vibration</td>
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<td>Bearing failure</td>
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### Material bins

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### Water pumps

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<tbody>
<tr>
<td>Defective bearing</td>
<td>Low pressure</td>
<td>Pump cavitation</td>
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<td>Pump cavitation</td>
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### Magnet separator drum

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<tr>
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<tbody>
<tr>
<td>Magnet trough blocked</td>
<td>Drum motor tripping</td>
<td>Defective bearing</td>
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<td>6</td>
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<td>4</td>
<td>80</td>
</tr>
</tbody>
</table>
Appendix A3

Downtime report

January

- Pumps: 2:45:00
- Conveyors: 0:00:00
- Vibrator feeders: 0:00:00
- Bins: 9:00:00
- Scales: 0:00:00
- Crushing: 50:19:00
- Magnet sep: 5:00:00
- Planned shutdown: 35:00:00
- Grizzly: 0:00:00
February

- Pumps 0:00:00
- Conveyors 28:13:00
- Vibrator feeders 0:00:00
- Scales 0:00:00
- Crushing 50:18:00
- Bins 3:30:00
- Grizzly 0:00:00
- Magnet sep 0:00:00
- Planned shutdown 103:10:00