A structured approach for the reduction of mean time to repair of blast furnace D, ArcelorMittal, South Africa, Vanderbijlpark

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ABSTRACT

Organizations are expected by their shareholders to continually deliver above industry returns on capital invested and to remain competitive in the industry of choice through productivity, safety and quality. The maintenance function is a key area in which competitiveness through efficiencies and world-class performance can be attained by focusing on the prevention and reduction of long and costly equipment repair times.

The question is: *how can the mean time to repair of equipment already installed in the plant be reduced?*

To answer the above question correctly and comprehensively, the research explored mixed methods in finding answers. Quantitative methodology using a survey was used for data collection. Observations and interviews were held with maintenance personnel to uncover information that couldn't have been obtained by means of a survey.

The survey was limited to equipment performance measures, human factors, environmental factors, planning, spare parts, maintainability, procedures and training. To test consistency and accuracy of representation of the total population under study, a reliability test was done by using Cronbach's alpha coefficient. To determine whether there are any differences between groups, an ANOVA test was used. Cohen's d-value was used to determine practically significant differences between one set of data with another and correlation analysis was used to determine the relationships between the variables.

The approach designed and delivered by this research flowed from the existing body of knowledge, case studies and survey findings. The approach adopts some of the elements of the failure mode and effects analysis (FMEA) procedure and differs from other work that has been done by others by taking into account the competency and experience of maintenance personnel and assigning to them factors which are used to compute anew MTTR of the equipment. The cost of implementing the recommended corrective actions for realising the new MTTR is determined and

evaluated against an improved equipment availability that will be achieved as a result of the recommended corrective actions assuming that the failure rate of the equipment remains constant. This evaluation step imbedded within the approach is valuable for the maintenance function and management for decision making in ensuring that resources at the organization's disposal are used productively.

Validation and test results of the approach showed that the MTTR of equipment installed in the plant can be reduced. The results also indicated that through the use of the designed approach a regular pattern of repair or replacement times can be followed well in advance and that it is practical, user friendly and it also delivers on its objective of offering a structure for analysis and decision making aimed at reducing the MTTR.

Included with this dissertation is feedback information that can be included in a maintenance job card feedback section to capture information about factors that can be improved to lower the MTTR as part of a continuous improvement process. Included also is a spare part development and management procedure that can be used by the maintenance function.

Recommendations on training of maintenance personnel on the maintainability of equipment, the FMEA procedure and maintenance procedures are highlighted.

Information that flowed from this approach will be valuable for continuous plant performance improvement and during the design, installation and operation stages of a blast furnace.

Keywords: mean time to repair, reliability, availability, maintainability, maintenance strategies, failure mode and effects analysis (FMEA), blast furnace, ArcelorMittal South Africa, training, procedures, spare parts, competency, experience.

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Keywords

ArcelorMittal South Africa
Availability
Blast furnace
Competency

Experience
Failure Mode and Effects Analysis (FMEA)
Maintainability
Maintenance procedures
Maintenance strategies
Mean time to repair
Reliability
Spare parts
Training

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List of Symbols and Acronyms

AMSA	–	ArcelorMittal South Africa Limited
ANOVA	–	Analysis of Variance
ATE	–	Automatic Test Equipment
BFD	–	Blast Furnace D
BITE	–	Built In Test Equipment
BLT	–	Bell Less Top
BOM	–	Bill of Materials
CMMS	–	Computerized Maintenance Management System
CMT	–	Corrective Maintenance Time
COI	–	Cost of Implementation
FMEA	–	Failure Mode Effect Analysis
FMECA	–	Failure Mode Effect and Criticality Analysis
LCC	–	Life Cycle Cost
MDT	–	Mean Down Time
MTBF	–	Mean Time Between Failures
MTBM	–	Mean Time Between Maintenance
MTTR	–	Mean Time To Repair
NPV	–	Net Present Value
OEM	–	Original Equipment Manufacturer

PaM	–	Proactive Maintenance
PdM	–	Predictive Maintenance
PM	–	Preventive Maintenance
RAM	–	Reliability, Availability and Maintainability
RCA	–	Root Cause Analysis
RCM	–	Reliability Centred Maintenance
RPN	-	Risk Priority Number
RtFM	–	Run to Failure Maintenance
SAP	–	Systems, Applications and Products

A_a	–	Achieved availability
A_i	–	Inherent availability
A_o	–	Operational availability
d	–	Cohen's difference value
α	–	Cronbach's coefficient alpha
λ	–	Failure rate
r	–	Pearson's correlation coefficient
μ	–	Repair rate

Glossary of Terms

-A-

Availability: A measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called for at an unknown (random) time (MIL-STD 721C).

Accessibility: means having sufficient workspace and access to perform maintenance safely and efficiently Mostia (2004).

-C-

Component: A piece of electrical or mechanical equipment viewed as an entity for the purpose of reliability evaluation (TM 5-698-1).

Corrective maintenance (CM): Any maintenance activity which is required to correct a failure that has occurred or is in the process of occurring. This activity may consist of repair, restoration or replacement of components Dunn (2011).

Criticality: A relative measure of the consequences of a failure mode and its frequency of occurrences SYDNEYWATER (2010).

-D-

Detection: The ability of a test, combination of tests, or a diagnostic strategy to identify that a failure in some system element has occurred Esker *et al* (1990).

Downtime: That element of time during which an item is in an operational inventory but is not in condition to perform its required function.

-E-

Equipment: A general term designating an item or group of items capable of performing a complete function SYDNEYWATER (2010).

-F-

Failure: Event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified SYDNEYWATER (2010).

Failure effect: The consequence(s) a failure mode has on the operation, function, or status of an item. Failure effects are classified as local effect, next higher level, and end effect.

Failure mode: The specific condition that causes a functional failure. The failure mode describes what specifically causes the item to fail or to perform below an acceptable level DTIC (2011).

Functional failure: The failed state of the system (e.g., the system falls outside the desired performance parameters) DTIC (2011).

-I-

Interchange-ability: A component's ability to be replaced with a similar component without a requirement for recalibration (NASA/TM-4628:5).

Isolation: Determining the location of a failure to the extent possible, by the use of accessory equipment.

-L-

Localization: The ability to say that a fault has been restricted to some subset of possible causes Esker *et al* (1990).

Logistic delay time (LDT): The element of downtime during which no maintenance is being accomplished on the item because of either supply or administrative delay.

-M-

Maintenance: The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to a state in which it can perform a required function Alshayea (2010).

Mean downtime (MDT): The average downtime caused by preventative and corrective maintenance, including any logistics delay time.

Mean time to repair: The average time it takes to diagnose and correct a fault, including any reassembly and restart times Reussner *et al* (2003).

Modularization: A continuum describing the degree to which a system's components may be separated and recombined Babylon (2011).

-P-

Preventive maintenance (PM): Predetermined work performed to a schedule with the aim of preventing the wear and tear or sudden failure of equipment components IAPA (2007).

Proactive maintenance (PaM): A maintenance strategy that focuses on the process of learning from past maintenance problems in order to reduce future maintenance work and improve equipment reliability by addressing root causes Slater (2010).

-R-

Reliability: The measure of probability that equipment (or process) will perform its designed function for a specified period Vesier (2004).

Reliability Centred Maintenance (RCM): A disciplined logic or methodology used to identify preventive and corrective maintenance tasks to realize the inherent reliability of equipment at a minimum expenditure of resources, while ensuring safe operation and use (TM 5-698-1).

Run to failure maintenance (RtFM): A maintenance strategy where no routine maintenance tasks are performed on the equipment (SKF, 2010).

-S-

Standardization: The attainment of maximum practical uniformity in an item's design.

-T-

Testability: A design characteristic which allows the status (operable, inoperable, or degraded) of an item to be determined and the isolation of faults within the item to be performed in a timely manner (MIL-HDBK-2165).

Tradesman: A skilled worker TheFreeDictionary (2011).

CHAPTER 1: INTRODUCTION

In this chapter maintainability, mean time to repair, maintenance strategies and failure mode and effects analysis will be introduced to form the basis of the research. Furthermore the research problem, purpose, objectives, methodology and outline will also be discussed. Preliminary chapter divisions are also given in this chapter.

1 BACKGROUND

Every organization depends on the availability and efficiency of its resources for it to remain competitive in a very challenging economic climate. The proper functioning of its assets used in the production line is crucial for delivering a product on time and that meets the expectations of customers. Thus the reliability, availability and maintainability of these assets must remain high to enable the organization to meet its business objectives through committed resources.

Carlier *et al* (1996) point out that the limitations of system maintainability influence its unavailability. Unavailability of equipment affects the maintenance function responsible for ensuring its availability through maintenance actions and also the competitiveness of the organization using these assets for production. To achieve the required equipment availability, it must be highly reliable and have short corrective maintenance periods that are a result of effective maintainability. By achieving good reliability and maintainability design, the availability of the equipment is thus met.

1.1 Introduction to maintainability and mean time to repair

1.1.1 Introduction to maintainability

Barabady (2005: 1) in his study of *Improvement of system availability using reliability and maintainability analysis* states that equipment reliability, availability and maintainability (RAM) have assumed great significance in recent years due to a competitive environment and overall operating cost/production cost.

Thornton (2001) states that the maintenance of equipment can be ten times more difficult in the field or environment where it is utilized or used than in an environment designed for the performance of its maintenance. To minimize and eliminate unnecessary maintenance delays, it becomes important that operational maintainability of equipment be known especially in its environment where it is utilized or used.

Although maintainability requirements need to be allocated and managed in the design stage of a product, effective management and understanding of the influence of maintainability of equipment in operation by maintenance practitioners has the potential of improving the performance of an organization in terms of productivity, safety and quality (Madu, 2004). Thus a shift from failure-avoidance to failure-recovery needs to be investigated by the organization in a quest of preventing and reducing the repair times of equipment (Jiun Song *et al*, 2002).

The operational maintainability of equipment needs to be determined qualitatively and quantitatively to ensure that its impact on the competitiveness of the organization is known and understood to ensure that corrective actions effectively address the gaps identified. This task has to be planned and executed with the assistance of a method that will yield results that are independent of the executer.

1.1.2 Introduction to the mean time to repair

When equipment fails, steps need to be taken by trained and competent maintenance personnel on repair procedures to repair or restore the equipment to its original state. The repair times and costs associated with the corrective maintenance can be reduced by effectively performing maintenance tasks required to restore the equipment. An index known as the **mean time to repair (MTTR)** is used by maintenance practitioners to measure the maintainability of equipment.

The MTTR analyses how long corrective maintenance tasks take in an event of a system failure. Corrective maintenance activities include (Blanchard & Fabrycky, 1998: 404; Tarelko, 1995: 86) failure detection, preparation for maintenance, localization and isolation of a cause, technical delays, disassembly, waiting for spare

parts, rebuilding of damaged parts, an interchange, reassembly, an alignment and adjustment and condition verification.

The MTTR of equipment installed in a plant tends to be accepted by maintenance practitioners as an inherent component of equipment design and installation because of no methodology at their disposal that they can use to scientifically determine its baseline figure. The knowledge of a baseline MTTR for equipment in operation can enable maintenance practitioners to effectively address any deviations and ensure consistency and improvement of equipment recovery.

The development of a methodology that can be used by maintenance practitioners to identify, quantify, document and analyse with the objective of reducing the MTTR of equipment has the potential of reducing breakdown durations, improve plant availability, add value to the organization's bottom line, and improve the company's competitiveness through the maintenance function.

1.2 Introduction to maintenance strategies

Production losses as a result of equipment failure in a manufacturing facility happen as equipment wears and tears because of usage. It is stated by Löftsen (1999) that the purpose of maintenance management is to reduce the adverse effects of equipment breakdown and to maximize the facility availability at minimum cost.

de Castro *et al* (2006) point out that if equipment reliability is improved, it can function for longer periods of time and if the maintenance program is improved, it can be repaired quickly thus improving its availability.

Every strategy adopted for the plant must be supported by resources to ensure that it becomes a success by achieving its objectives. A number of maintenance strategies are found in practice in many industries that enable organizations to achieve a competitive advantage.

These strategies include:

- Run to failure maintenance (RtFM)
- Preventive maintenance (PM)
- Reliability centred maintenance (RCM)
- Proactive maintenance (PaM)
- Predictive maintenance (PdM)

No matter what maintenance strategy is adopted for equipment, a time comes when maintenance has to be performed when the equipment fails. The MTTR of the equipment affects its availability which is usually visible to management of the organization. The need for a holistic approach for documenting, quantifying and evaluating the value that an improved MTTR of plant equipment can add in achieving the desired or set availability for equipment becomes important for management for decision making on corrective actions that flow form such an approach.

1.3 Introduction to failure mode and effects analysis

Although equipment failure is not desirable, it is an intrinsic part of equipment design. It is estimated that the spending on maintenance of equipment and facilities by industry in the US is more than $200 billion per year Tsarouhas *et al* (2009). The maintenance function is tasked with ensuring that the reliability of assets is maintained or improved through preventive maintenance actions performed at a predefined schedule.

The effectiveness of these actions is evaluated using performance measures like availability and unplanned stoppages Auodia *et al* (2008). These performance measures are being escalated and discussed at higher management levels within an organization thus causing the maintenance function to be put under a spotlight.

Resources are made available and are committed by management to ensure that in an event of a failure, the failure is resolved with a low MTTR. The reduction of the MTTR cannot be realized by itself unless mechanisms are put in place to support the

maintenance function in ensuring that assets are repaired with the lowest possible downtime. Item failures and modes that are likely to result in long repair times need to be identified, documented, quantified and analyzed so that corrective actions can be implemented to minimize maintenance actions durations.

The failure mode and effects analysis (FMEA) is a tool used by reliability engineers to identify critical components whose failure will lead to undesirable outcomes. When criticalities of the failures are assessed, the method is known as FMECA. According to Yang *et al* (2006) potential failures and impacts of each item failure through the application of the FMECA are examined and preventive measures and improvement proposals are adopted to eliminate the consequences of these failures.

The FMEA procedure can be used to identify and quantify repair times to complete corrective maintenance activities with respect to each failure mode of equipment taking into consideration its maintainability characteristics. A **maintenance-maintainability** centered approach driven by the identification of failure modes of equipment with long repair times can enable the maintenance function to reduce the MTTR by implementing corrective actions where gaps are identified.

1.4 PROBLEM FORMULATION AND PURPOSE

1.4.1 Problem Formulation

The previous paragraphs have introduced maintainability, maintenance strategies, the MTTR and FMEA. Shallow knowledge, understanding and appreciation of the impact of maintainability, maintenance strategies and the MTTR on the performance of the maintenance function and the organization can be a barrier in unlocking and improving the competitiveness of the organization according to its business strategy and objectives. This potential of improved competitiveness must be taken full advantage of and speedily once known as organizations are competing for a small market not only locally but also globally.

It is usually accepted by management that equipment failure occurs after some time as it is used for production. It is important that the consequences of failures are

minimised and the benefits of corrective actions to minimize exposing the organization to a loss of revenue and image as a result of a failure also be quantifiable.

Research conducted by others on equipment maintainability has focused on tools for predicting maintainability during its design stage and not on operations too. The MTTR is a challenge faced by maintenance practitioners “in the field” on a daily basis when management ask *what* is an acceptable repair time for the equipment , *what* corrective actions will be implemented to prevent a recurrence and *how* is this going to improve the availability of the plant.

The research aims to answer the following question:

How can the mean time to repair of equipment already installed in the plant be reduced?

Therefore, it is valuable to conduct a scientific investigation that leads to the discovery and interpretation of information into the problem of prolonged and inconsistent corrective maintenance times which contribute to a loss of revenue as a result of a high MTTR. A proactive approach for the reduction of the MTTR is more desirable than a reactive one because each action to avert prolonged and unmanaged MTTR has a direct impact on profitability.

A structured approach for the reduction of the current MTTR of plant equipment that builds on the existing body of knowledge must be developed. The deliverables of the approach must be measureable to enable management to make informed decisions about the corrective actions that will need to be implemented to realize the lower MTTR at an acceptable premium. Marquez and Geguedas (2002) note that the better the maintenance resources the faster the repair, and therefore the lesser the time the system will be in a corrective maintenance state.

1.4.2 Research purpose

The purpose of the research is to describe and develop an approach that can be used by the maintenance function of the blast furnace area to reduce the MTTR of plant equipment installed at Blast Furnace D (BFD), ArcelorMittal South Africa Limited (AMSA), Vanderbijlpark. Historic MTTR data for the blast furnace are given in Table 1.4.2 below with an average MTTR of 3.33 hours recorded.

Table 1.4.2: Historic MTTR of Blast Furnace D

Year	Mean Time To Repair (hours)
2007	2.64
2008	3.86
2009	4.40
2010	2.44
2011	3.30

In an attempt to reduce the MTTR of equipment already installed in the plant, the approach described and developed will take into consideration the impact of equipment **failure mode and effects, maintainability, experience and competency** of maintenance personnel.

The cost of implementing corrective actions that flow from the approach will be evaluated against equipment availability that will be achieved by reducing the MTTR.

1.5 FOCUS AND OBJECTIVES

1.5.1 Research focus

Breakdown of equipment is undesirable for the maintenance function and management because of its effect on resources and cost e.g. overtime, loss of production, safety, etc. When a failure occurs, it is required of the maintenance

function and personnel that repairs are undertaken without any delay and equipment put back into operation with minimum downtime and cost as far possible.

The tendency after such an event is to find the cause of the failure, which is usually linked to the reliability of the equipment. The question of what needs to be done in the future to ensure that the time taken to repair the equipment is reduced is not usually addressed. An opportunity to address factors that might have contributed to the long repair time after a failure is lost because of a lack of knowledge of the equipment's baseline MTTR and an approach that will assist the maintenance function to proactively address potential future failures that will result in a repeat.

Maintenance practitioners and management must realize that the performance of the organization can be improved through the reduction of the MTTR of plant equipment. It is envisaged that through the research, an approach that will enable blast furnace maintenance practitioners to realize potential gains for the organization by reducing the MTTR will be developed. It is furthermore the intention of this research to make management aware of the benefits that will result as a consequence of an overall lower MTTR of the plant.

1.5.2 Research demarcation and motivation

The research will be limited to:

- The maintenance function responsible for maintaining BFD at AMSA, Vanderbijlpark.
- The analysis of the impact of the current MTTR on the performance of the plant.
- The analysis of repairable equipment with a constant failure rate.
- The identification and documentation of maintainability characteristics that directly affect plant equipment.
- The design of a structured approach that can be used by the maintenance function to reduce the MTTR of plant equipment.

The identification of factors which negatively impact the reduction of the MTTR will enable the maintenance function to understand, appreciate and take advantage of possible opportunities which result in an improved MTTR and availability of plant equipment.

It is envisaged that data obtained and knowledge gained will also be used in the future as an input for continuous improvement for the design and construction of a new blast furnace.

1.5.3 Research objectives

Based on the discussions in the previous paragraphs, the primary objective of the research is to formulate and deliver a structured approach that can be used by maintenance practitioners to enable them to reduce the MTTR of BFD, AMSA, Vanderbijlpark.
The secondary objectives supporting the primary objective of the research are:

- To determine how the current corrective maintenance cycle of plant equipment affects the MTTR.
- To determine whether maintenance personnel understand the concept of equipment maintainability.
- To determine whether the level of maintenance personnel training bridges the gap of achieving a lower MTTR.
- To determine whether the level of education and competency of maintenance personnel contributes to the current MTTR.
- To determine whether there a relationship exists between human factors, environmental factors, maintainability, planning, procedures and the current MTTR of plant equipment.
- To determine whether a relationship exists between the experience of maintenance personnel and the use of procedures.

It is assumed that the MTTR of the plant can be reduced through the application of a methodology that uses experience and competency of maintenance personnel,

maintainability characteristics as inputs for quantification, evaluation and decision making for reducing the MTTR.

1.6 METHODOLOGY

1.6.1 Analysis of literature and sources of information

The research will commence with an analysis of literature and sources of information from the following sources:

- Journals
- Technical papers
- Dissertations and
- Internet

The research will adopt a descriptive and exploratory research approaches to describe and develop new knowledge about the effects and criticality of equipment maintainability attributes on corrective maintenance repair times with the aim of improving the MTTR. This will entail an extensive study and critical analysis of work done by others in determining the impact of maintainability characteristics on the MTTR of equipment.

1.6.2 Empirical investigation

Qualitative and quantitative research methods will be used for this research in meeting both the primary and secondary objectives of the research mentioned in the previous paragraphs. The quantitative research method allows for the measurement and analysis of the statistical data, as well as to determine relationships between one set of data with another (Fox & Bayat, 2007). The results obtained from the empirical investigation shall be compared with results obtainable from literature sources. Finally, the results of the approach shall be explored and recommendations where necessary be made.

1.7 RESEARCH OUTLINE

With the information collected by means of the methodologies mentioned in the previous paragraphs, maintainability, maintenance strategies, the MTTR and FMEA and the structured approach of reducing the MTTR of Blast Furnace D will be discussed in detail. Conclusions and recommendations regarding the delivered approach for reducing the MTTR of plant equipment will be drawn, in summary of and conclusion to the research.

1.8 CHAPTER SUMMARY

In this chapter maintainability, maintenance strategies, the mean time to repair, failure mode and effects analysis, the research problem and purpose, research objectives, research methodology and outline were introduced. In *chapter 2*, the focus on the body of knowledge that is relevant to the research problem will be discussed.

CHAPTER 2: LITERATURE REVIEW

In this chapter a brief background of Blast Furnace D and literature found on maintenance strategies, maintainability attributes, maintainability measures and functions and the failure mode and effects analysis will be discussed to form the basis for answering the research question of *chapter 1, section 1.4.1*.

2.1 History of Blast Furnace D

Blast furnace D is located at the Vanderbijlpark Works of ArcelorMittal South Africa Limited. AMSA is the largest steel producer on the African continent, with a production capacity of 7.8 million tonnes of liquid steel per annum (ArcelorMittal South Africa, 2011). The plant forms an integral part of the iron making process of the company.

The furnace was rebuilt in 2007 to increase its capacity to 154 000 ton/month. Raw materials such as iron ore, coke and dolomite are charged into the blast furnace where they are converted into liquid iron as shown in the process flow of Figure 2.1 (ArcelorMittal South Africa, 2011).

The blast furnace plant is broken down according to the following functional areas that are integral for the production of liquid iron (ArcelorMittal South Africa, 2008):

- Stock house
- Furnace top
- Cast house
- Slag granulation
- Gas-cleaning and
- Hot blast stoves

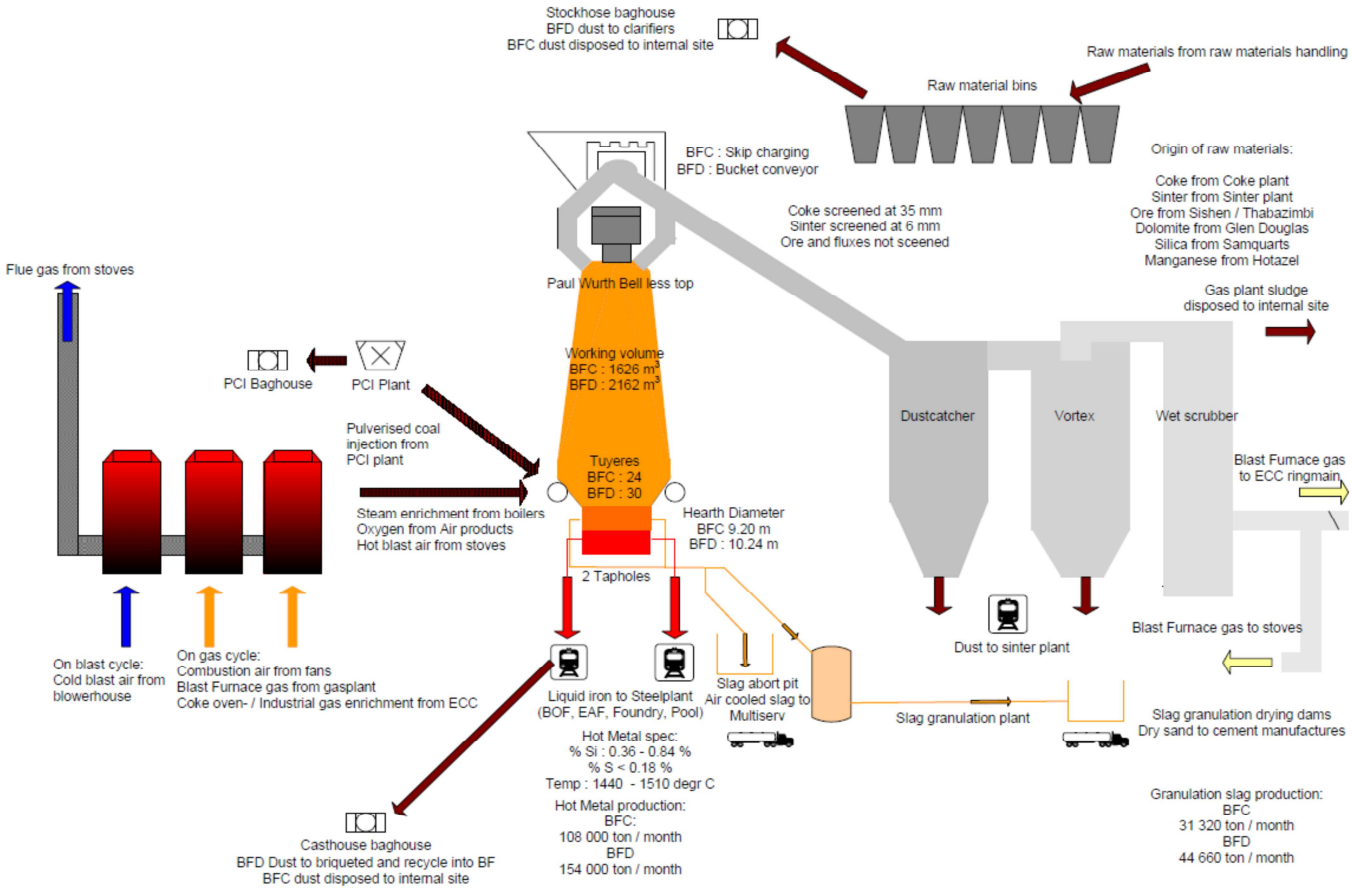


Figure 2.1: The blast furnace process flow

Source: ArcelorMittal South Africa (2008)

2.1.1 Stock house

Raw materials are received and stored in the Stock house area of the plant. For material handling and processing, conveyors, chutes and screens are installed to serve this purpose in this area of the plant. Raw materials are accurately weighed for exact size fractions to the charging system. As a result of handling raw materials, dust is usually generated in this area and tends to hamper the execution of maintenance.

2.1.2 Furnace top

The furnace top consists of the furnace charging through the Bell Less Top (BLT), top weigh hopper equalisation and relief system, BLT Cooling, and hydraulic and lubrication systems. The BLT equipment allows for controlled charging of burden

materials into the furnace via a chute located in the furnace top. The chute is able to rotate and change its angle of elevation to suit the burden distribution pattern. Equipment installed at the furnace top is exposed to the elements of the environment as a result of the furnace construction.

2.1.3 Gas-cleaning

The blast furnace gas cleaning system is to remove particulate matter from the blast furnace gas. This plant is made up of a dust catcher, vortex and wet scrubber. The dust catcher and vortex trap particulate matter in the gas generated as a result of the melting process of the blast furnace. Remaining particulate matter in the gas is washed off by water sprays in the wet scrubber.

Equipment installed at the in this area of the plant consists of slurry pumps, scrappers and hydraulic pumps. In an event of equipment failure it must be repaired as quickly as possible because of its impact on production targets set by the organization.

2.1.4 Cast house

Cast house equipment includes hydraulic clay guns, hydro-pneumatic taphole drills, troughs and tilting runners where iron and slag are separated and iron is directed toward the torpedo responsible for transporting the molten iron to another plant for further processing.

The hydraulic taphole drill provides drilling performance, employing a combination of high rotational drilling torque with a rapid percussive rate at medium impact energy. Clay guns are designed for high clay ramming pressures, fast slew and automatic operation. Equipment installed in this area of the plant is exposed to high hydraulic pressures and extreme temperatures. Cast house equipment is required to be highly reliable and always available for use due to safety and operations constraints.

2.1.5 Slag granulation

The melted (liquid) slag at the temperature of 1300℃ – 1500℃ tapped separated from molten iron is led into a granulation stack through a channel system where it is quenched by pressurised water stream. The granulation water breaks up the slag stream and helps to push the slag into the granulation basin below the water level (Leyser & Cortina, 2006). The slag is transported to a dewatering drum via pumps where it is separated from the water and transported to the storage area by a conveyor. Equipment installed in this area of the plant is exposed to high temperatures, high wear and elements of the environment.

2.1.6 Hot blast stoves

They preheat incoming air before use in a blast furnace. Consistent delivery of preheated blast air to the furnace within a specified temperature range is key to controlling the thermal state of the blast furnace. The hot blast stove system consists of stoves, combustion fans, burners, refractories and hydraulic operated valves.

Although various measures have been taken to protect hot blast stoves from typical damage, some wear and tear to their parts during their long life is unavoidable Yamada et al (2008). Equipment installed in this area of the plant is exposed to high temperatures, noise, and challenges with regard to handling and accessibility.

2.2 History of maintenance

The history of maintenance can be categorized according to pre-World War II, post-World War II and1980 onwards. The pre-World War II era or first generation maintenance stands out as the “fix the equipment when it breaks” maintenance, simple equipment, over designed and easy to repair equipment (Cooke, 2003). The post-World War II or second generation maintenance saw a need to prevent equipment failures by industry through preventive maintenance which led to a demand for reliable equipment.

Alshayea (2010) states that the 1980 era saw industries demanding an integrated approach to equipment maintenance with focus on equipment safety, quality, reliability, availability and the need to reduce the costs associated with the maintenance of equipment.

2.2.1 Maintenance definition and objectives

All manufacturing companies choose to compete in the market based on some competitive priorities like cost, quality, flexibility and other priorities, depending upon their manufacturing capabilities (Pinjala *et al*, 2006). It is to the benefit of an organization to realize that equipment maintenance and its reliability are also important strategies that can affect the ability of an organization to compete effectively Madu (2000).

Maintenance is defined as:

- The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to a state in which it can perform a required function (Alshayea, 2010).
- All actions necessary for retaining an item in, or restoring it to, a specified condition (NASA-STD-8729.1, 1998: 3-6).

A maintenance perspective within an organization is shown in Figure 2.2.1. The purpose of performing equipment maintenance is solely focused on ensuring that the equipment will be able to perform its function when required. Al-Najjar (2007) notes that negligence of maintenance and its role in the production process allows rapid degradation of machine and product quality.

The objectives of equipment maintenance managed by the maintenance function in supporting the primary objectives of the business are;

- To provide production with the long and short-term manufacturing system availability requirements at a minimum resource cost (Zeng, 1997).

- To preserve equipment performance to meet output targets (Ip *et al*, 2000).
- To optimise resources utilisation at its disposal.
- To reduce or eliminate equipment downtime.
- To optimise the useful life of equipment.

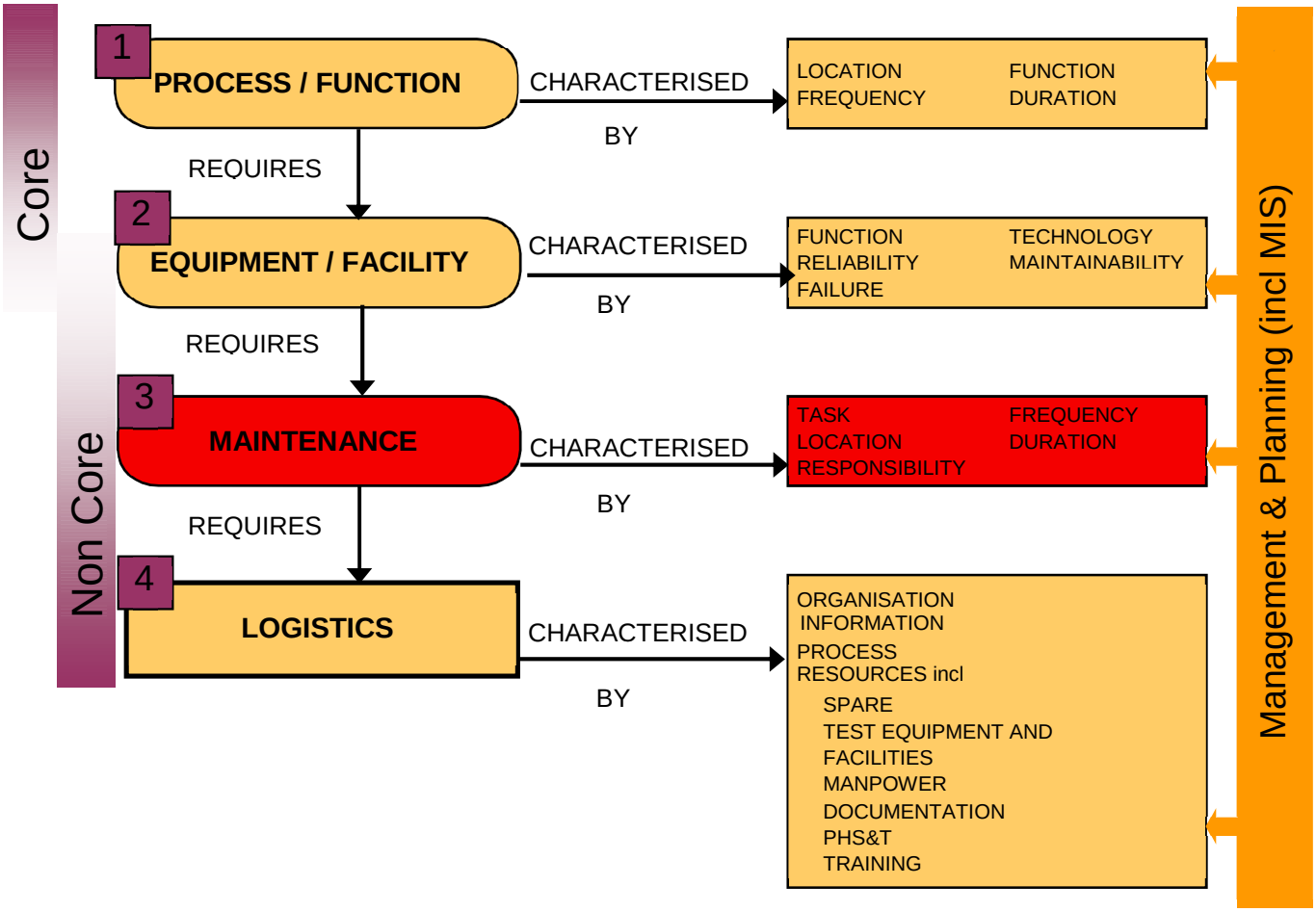


Figure 2.2.1: Maintenance in perspective

***Source*:** Wichers (2008)

2.2.2 Maintenance strategies

Strategy means a long term plan of action designed to achieve a particular goal or set of goals or objectives (Rapid Business Intelligence Success, 2008). The maintenance function is tasked not only with defining the goals appropriate for

different levels of maintenance execution, but also a common way to attain these goals.

Strategies adopted by the maintenance function for plant equipment are adopted for the elimination of equipment failures but they also attempt to address how such failures can be rapidly detected and corrected in the minimum time.
Maintenance strategy is defined as;

- A coherent, unifying and integrative pattern of decisions in different maintenance strategy elements in congruence with manufacturing, corporate and business level strategies; determines and reveals the organizational purpose; defines the nature of economic and noneconomic contributions it intends to make to the organization as a whole (Pinjala *et al*, 2006).

- A long-term plan, covering all aspects of maintenance management which sets the direction for maintenance management, and contains firm action plans for achieving a desired future state for the maintenance function (Kwaliteg, 2011).

- A management method used in order to achieve the maintenance objectives (Kans, 2008).

Moubray (as quoted by Eti *et al*, 2000) states that developing and executing a maintenance strategy consists of three steps;

1. Formulate a plan of what needs to be done for each component (i.e. work identification).
2. Acquire the resources (skilled personnel, spares and tools) needed to execute the proposed procedure effectively.
3. Implement the strategy (i.e. acquire and deploy the systems needed to manage the resources effectively).

A number of maintenance strategies are found in practice in many industries that enable organizations to achieve a competitive advantage. These strategies include:

- Run to failure maintenance (RtFM)
- Preventive maintenance (PM)
- Reliability centred maintenance (RCM)
- Proactive maintenance (PaM) and
- Predictive maintenance (PdM)

Each maintenance strategy can be applied as a stand-alone strategy or be combined with the other strategies to achieve the optimum benefits for the organization. It should be noted that a maintenance strategy gives better results as it is allowed to evolve as knowledge and experience is gained about the equipment. A good maintenance strategy has to deliver a low cost of implementation when it is compared with the consequences of not performing the maintenance required.

2.2.3 Run to failure maintenance (RtFM)

Run to failure maintenance (RtFM) is the oldest known maintenance strategy and it can be described as a fire fighting approach. RtFM is a strategy where no routine maintenance tasks are performed on the equipment (SKF, 2010). The repair, replacement or restoration of equipment to its baseline functional level is conducted only after a failure has occurred as illustrated in Figure 2.2.3.

To perform maintenance on the equipment, it is taken out of operation for repair, replacement or restoration by maintenance personnel and then put back in operation after completion of the maintenance tasks. Some of the major expenses incurred by industry relate to the replacements and repairs of manufacturing machinery in a production processes (Percy & Kobbacy, 2000).

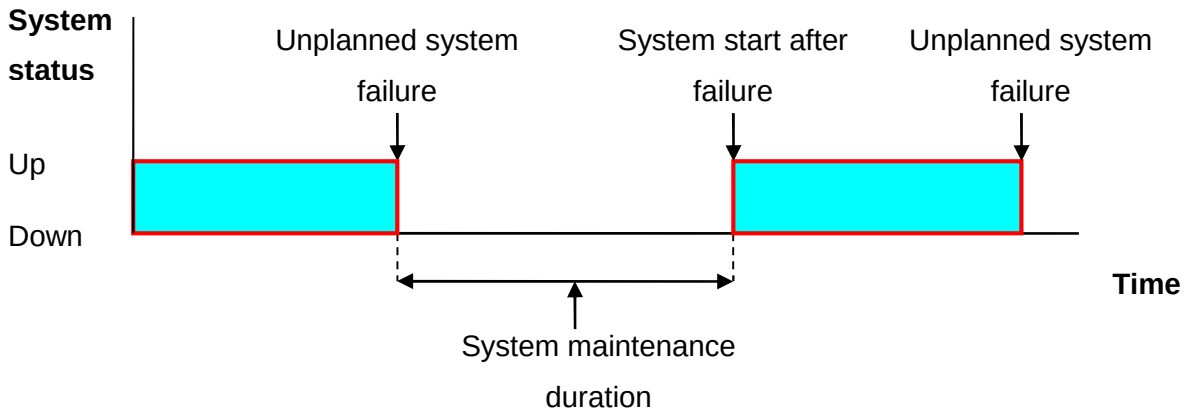


Figure 2.2.3: System status and maintenance duration after system failure

Source: Carlier *et al* (1996)

The disadvantages of this type of maintenance strategy are:

- Its activities are expensive due to unplanned downtime of equipment (RFKCorsa, 2011).
- Using this type of maintenance, the occurrence of a failure in a component can cause failures in other components in the same equipment, which leads to low production availability.
- Its activities are very difficult to plan and schedule in advance.

This type of maintenance of strategy is useful in the following situations:

- The failure of a component in a system is unpredictable.
- The cost of performing run to failure maintenance activities is lower than performing other activities of other types of maintenance.
- The equipment failure priority is too low in order to include the activities of preventing it within the planned maintenance budget.

2.2.4 Preventive maintenance

The preventive maintenance is predetermined work performed to a schedule with the aim of preventing the wear and tear or sudden failure of equipment components IAPA (2007). This type of maintenance relies on the estimated probability that the

equipment will fail in the specified interval (Swanson, 2001). Preventive maintenance tries to determine a series of checks, replacements and/or component revisions with a frequency related to the failure rate (Bevilacqua & Braglia, 2000).

The maintenance work undertaken may include equipment lubrication, parts replacement, cleaning and adjustment. Figure 2.2.4 shows maintenance activities carried out as the functional level of equipment degrades.

The scheduling of maintenance work is either done through qualitatively or quantitatively analysis. Quantitatively analysis requires that equipment be modeled and the preventive maintenance strategy optimized to improve the strategy (Percy and Kobbacy, 2000).

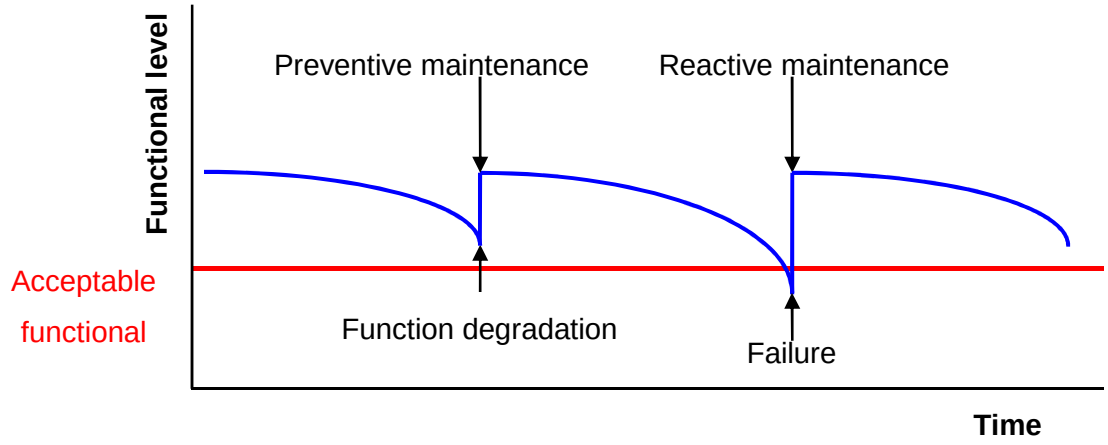


Figure 2.2.4: Maintenance activities according to functional level of equipment.
Source: Takata *et al* (1995).

As illustrated from the figure above, preventive maintenance action is only taken on the equipment while it is still operating, which is carried out in order to keep the system at the desired functional level (Park *et al*, 2000).

Eti *et al* (2006) list the following advantages of the preventive maintenance strategy;

- Tasks are planned rather than reactive thus ensuring that resources needed to successfully execute maintenance activities are made available in advance.

- Reduce the amount of reactive maintenance to a level that allows other practices in the maintenance process to be cost effective.
- Reduce breakdowns and emergency shutdowns.

Espinoza (1995: 31) notes the following disadvantages with implementing the preventive maintenance strategy;

- It is inappropriate for equipment where the design life of the parts involved in failure mode is less than the minimum expected maintenance cycle.
- It can cause failures as a result of inadequate or improper repair procedures.
- It can be costly and unnecessary to perform the maintenance task when it is scheduled.

2.2.5 Predictive maintenance

Carnero (2005) states that predictive maintenance is a maintenance policy in which selected physical parameters associated with an operating machine are sensed, measured and recorded intermittently or continuously for the purpose of reducing, analyzing, comparing and displaying the data and information so obtained for support decisions related to the operation and maintenance of the machine.

The purpose of predictive maintenance is to maximize equipment reliability and availability by determining the need for maintenance tasks based on the condition of the equipment. Techniques employed in predictive maintenance include vibration measurement, infrared thermal imaging, oil analysis and tribology, ultrasonic and motor current analysis (Dunn, 2009). The technique applied is chosen according to the need of the plant and equipment.

Carnero (2006) categorises predictive maintenance into two categories, namely;

- ***Statistical-based Predictive Maintenance***. The information generated from all stoppages facilitates development of statistical models for predicting failure and thus enables the developing of a preventive maintenance policy.

- ***Condition-based Predictive Maintenance***. Condition-based monitoring is related to the examination of wear processes in mechanical components. The wear process is preceded by changes in the machine's behaviour although does not cause sudden mechanical failure.

Successful implementation of predictive maintenance requires management commitment, technologies and highly skilled personnel to integrate available equipment condition indicators to make timely decisions about maintenance requirements about critical equipment.

Advantages of predictive maintenance include the following (Carnero, 2004):

- Better scheduling of maintenance actions and human resources as maintenance tasks on equipment are conducted only when it is required by the equipment.
- Improvements in the quality of products and of maintenance as well as in the quantity and quality of the information available about machinery and
- An increase in the availability and safety of the plant.

The US DoE (2011: 5.4) in its guide to achieving operational excellence lists the following disadvantages of predictive maintenance:

- High investment in diagnostic equipment.
- Increased staff training requirements and
- Savings potential not readily seen by management.

The IAEA (2007: 3) states that predictive maintenance is not a substitute of other traditional maintenance strategies and it cannot totally eliminate the continued need for either or both of the traditional strategies, i.e. run-to-failure and preventive, but predictive maintenance can reduce the number of unexpected failures.

2.2.6 Reliability centred maintenance

Reliability Centred Maintenance (RCM) originated in the aviation industry in the 1960's because of the need to lower preventive maintenance costs in attaining a certain level of reliability (Bertling *et al*, 2005). RCM is a disciplined, logic or methodology used to identify preventive and corrective maintenance tasks to realize the inherent reliability of equipment at a minimum expenditure of resources, while ensuring safe operation and use (TM 5-698-1).

The goal of RCM is to determine the criticality of equipment in any process, and based on this information, design a customized preventive or predictive maintenance strategy for the organization (Jabar & SdnBhd, 2003). RCM employs run to failure maintenance, preventive maintenance, predictive maintenance and proactive maintenance in its implementation to increase the probability that the reliability of equipment will be sustained or improved through a design-out solution (Afefy, 2010).

RCM answers the following questions with regard to equipment (TRO Solutions, 2011);

1. What are its current function and performance standards?
2. How does it fail to fulfil these functions and standards?
3. What are the causes of each functional failure?
4. What happens when each failure occurs?
5. How does each failure matter?
6. How do you predict or prevent each failure?
7. What if you can't predict or prevent a failure?

RCM takes cognizance of the fact that not every failure mode must be or can be addressed by a maintenance based solution. If the maintenance solution is not cost effective, then a design out solution is recommended.

Gabbar*et al* (2003) record the following RCM disadvantages:

- It is a time-and effort-consuming process and requires considerable amount of resources, especially for large number of assets for complex plants.
- The available information is not adequate to decide the suitable maintenance strategy and to optimize its cost as maintenance and operational systems are isolated from design and engineering systems and
- There are non-engineering factors involved in the maintenance problems i.e. management and human factors.

Adale (2009: 14) notes the following advantages of RCM;

- Reduced probability of sudden equipment failures.
- Enables the maintenance function to focus maintenance activities on critical components.
- Increases component reliability and
- The procedure incorporates root cause analysis.

2.2.7 Proactive maintenance

Proactive maintenance does not consider scheduling and the condition of equipment for the execution of maintenance activities. The strategy has as its goal the elimination of equipment failures and improvement of equipment reliability by addressing the root causes of equipment failures (Slater, 2010).

Root causes are determined by using the Root Cause Analysis (RCA) technique which is designed for use in investigating and categorizing the root causes of events with quality, reliability and production impacts. The RCA technique identifies not only what and how an event occurred, but also why it happened so that corrective measures that eliminate a reoccurrence can be implemented (Rooney and VandenHeuvel, 2004). Information from previous equipment failures is used to assist in the successful identification, analysis and implementation of corrective actions after the completion of a RCA.

The RCA technique as a tool can assist with improving maintenance effectiveness with respect to maintenance tasks that take a long time to complete or require intense human resource commitment. For continuous improvement these tasks can be investigated to determine if changes can be undertaken to make these tasks more economical through procedures changes, special tools or jigs, or modifications to the machine (Taylor, 1996).

2.3 Reliability, availability and maintainability

2.3.1 Reliability

Reliability is the most known equipment characteristic as a result of its emphasis in literature and industry. Reliability is defined as the probability that an item can perform a required function for a specified period of time under specified conditions (Vesier (2004), Shouri *et al* (2008)). Reliability of equipment is generally expressed as:

$$\mathrm{R(t)} = e^{-\int_0^t Z(t)dt} \qquad (1)$$

For a component with a constant failure rate equation (1) reduces to:

$$\mathrm{R(t)} = e^{-\lambda t} \qquad (2)$$

High equipment reliability is important for ensuring that it always delivers on the purpose that it was acquired for.

2.3.2 Availability

According to Nilsson and Betling (2007) availability is the fundamental measure of equipment reliability. Equipment availability is a common measure used in industry as a performance criterion for repairable systems that accounts for both the reliability and maintainability properties of a component or system. According to (MIL-STD 721C) availability is defined as a measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called for at an unknown (random) time.

2.3.2.1 Inherent availability

One basic measure of availability, called inherent availability, is useful during the design process to assess design characteristics. Inherent availability is the steady state availability when considering only the corrective downtime of the system. It is defined as the expected level of availability for the performance of corrective maintenance only Katukoori (2011). The inherent availability of a system is expressed as:

$$A_i = \frac{\mathrm{MTBF}}{\mathrm{MTBF+MTTR}} \qquad (3)$$

MTBF = mean time between failures
MTTR = mean time to repair

A_i excludes preventive maintenance, logistics, and administrative delays, etc. According to de Castro (2006), an exponential distribution is initially assumed to be representative for the reliability and statistical models. The mean time between failures is expressed as:

$$\mathrm{MTBF} = \int_0^\infty \mathrm{R(t)dt} = \int_0^\infty \mathrm{e}^{-\lambda t}\mathrm{dt} = \frac{1}{\lambda} \qquad (4)$$

MTBF = mean time between failures
λ = constant failure rate of component

The mean time between failures describes the expected time between two consecutive failures for a repairable system.

2.3.2.2 Achieved availability

Achieved availability is defined as the achieved level of availability for the performance of corrective and preventive maintenance Katukoori (2011).

$$A_a = \frac{\mathrm{MTBM}}{\mathrm{MTBM+MDT}} \qquad (5)$$

MTBM = mean time between maintenance

MDT = mean down time

Achieved (equipment) availability fulfils the need to distinguish availability when planned maintenance shutdowns are included, whereby it assumes zero supply and maintenance resources delay times SKF (2011).

2.3.2.3 Operational availability

A_o includes corrective and preventive maintenance time, administrative delay time, and logistic support time.

$$A_o = \frac{\text{Uptime}}{\text{Uptime+Downtime}} \qquad (6)$$

Operational availability is required to isolate the total effectiveness and efficiency of maintenance operations SKF (2011).

2.3.3 Introduction to maintainability

The known maintainability user requirement as part of a system design was recorded in 1901 when the US Army required the Wright brothers to deliver an airplane that should be “simple” to operate and maintain (AMCP-706-133). Maintainability has become more important as a result of increased systems complexity; support costs, knowledge and skills demand to successfully execute maintenance activities NIOSH (2008).

2.3.3.1 Maintainability definition

Equipment or system maintainability as a design characteristic affects the ease of maintenance, repair times and ultimately the cost of preventing failures or correcting failures through maintenance actions. In designing for maintainability the objectives include but are not limited to equipment that is serviceable (easily repaired) and

supportable (can be cost-effectively kept in or restored to a usable condition). Figure 2.3.3.1 depicts some of the requirements of equipment maintainability.

Blanchard and Fabrycky (1998: 402) define maintainability as;

- A characteristic of design and installation which is expressed as the probability that an item will be retained or restored to a specified condition within a given period of time, when maintenance is performed in accordance with prescribed procedures and resources.

- A characteristic of design and installation that is expressed as the probability that maintenance will not be required more than *x* times in a given period, when the system is operated in accordance with prescribed procedures.

- A characteristic of design and installation that is expressed as the probability that the maintenance cost for a system will not exceed *y* dollars per designated period**,** when the system is operated in accordance with prescribed procedures.

Hao *et al* (2002) define maintainability as the relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at prescribed maintenance level.

Chen and Cai (2004) state that the focus of designing for maintainability is to make systems that require minimal maintenance and that are easy and inexpensive to fix when they fail. The original equipment manufacturer quantitatively determines the maintainability characteristics of equipment at the design stage to set the maintenance procedures and the time it takes to perform repairs on equipment (Sharma & Kumar, 2008).



Figure 2.3.3.1: Equipment maintainability features

Source: Barabady (2005)

2.3.3.2 Importance of maintainability

Equipment that takes a long time to perform maintenance on and require the commitment of personnel and other resources to ensure that it remains operable will have an impact on its availability and maintenance costs. For the maintenance function, increased equipment maintainability reduces the maintenance effort and enables the same resources to accomplish more using fewer resources (Van Deursen *et al*, 2006).

The maintenance function can add value by analysing and implementing corrective actions for the maintainability distribution of repair times of plant equipment so that a regular pattern of repair or replacement times can be followed well in advance (Sharma & Kumar, 2008).

2.3.4 Maintainability attributes

Many researchers have made attempts in developing methodologies for evaluating the maintainability of systems based on maintainability attributes Wani (1999). Maintainability attributes have a direct influence on the time it takes to execute maintenance activities. Coulibaly *et al* (2008) classify the maintainability of a system according to design and related criteria.

2.3.4.1 Maintainability design attributes

Design defines intrinsic maintainability attributes for ease of maintenance. Preventive and corrective maintenance actions are influenced by reparability, standardization, interchangeability, accessibility, modularization, testability and diagnostic ability.

2.3.4.1.1 Standardization

Standardization may be described as the attainment of maximum practical uniformity in an item's design. Poor consideration of standardization during the design phase of a system can contribute to lower reliability and increased maintenance that can lead to poor performance by the maintenance function.

The advantages of standardization include the following (DOD-HDBK-791):

- Reduction of training requirements both in number of personnel and the level of skill required.
- Reduction in design time, manufacturing cost, and maintenance time and cost.
- Elimination of the need for special or close tolerance parts of components.
- Reduction of inventories or repair parts and their associated documentation.

2.3.4.1.2 Interchange-ability

Interchangeability refers to a component's ability to be replaced with a similar component without a requirement for recalibration (NASA/TM-4628: 5).

There are two distinct types of interchangeability: physical and functional. In physical interchangeability, two items can be connected, used, and mounted in the same location and in the same manner. With functional interchangeability, two given items serve the same function. Interchangeability as a design parameter reduces the number of maintenance procedures and consequently reduces maintenance costs

2.3.4.1.3 Accessibility

Since the majority of maintenance activities entail inspection either visual or touch, adjustment, repair or replacement, accessibility to equipment and its components is important for effective maintenance. Accessibility means having sufficient workspace and access to perform maintenance safely and efficiently (Mostia, 2004).

Accessibility impacts maintenance times if not inherent in the design, especially on equipment where regular maintenance is required. When accessibility is poor, other failures are often caused by removal or disconnection and incorrect re-installation of other items that hamper access, causing rework (NASA/TM-4628: 5).

2.3.4.1.4 Modularization

Modularity is a general systems concept, typically defined as a continuum describing the degree to which a system’s components may be separated and recombined (Babylon, 2011). Modular products consist of detachable modules, which can be manufactured, assembled, and serviced separately (Gu & Sosale, 1999).

Modularization advantages include the following:

- Relative ease in maintaining a divisible configuration.

- Less time consuming and costly maintenance staff training.
- Simplified new equipment design and shortened design time.
- Easy to divide up maintenance responsibilities.
- Lower skill levels and fewer tools required.

2.3.4.1.5 Testability

In MIL-HDBK-2165 testability is defined as a design characteristic which allows the status (operable, inoperable, or degraded) of an item to be determined and the isolation of faults within the item to be performed in a timely manner. Testability provides the capability to test, detect, diagnose or isolate equipment faults in the life-time of equipment through alarms, built-in test equipment (BITE) and automatic test equipment (ATE) (Cai *et al*, 2007).Testing should identify all the causes of malfunctioning and indicate suitable corrective actions because the speed with which faults are diagnosed can greatly influence downtime and maintenance costs (NASA/TM-4628: 5).

Esker *et al* (1990) in the study of integrating design for testability and automatic testing for avionics note that the most major consideration is to design testability into a system and take advantage of the resulting testability to define effective troubleshooting procedures.

For maintenance personnel to be able to resolve failures, testability becomes important when the desired performance of equipment in the plant is to be achieved. Ambiguity during fault localization and isolation must be eliminated to avoid additional delays as a result of false maintenance actions such as false disassembling, or needs of a long procedure of test to isolate the failure Lefebvre *et al* (2007).

2.3.4.2 Maintainability support attributes

2.3.4.2.1 Environmental factors

The impact of environmental factors on the maintainability of equipment has to be considered during the installation phase to protect maintenance personnel from working near high temperatures, steam extremes etc. According to Mason (1990) machine which is difficult to maintain routinely is less likely to receive the required standard of maintenance as a result of poor working conditions.

2.3.4.2.2 Human factors

Humans are important for the successful execution of maintenance tasks. Human factors engineering is applied to minimize the time and effort required to perform preventive and unscheduled maintenance CSR (2011). There are various reasons that can lead to long maintenance durations as a result of poorly considered human factors during the design and installation stage of equipment.

Human factor engineering takes into consideration of lighting in the work area, training of personnel, equipment design, noise levels, tools and poorly written equipment maintenance and operating procedures in ensuring that in humans can execute maintenance effectively.

2.3.4.2.3 Logistics

Tools, test equipment, documents, spare parts and consumables which form part of logistic support are important to the maintenance function in its quest of reducing equipment repair times.

The requirement of special tools and support facilities should be minimized to ensure that maintenance can be executed effectively by personnel at the organization level. Taylor (1997: 4) states that proper tools, equipment and consumable supplies should be available and accessible for maintenance activities.

2.3.5 Maintainability measure

Various parameters to measure maintainability are found in literature. A commonly used index to measure system maintainability is the mean time to repair (MTTR) and a limit for the maximum repair time Barringer (1997).

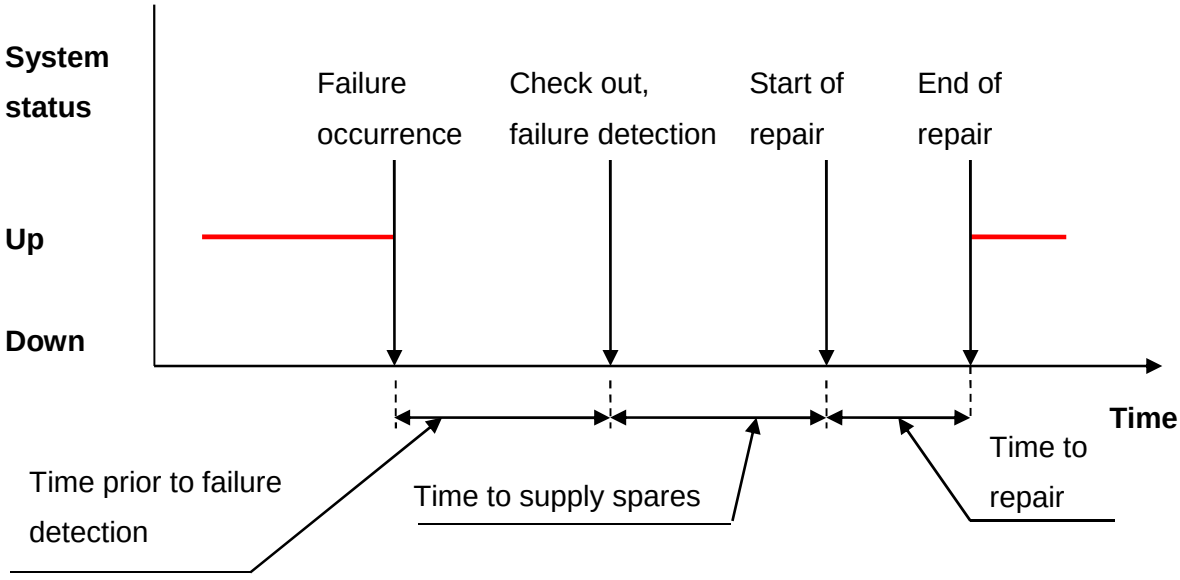


Figure 2.3.5: Equipment down times.

Source: Adapted from Carlier *et al* (1996)

Maintenance activities times at an organizational level will typically follow the sequence shown in Figure 2.3.5 which include failure occurrence, check out and failure detection, preparation for maintenance, disassembly, waiting for spare parts, an interchange, reassembly, an alignment and adjustment and condition verification.

The time taken to repair equipment for a given maintenance action can also be affected by the skill of the maintenance personnel, the maintenance policy and concept, and effectiveness of maintenance manuals and procedures.

2.3.6 The mean time to repair

Reussner *et al* (2003) define the mean time to repair as the average time it takes to diagnose and correct a fault, including any reassembly and restart times. Dhillon (2006) expresses the MTTR as;

$$MTTR = \frac{\sum_{i=1}^{k} \lambda_i CMT_i}{\sum_{i=1}^{k} \lambda_i} \quad (7)$$

where

k = number of components

λ_i = failure rate of component i, for i = 1, 2, 3, …,k

CMT_i = corrective maintenance/repair time required to repair component i, for i = 1, 2, 3,...,k

For equipment with a constant repair rate the MTTR is expressed as:

$$MTTR = \frac{1}{\mu} \quad (8)$$

μ = constant repair rate.

The calculation of the MTTR of equipment takes into consideration the removal and replacement times which are required for the maintainer to access the failed unit before the equipment is restored.

2.3.7 Inherent cost of mean time to repair

In many situations decisions have to be made about the investment required in attaining an acceptable MTTR of equipment. The investment is based on the maintenance resources that will result in the shortest repair time for each failure mode of the equipment. From Figure 2.3.7 below, it can be seen that it would require infinite resources to achieve a MTTR of zero. If no resources are committed on repair effort during the design stage of the system, the MTTR would be infinite. Thus to reduce the repair effort resources must be committed at an acceptable premium to the organization.

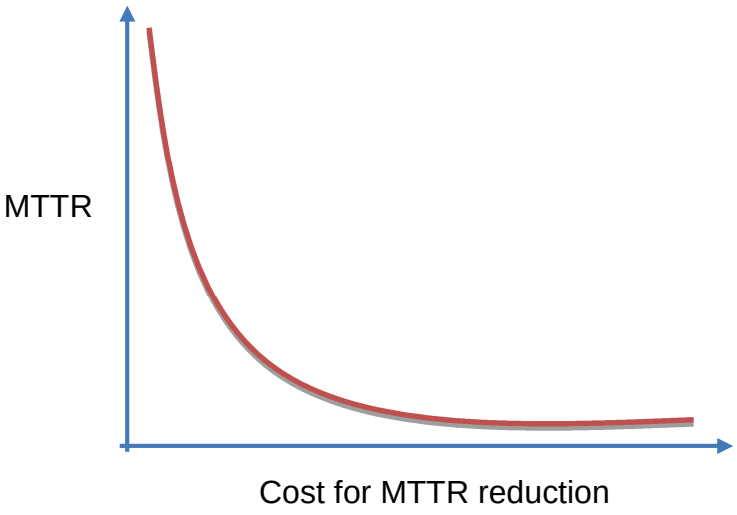


Figure 2.3.7: MTTR vs cost curve

Source: Grover & Sack (2007)

According to Grover and Sack (2007) the overall shape of the curve indicates that relatively large reductions in MTTR can be obtained in return for the very first investments towards establishing a repair force, spares inventory, etc., but thereafter, each further reduction in MTTR will be more costly to achieve.

2.3.8 Operational cost of mean time to repair

For the maintenance function the cost associated with equipment repair can contribute a large proportion of the overall maintenance cost. Investment in special tools, specialist training, material handling equipment, compilation of maintenance procedures, continuous training and development of maintenance personnel etc. can put pressure on the maintenance function if the benefits are not derived as quickly as possible.

Sanchez and Bagajewicz (2000) in their study consider both the capital layout and corrective maintenance costs in determining the life cycle costs (LCC) associated with equipment. LCC calculates the total cost for a technical system during its lifetime and its goal is to minimize the total lifetime cost (Nilsson and Bertling, 2007). Costs associated with corrective maintenance include repair costs (replacement components, labour, consumables), lost production and lost sales Nace (2010).

Thus the maintenance function has to consider the LCC associated with the effort required for reducing the MTTR of the equipment.

2.4 Introduction to failure mode and effects analysis

The failure mode and effects analysis (FMEA) procedure was first used in the 1960's in the Aerospace industry during the Apollo missions (Kmenta, 2002). The procedure is extensively utilized at an early stage of a system or product development to aid in the evaluation of the design and to provide a basis for establishing corrective action priorities (MIL-STD-1629A: 5).

2.4.1 Failure mode and effects analysis definition

The following FMEA procedure explanations are found in literature;

- It is an inductive bottom-up method of analyzing a system design or manufacturing process in order to evaluate the potential for failures (Relex, 2008).
- It is a disciplined approach used to identify potential failures of a product or service and then determine the frequency and impact of the failure (Almannai *et al*, 2008).

The objective of the FMEA procedure is to identify individual component failure modes, their causes and their effects on system operation (Zafiropoulus & Dialynas, 2005). Barringer (2009) takes note that the FMEA process is a team approach best performed during the design phase of a product or system but it also works for existing problems.

By providing a structured approach for considering potential failures and their effects, FMEA is an important process applied to the development of reliable and maintainable systems (Montgomery & Marko, 1997). According to Franceschini and Galetto (2001) FMEA can be considered as a decision-making support tool for designers.

2.4.2 Failure mode and effects analysis disadvantages

Kmenta *et al* (1999), Hunt *et al* (1993) and Hughes *et al* (1998) document the following disadvantages of the FMEA process;

- It does not capture many potential failures
- It is subjective, tedious, time consuming and repetitive
- Performing FMEA late does not affect important design and process decisions
- It requires the ability to reason about the implications of the failure modes on the operation of the system
- It requires detailed knowledge of the system under consideration

2.4.3 The risk priority number

The traditional FMEA process uses the Risk Priority Number (RPN) to measure the risk and severity associated with each failure mode. The RPN is a product of Occurrence (O), Severity (S), and Detection (D).

RPN = Severity x Occurrence x Detection (9)

The RPN factors are explained below (FMEA-FMECA, 2011):

- **Severity (S)** - Severity is a numerical subjective estimate of how severe the customer (next user) or end user will perceive the effect of a failure.
- **Occurrence (O)** - Occurrence or sometimes termed likelihood is a numerical subjective estimate of the likelihood that the cause, if it occurs, will produce the failure mode and its particular effect.
- **Detection (D)** - Detection is sometimes termed effectiveness. It is a numerical subjective estimate of the effectiveness of the controls to prevent or detect the cause or failure mode before the failure reaches the customer. The assumption is that the cause has occurred.

2.4.4 The failure mode and effects analysis procedure

The first phase of the procedure starts with the identification of potential failure modes and their effects and then followed by the performance of criticality analyses to determine the severity of the failure modes Teng and Ho (1996). When criticalities of the failures are assessed, the method is known as FMECA. Thus FMECA is an extension of FMEA.

The extent of effort and sophistication of approach used in the FMEA is dependent upon the nature and requirements of the individual exercise. This makes it necessary to tailor the requirements for an FMEA to each individual exercise. Tailoring requires that, regardless of the degree of sophistication, the FMEA must contribute meaningfully to decision. The FMEA process is given in Figure 2.4.4.

FMEAs consist of similar discrete steps given below (Relex, 2008):

- ***Define the system to be analyzed***. Complete system definition includes identification of internal and interface functions, expected performance at all indenture levels, system restraints, and failure definitions.

- ***Construct block diagrams***. Functional and reliability block diagrams that illustrate the operation, interrelationships, and interdependencies of functional entities should be obtained or constructed for each item configuration involved in the system's use.

- ***Identify all potential item and interface failure modes***. Define the effect of the failure mode on the immediate function or item, on the system, and on the mission to be performed.

- ***Evaluate each failure mode***. Analyze the worst potential consequence that may result due to the failure mode and assign a severity classification category.

- ***Identify failure detection methods****.* Identify compensating provisions for each failure mode.

- ***Identify corrective actions****.* Determine the design or other actions required to eliminate or control the risk.

- ***Identify effects of corrective actions****.* Establish the outcomes that occur from implementing corrective actions.

- ***Iterate or repeat the analysis until all potential failures pose an "acceptable" level of risk****.* What constitutes an "acceptable" risk must be clearly defined by the individual or agent authorizing the FMEA.

- ***Document the analysis.*** Summarize the problems that could not be corrected by design and identify the special controls that are necessary to reduce failure risk.

In addressing some of the limitations of the traditional FMEA procedure during the design stage, Rhee and Ishii (2002) recommend a life cost-based FMEA process that takes into consideration the maintenance labor cost, material cost, and opportunity cost of a failure aimed at comparing and selecting design alternatives that can reduce the overall life cycle cost of a particular system.

From the maintainability point of view, for the FMEA process to benefit an analyst it must take into consideration failure detection, corrective maintenance and other information and activities necessary for increasing or improving the maintainability of a system or equipment.

In essence through the FMEA process, potential maintenance tasks pertaining to the equipment being analysed can be identified and repair times computed. All recommended actions which result from the FMEA can then be evaluated, documented and implemented. Actions that cannot be implemented can also be documented.

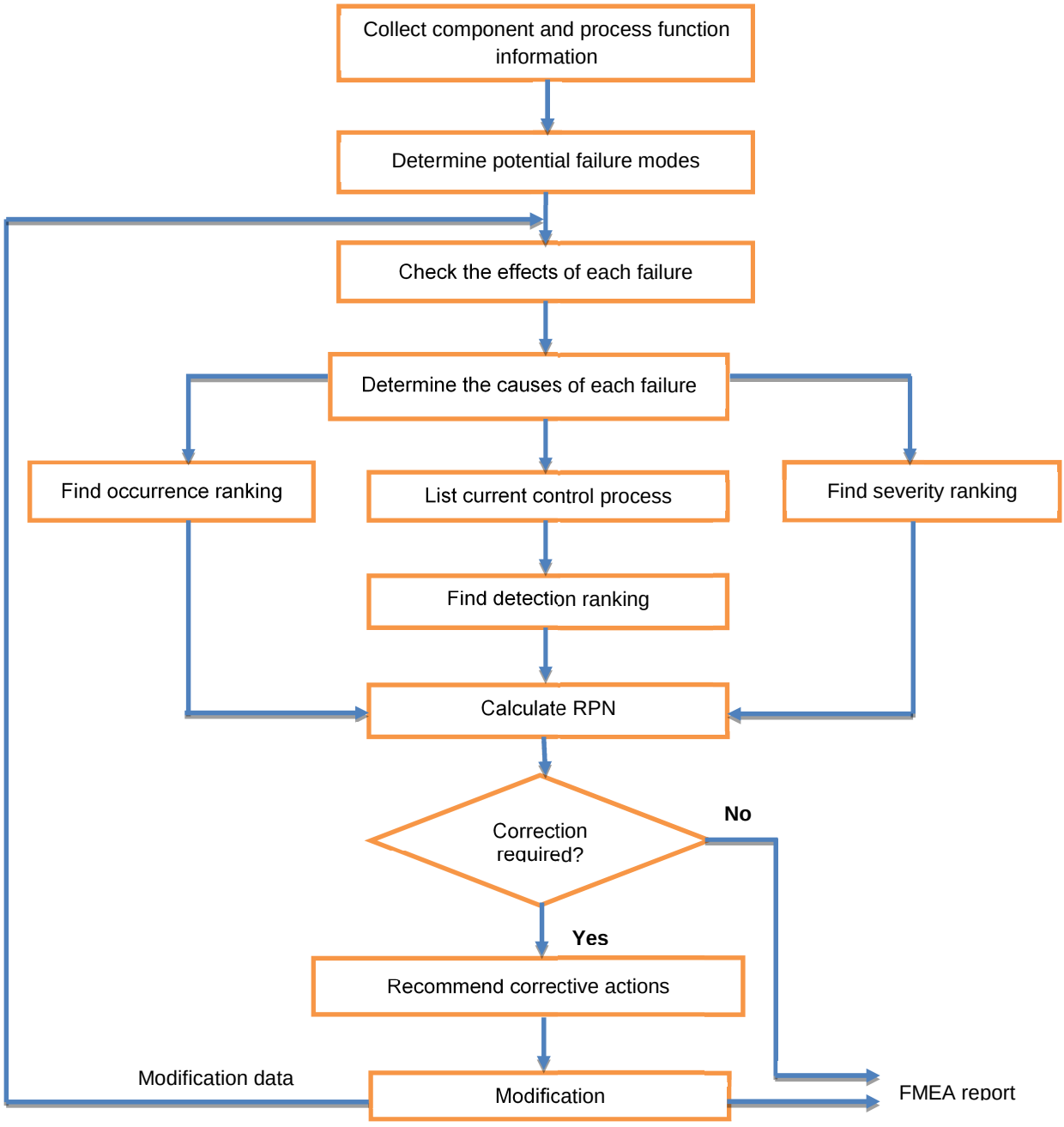


Figure 2.4.4: The FMEA procedure

Source: Teng and Ho (1996)

2.5 CHAPTER SUMMARY

In this chapter maintenance and maintenance strategies, maintainability attributes, maintainability measure and function and the failure mode and effects procedure were discussed. In chapter 3 of this research, the research methodology will be discussed in detail to enable the research to answer the question poised in *chapter 1, section 1.4.1*.

CHAPTER 3: METHODOLOGY

In chapter 2 of this research, the body of knowledge that is relevant to the research was discussed. An introduction to the methodology that will be followed by this research was first introduced in *chapter 1, section 1.6.1 and 1.6.2*.

This chapter builds on the discussion of *chapter 1*. The research methodology will be discussed and it would be illustrated that care has been taken on choosing a methodology that follows a definite set of procedures and steps in conducting the research.

3.1 Research topic analysis

The reasons, evidence, importance, and the major arguments that justify the research will be investigated. This research intends to deliver on the primary and secondary objectives of the problem being researched. Therefore, it was imperative to describe in detail the components of the dissertation topic to ensure that the research methodologies are valid and able to deliver on conclusive statements about the research with minimum bias.

The primary objective of this research is to deliver a ***structured approach*** for the ***reduction of the MTTR*** of plant equipment installed at BFD.

3.1.1 Structured approach

One of the many definitions of structure is the way in which parts are arranged or put together to form a whole. For maintenance personnel assigned to the blast furnace, “putting together” maintenance management principles and knowledge to effectively utilize both technical and non-technical resources to mitigate the consequences of production loss as a result of long corrective maintenance tasks is significant. An approach that was operational, unambiguous and not burdensome in meeting the demand of reducing the MTTR of plant equipment was important and in the context of this research must be scientific, methodological and reliable in its execution. The

execution of each component or part of the approach had to be consistent and quantifiable if achievable, to deliver on credible corrective actions for lowering the MTTR of the plant. The structured approach adopted for this research marries both the theoretical and practical spectrums.

3.1.2 Reduction of the mean time to repair

Reduction is defined as the amount by which something is lessened or diminished. The overall impact of the MTTR of plant equipment had to be determined quantitatively to exactly know its baseline and by how much the MTTR can be reduced through the implementation of corrective actions. The reduction of the MTTR to an acceptable, manageable and cost-effective level by the maintenance function through a structured approach was to have positive results on the availability of the plant.

3.2 Research purpose

The ultimate goals of research are to formulate questions and find answers to those questions Dane (2010: 6). This research aimed to answer the question raised in *chapter 1, section 1.4.1*. It also aimed to describe and develop a structured approach that can be used by maintenance practitioners at the blast furnace to methodically reduce the MTTR of operational plant equipment with the objective of improving the performance of the plant and effectiveness of maintenance resources in achieving business objectives.

It is common to find a research that explores mixed methods in finding answers to the research question. These research methods include but are not limited to exploratory, descriptive and explanatory.

- ***Exploratory*** research is conducted into a research problem or issue when there are very few or no earlier studies to which can be referred for information about the issue or problem Palgrave MacMillan (2011). The aim of this type of study is to look for patterns, ideas or hypotheses, rather than testing or confirming a hypothesis Hairston (2010).

- ***Descriptive*** research involves either identifying the characteristics of an observed phenomenon or exploring possible correlations among two or more phenomena Pearson Prentice Hall (2010). It describes data and characteristics about the population or phenomenon being studied.

- ***Explanatory*** research according to Dane (2010: 9) aims to understand phenomena by discovering and measuring causal relations among them. It is used to determine whether or not an explanation (cause-effect relationship) is valid or which two or more of competing explanations is valid.

The purpose of using an exploratory research approach for the research problem was to uncover new information and knowledge about the effects and criticality of plant equipment maintainability attributes on corrective maintenance repair times that might have been overlooked in the past. Through an exploratory research, a structured approach for identification, evaluation and documenting causes and necessary corrective actions after analysing the benefits of a reduced MTTR on the availability of critical equipment was developed.

Adopting a descriptive approach will serve to describe systematically the magnitude, variances, relationship and significance of both technical and non-technical factors that affect and contribute to unsatisfactory MTTR and ultimately the availability of plant equipment. What to do to improve the current status will also be described.

The conclusion and recommendation of this research will flow from the approaches discussed in the previous paragraphs and *section 3.5.1*.

3.3 Research design

Research in literature is defined as;

- A detailed study of a subject, especially in order to discover (new) information or reach a (new) understanding (Cambridge Dictionaries Online, 2011).

- The systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions (Google Dictionary, 2011).

According to Yin (1994) a research design is an action plan for getting from here to there, where here may be defined as the initial set of questions to be answered, and there is some set of conclusions about these questions. According to De Vaus (2001: 9) the function of a research design is to ensure that the evidence obtained enables us to answer the initial question as unambiguously as possible.

The selection of a research method that enabled the establishment of facts with regard to the problem being researched is pivotal to the adoption of the solution that solves the research problem. Proven theories and research methods were applied to address the dissertation problem to ensure an adequate understanding of the problem is being researched. This included both technical and non-technical factors that might be relevant to the research problem.

3.4 Research approach

3.4.1 Qualitative research

Qualitative research aims at understanding, it answers primarily the *how* questions Maima (2011). According to Strauss and Corbin (1990: 17) qualitative research, broadly defined, means any kind of research that produces findings not arrived at by means of statistical procedures or other means of quantification.

3.4.2 Quantitative research

Quantitative research aims at (causal) explanation, it answers primarily the *why* questions Maima (2011). The objectives of this research have been clearly defined in *chapter 1, section 1.5*. Thus to classify features, count them, and construct statistical models in an attempt to explain what is observed the quantitative approach was adopted.

For this approach to successfully assist with discovering and analysing the research problem a questionnaire was designed and plant data used. These approaches are further discussed in detail in *section 3.5*.

3.4.3 Induction, deduction and abduction

In literature three research approaches are found. These research approaches are induction, deduction and abduction.

- ***Induction*** is going from the particular to the general, i.e. building a general knowledge from particular situations Stroppa (2007). The purposes of using an inductive approach to research are as follows:

1. To condense extensive and varied raw data into a brief summary format.
2. To establish clear links between the research objectives and the summary findings derived from the raw data and
3. To develop of model or theory about the underlying structure of experiences or processes which are evident in the raw data

- ***Deduction*** involves arguments that move from a general to a particular or less general situation Wadham (2009). According to Kell and Oliver (2003) an experimenter has an idea, designs and performs a controlled experiment with a predicted outcome that leads (for a well-designed experiment) to data that are either consistent or inconsistent with the hypothesis. Deduction can't lead to new knowledge but it relies on true premises Yu (1994).

- ***Abduction*** is the process before any rational processes begin. It may be a guess or a lateral thought that is then tested Wadham (2009). By its very definition abduction leads to a hypothesis which is entirely foreign to the data. It is a combination of induction and deduction. Despite the long history of abduction, abduction is still unpopular among texts of logic and research methodology, which emphasize formal logic Yu (1994).

A deductive approach was used for the research to review the contribution of the body of knowledge that is relevant to the research problem. An understanding of the many components that constitute the ultimate derivation of the MTTR of equipment was important to comprehend to thoroughly answer the research question.

An inductive approach was used to derive and deliver the research approach after data collected from the organization's Computerised Maintenance Management System (CMMS) was used to determine links between operational equipment maintainability attributes and any other contributory factors to the current MTTR of the plant.

3.5 Data collection method

The method used to collect data is crucial for the problem being researched. A researcher has to know beforehand the method that will be used for collecting data and the benefits of choosing such a method. According to Blaikie (2003) data used for a research can be divided into the following three categories:

- ***Primary data*** is generated by a researcher who is responsible for the design of the study and the collection, analysis and reporting of the data. The new data is used to answer specific research questions. The researcher can describe why and how they were collected.

- ***Secondary data*** is the raw data that has already been collected by someone else, for some general information purpose and

- ***Tertiary data*** has been analysed by either the researcher who generated them or an analyst of secondary data. In this case the raw data may not be available, only the results of the analysis.

Primary data was sourced through a survey and direct communication with plant tradesmen, supervisors, technicians and maintenance engineers assigned to the blast furnace.

Secondary data about the MTTR of plant equipment was sourced from the CMMS used by the organization. The data is generated by the maintenance function when a request in the form of a notification is initiated for corrective maintenance after equipment failure. This data was preferred because of its reliability and its use for compiling management reports. The data is also scrutinized for completeness and correctness and then used by the maintenance function for necessary actions required for monitoring the performance of plant equipment.

Plant data was used to determine trends and establish a baseline from which improvements can be made for improving the MTTR where necessary. According to Perry (1998) the purpose for the mixed methods approach is to provide more perspectives on the problem being researched

3.5.1 Identification of case studies

To fully understand the effect of equipment maintainability on the MTTR of BFD and to ensure that the facts being collected are correct, a case study approach by direct observation was employed by the research. The case study method can be qualitative or quantitative since data can be obtained from fieldwork, observation and archival records Yin (1981). The benefits of this research methodology as noted by Meredith (1998) are the following;

- The phenomenon can be studied in its natural setting and meaningful, relevant theory generated from the understanding gained through observing actual practice.

- The case study method allows the much more meaningful question of *why*, rather than just *what* and *how*, to be answered with a relatively full understanding of the nature and complexity of the complete phenomenon.

The data presented in this research was the result of using the research approaches mentioned in the previous paragraphs.

Sources of evidence included plant equipment documentation, archival records and direct observation of maintenance execution to generate bothqualitative and quantitative data. According to Yin (1994) the findings of a case study could be generalized to theoretical propositions.

3.5.2 Observation

This type of data collection method was expected to yield good results because of direct observation and knowledge of the function's maintenance management philosophy, culture and systems. Familiarity with maintenance personnel assigned to the blast furnace also added an advantage because people felt at ease. During an observation, the objective was to try to be as un-obstructive as possible so that the data collected was not biased.

3.5.3 Questionnaire

Kirakowski (2000) defines a questionnaire as a method for the elicitation, recording and collecting of information. The questionnaire was designed to address the research problem of reducing the MTTR of BFD by defining its goals to ensure that a good questionnaire design was delivered (Walonick, 1993).

The objectives of the questionnaire were the following;

- To determine the level understanding.
- To determine the level of influence of human factors on the successful execution of maintenance tasks.
- To determine the level of influence of the environment on the successful execution of maintenance tasks.
- To determine the level of maintenance planning.
- To determine the level of equipment support.
- The level of plant equipment maintainability attributes.
- To determine the level of maintenance procedures use by personnel.

- To determine the level of training received by personnel to be able to successfully execute equipment maintenance.

This methodology had been chosen for the research because it presents questions that are uniform and less biased, non-intrusive, and it can be completed at the respondent's leisure and the results are easy to analyse. For the research to be reliable, the response rate was maximised by encouraging the target population to complete the questionnaires during forum meetings held daily in the morning.

3.5.3.1 Questionnaire design

The questionnaire was designed to quantitatively assess the comprehension, opinions, perceptions, expectations and reactions of maintenance personnel with regards to the maintainability of the blast furnace equipment.

The development of the questionnaire for the research enabled the research to answer research questions. For this outcome to be attained, a nine steps process of developing a questionnaire recommended by Churchill and Iacobucci (2002) was followed. The process used to develop the questionnaire used for the research is shown in Figure 3.5.3.3 below.

Other experts in the field of maintenance engineering and management were requested to be involved with the questionnaire design process so that their input can improve the quality of the questionnaire and uncover perspective not considered for the research.

3.5.3.2 Information sought

The questionnaire aimed to quantitatively measure critical components of equipment maintainability that impact the MTTR as documented in the literature review of *chapter 2* of this research.

3.5.3.3 Sequence of questions

The sequence of questions commenced with Section A which aimed at sourcing demographics of respondents. Section B measured the components mentioned in *section 3.5.5* for uncovering new information that served as valuable information for the design of the structured approach that was delivered by the research.

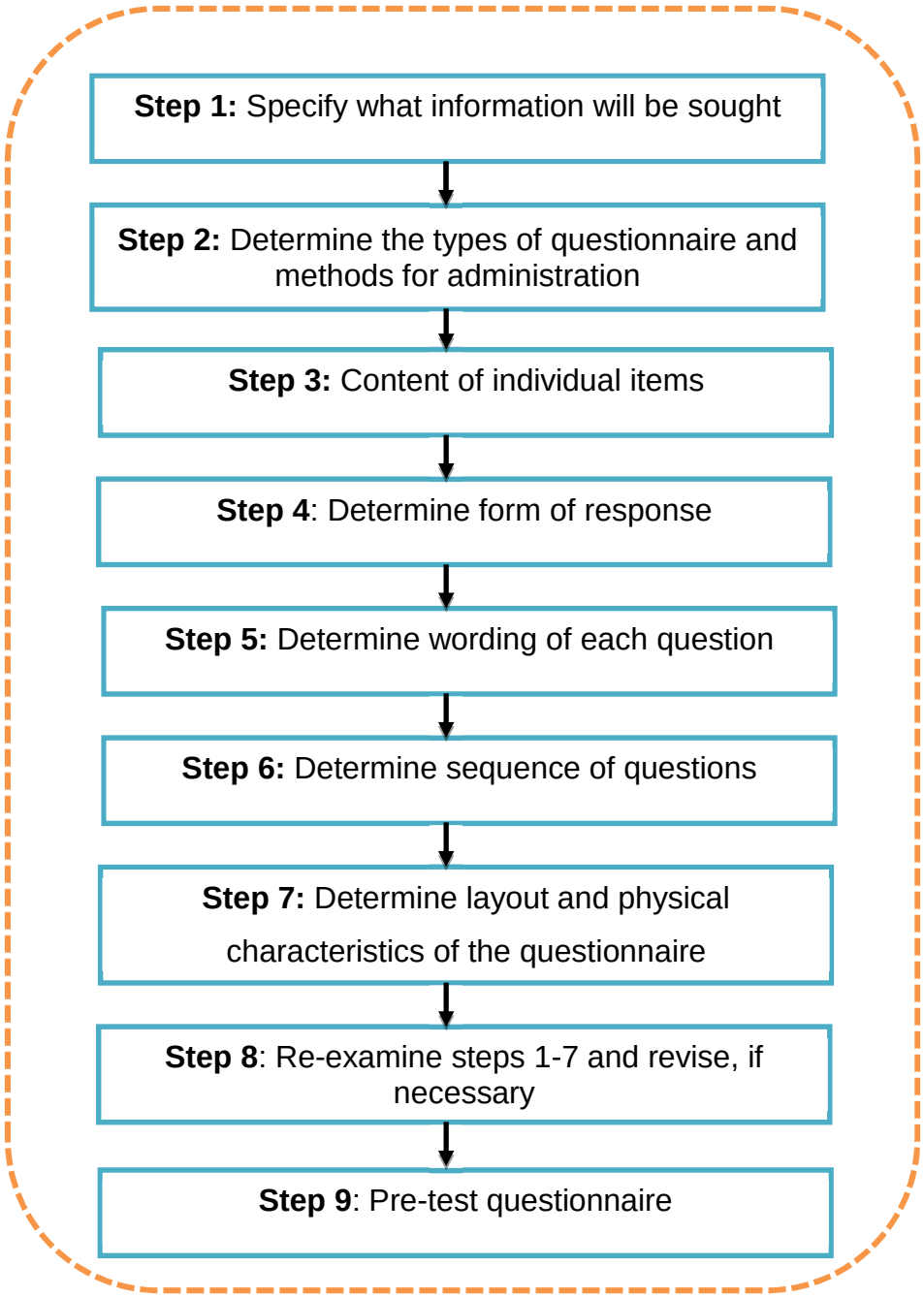


Figure 3.5.3.3: Questionnaire development process

Source: Churchill and Iacobucci (2002, p. 315)

3.5.3.4 Pre-test questionnaire

The first pre-testing session of the questionnaire was held with a consultant in the Statistical Consultation Services of the North-West University, South Africa to check the questionnaire for its content, reliability and thoroughness. Her recommendations were implemented in the revised questionnaire which was sent out during the survey.

The second pre-testing session of the questionnaire was held with maintenance personnel. This session involved testing the wording of the questions, identifying ambiguous and other difficulties with questions which may be encountered by maintenance personnel in completing it. This was valuable for eliminating problems that might have been encountered by respondents which would have contributed to unusable data.

3.5.4 Interviews

Interviews were held with individuals rather than with a group to avoid the dominance of one person. A semi structured interview with clear objectives derived from the information sought from the candidate was in line with the problem researched.

3.6 Data analysis

Data analysis enabled the researcher to reduce raw data from complex to information and meaning. It is a body of methods that help to describe facts, detect patterns, develop explanations, and test hypotheses Macintosh (1997). After data is collected, the researcher must evaluate the data to determine if it meets expectations according to its characteristics and quality. The choice among possible analyses must be based partly on the nature of the data—for example, whether many observed values are small and a few are large and whether the data are complete GAO (1992).

3.6.1 Univariate analysis

It involves the examination across cases of a single variable, focusing on three characteristics: the distribution; the central tendency; and the dispersion Wikipedia (2011). It explores each variable in a data set, separately and describes the pattern of response to the variable. It describes each variable on its own.

3.6.2 Bivariate analysis

The aim of bivariate analysis is to see whether some independent variable impacts (statistically) upon some dependent variable de Roche (2008). In its simplest form, association simply refers to the extent to which it becomes easier to know or predict a value for the dependent variable if a case's value on the independent variable is known.

3.6.3 Inferential analysis

It tests for difference of means and statistical significance Connor (2011). The purpose of difference of means tests is to test hypotheses. Inferential analysis is concerned with estimating whether the characteristics or relationships found in a sample, or differences between samples, could be expected to exist in the population or population from which the sample or samples were randomly drawn Barabady (2005: 12).

The Analysis of Variance (ANOVA) is a data analytic technique based on the idea of comparing explained variance with unexplained variance Connor (2011). The common parametric tests of significance which are *t*-test, ANOVA test, effect sizes and Cohen's d-value will be used for inferential analysis.

3.6.4 Relational analysis

The most commonly used data analysis method is relational. The focus of relational analysis is to look for relationships. Correlation is a measure of the relation between

two or more variables StatSoft (2011). The correlation coefficient is free of the effects of scale of measurement, thus it allows comparing the strength of the association of two variables with that of two other variables (Forest Biometry Lectures, 2003).

Descriptive statistics was used to reveal correlation or relationship between variables of significance and also to determine if the measured relationship between variables is unlikely to have occurred by chance alone.

Inferential analysis was also used to test difference of means and statistical significance by using *t*-tests and ANOVA. Practically significant differences were used to test if the research findings were practically important or useful in real life**.** The analysis was conducted by using a statistics package.

Data obtained from the CMMS of the organization was used to determine the repair times and the trend of the MTTR with respect to each failure experienced by the equipment. The potential improvement benefits of a lower MTTR as a result of the structured approach of the research was measured with the use the current availability figures of the plant.

3.7 Research population

As a result of the number of observations that can be made during a research, the complete population cannot always be surveyed usually because of cost or time allocated for the research. A researcher must then choose a sample of the population to survey. The two types of sampling methods found in literature are probability and nonprobability sampling. These sampling methods for the purpose of this research are discussed below.

3.7.1 Probability sampling

Herek (2009) states that with probability sampling, all elements in the population have some opportunity of being included in the sample, and the mathematical probability that any one of them will be selected can be calculated.

- ***Random sample*** according to StatPac (2011a) is the purest form of probability sampling. Easton and McColl (1997) state that each individual in random sampling is chosen entirely by chance and each member of the population has a known, but possibly non-equal, chance of being included in the sample.

- ***Stratified sampling*** according to Castillo (2009) is a probability sampling technique wherein the researcher divides the entire population into different subgroups or strata, then randomly selects the final subjects proportionally from the different strata. Using stratified sampling, it may be possible to reduce the sample size required to achieve a given precision or it may be possible to increase the precision with the same sample size StatTrek (2011).

3.7.2 Nonprobability sampling

With nonprobability sampling population elements are selected on the basis of their availability or because of the researcher's personal judgment that they are representative Herek (2009).

- ***Quota sample*** is used by the researcher to deliberately divide the population into two or more strata (groups) Lund Research (2010). This method of sampling is not as representative of the population as a whole as other sampling methods Hunt and Tyrrell (2004).

- ***Purposive sample*** has as its objective to produce a sample that can be logically assumed to be representative of the population Sage (2011). The researcher selects the sample based on judgment

A purposive sample was used for the survey. The target sample for the distribution of the research questionnaire included engineers, technicians, tradesmen and supervisors working at the blast furnace. The sample was chosen because of its experience with the plant equipment, competency and role within the maintenance function which ultimately determines the current MTTR of the plant.

3.8 Reliability and validation

When the results of a research are presented, the reliability and validity of the results must be questioned and tested. The two are the most important and fundamental attributes of a scientific measurement procedure.

Reliability is defined as the extent to which a questionnaire, test, observation or any measurement procedure produces the same results on repeated trials Miller (2011).

Shuttleworth (2008) states that validity encompasses the entire experimental concept and establishes whether the results obtained meet all of the requirements of the scientific research method. Validity in a quantitative research according to Joppe (quoted by Forjoe, 2011: 64) is explained as follows:

“Validity determines whether the research truly measures that which it was intended to measure or how truthful the research results are. In other words, does the research instrument allow you to hit "the bull’s eye" of your research object? Researchers generally determine validity by asking a series of questions, and will often look for the answers in the research of others.”

According to Golafshani (2003) the definitions of reliability and validity in quantitative research with regard to results reveal whether the result is replicable, whether the means of measurement are accurate and whether they are actually measuring what they are intended to measure. Reliability is necessary for validity and is easier to achieve than validity Neuman (2003).

The empirical data obtained through a survey was tested for reliability and deemed to be reliable as a result of the structured approach that has been adopted for the

research. Because of an expected small population size for the research, validity of the research data was not performed.

3.9 Ethical considerations

The permission to conduct the research on the premises of ArcelorMittal South Africa Limited, Vanderbijlpark Works was sought from the organization before commencing with the research. A sample letter describing the research problem and its benefits, anonymity and confidential treatment of respondent's information formed part of the questionnaire. Voluntary participation by the respondents will also be emphasised.

3.10 CHAPTER SUMMARY

This chapter has discussed the research methodology and design adopted for data and information collection for this dissertation. The results and analysis of the research undertaken will be presented in the next chapter.

CHAPTER 4: RESULTS AND FINDINGS

Chapter 3 of this research highlighted the research methodology and design adopted for this dissertation.

This chapter contains the empirical results and findings of the research undertaken. The results and findings documented are based on a questionnaire survey and case studies conducted at the maintenance function responsible for maintaining the blast furnace.

The research maintained its focus on investigations that will provide answers to the research questions discussed in chapter 3 with the aim of solving the research problem at hand.

4.1 Case study

All interviewees were asked the same question with the intent of asking more questions as they give an answer and explanation on the key question. The question asked was:

Are repair times a concern for you each time that equipment maintenance has to be executed?

4.1.1 Case Study A

This case study refers to the Stockhouse area of the blast furnace. Equipment installed in this area of the plant includes conveyors, vibrating screens, hoppers, flow regulating gates, motors and vibrating motors. Raw material used for molten iron production is stored in bunkers and transported to the furnace top by means of conveyors. Equipment installed in this area requires intensive maintenance because of the strain in which it operates.

Mr T. Leyden, a Superintendent, responsible for the maintenance of all the equipment in this area was interviewed (2nd November 2011) and this is what he had to say.

"The repair times of plant equipment are definitely a concern for me. There are a number of things that can be done to improve the current situation with regard to the MTTR of equipment that falls under my responsibility. This includes formal and informal training of personnel, on the job training and just performing task observations to get personnel to a level that they can execute maintenance effectively. Personnel with years of experience must be encouraged to share their knowledge with new employees. It is however important that the process of improving the MTTR starts with critical plant equipment first to ensure that in an event of a breakdown, we are able to get that equipment back in operation as soon as possible."

Investigations further revealed the following:

- Moving maintenance personnel to different areas has had a negative impact because the new team members do not have the necessary skills and knowledge required for maintaining the equipment.
- Maintenance procedures are no longer relevant as a result of new equipment installed during the reline of the furnace.
- The baseline MTTR of each equipment installed in the plant is not known. Although the MTTR of the plant is reported monthly as part of the plant's performance measures.
- An approach that determines a baseline MTTR will cause everyone to know *what* needs to be improved and *how* to initiate improvements for the benefit of everyone involved with the maintenance of plant equipment.
- Plant operators frequently report incorrect faults because most of them do not even have plant experience.
- Accessibility of equipment is poor because it was not installed correctly during the reline of the furnace.

- The non-availability of the dust extraction system affects visibility in this area because of raw material dust that is generated when material is discharged.

4.1.2 Case Study B

The fume and dust extraction plants are used for reducing fumes and dust emissions. The dust extraction plant was installed in 1990 to extract dust in the Stockchouse area of the plant. The fume extraction plant was installed and commissioned 2005. It solely caters for the Casthouse area of the plant.

Mr S. Dunster, a Superintendent, responsible for the maintenance of both the fume and dust extraction plants was interviewed (4th November 2011) and this is what he had to say.

"Of course they are a concern for me because they affect resource utilization and equipment availability. I have recently been made responsible for the maintenance of both the fume and dust extraction plants. These plants are critical because their availability has to comply with environmental legislation regarding dust emissions of the furnace. In an event that compliance is not adhered, the organization can be requested by the local or provincial authority to lower its production until the situation is corrected. This can be costly for the business and have far reaching consequences. Thus it is very important for me and my team that in an event of equipment failure that we resolve it without delay.

However there are challenges that I am currently facing which make this almost impossible to consistently deliver. My team is made up of people who have never worked with the equipment installed in this plant. There are no maintenance procedures for the plants and access to OEM manuals and other documentation is very difficult."

Investigations further revealed the following:

- When the plant was designed and installed, the handling of equipment when it needs to be changed was poorly addressed during the design stage.
- Platforms were not installed to make equipment accessible.
- The bill of materials (BOM) of spare parts on the CMMS does not correspond to the equipment in the plant. This results in repeated procurement of wrong spare equipment.
- Equipment troubleshooting resides in the heads of maintenance personnel and is not documented in procedures or other means.
- There is no stability of personnel in assigned plant areas. Maintenance personnel are unable to reach the required level of competency with regard to equipment maintenance. This affects the effectiveness of maintenance execution and repair times.

4.1.3 Case Study C

The role of shift millwrights is to ensure that equipment faults and failures are attended to at the shortest possible time. They are usually the first people informed by plant operators of equipment failures. The MTTR of plant equipment also forms part of performance indicators for senior millwrights (5th November 2011) and it is used during performance appraisal.

Mr V. Bauer, a senior shift millwright was interviewed and this is what he had to say.

"*Yes, for me it is paramount that I ensure that I take the shortest possible time to rectify faults or failures. Every action I take has a bearing on the cost of molten iron production. If I take longer to repair the equipment even though the plant might not be stopped, my actions may result in furnace instability. Thus to lower the MTTR I have to have the all the spare parts I need on time, tools must be available, and my team must be highly skilled and have knowledge of equipment installed in this plant.*"

Investigations further revealed the following:

- The new safety standards that have been adopted by the organization are resulting in unnecessary delays because of the large amount of paper work that must be in place before maintenance can commence.
- Access to maintenance documentation e.g. manuals, procedures is a problem.
- All the steps that are required to be taken to repair a failure are not documented and stored in the CMMS used by the organization.
- Tools necessary for fault finding are not always available as a result of being kept in locked areas in the maintenance store.
- There is a lack of specific equipment training especially for critical plant equipment.

4.2 Background of empirical research

4.2.1 Ethical aspects

A sample letter attached as Appendix A describing the research problem and its benefits, anonymity and confidential treatment of respondent's information formed part of the questionnaire. Voluntary participation was emphasised for data collection. A sample of the questionnaire attached as Appendix B *(A structured approach for the reduction of the mean time to repair),* was distributed amongst maintenance personnel.

4.2.2 Research population

The target population included engineers, technicians, tradesmen and supervisors.

4.2.3 Questionnaire overview

The questionnaire consisted of two sections, Section A and B. Section A was included for the purpose of obtaining background information on respondents. Section B consisted of sixty two (62) statements which formed part of eight

subsections of the section. The questionnaire sections are divided according to the following:

- ***Section A: Demographics***

- ***Section B1: Equipment Performance Measures***
  This section measured the understanding of equipment performance measures (e.g. availability, cost, mean time between failures, mean time to repair) and maintenance.

- ***Section B2: Human Factors***
  This section measured the level of influence of human factors on the successful execution of maintenance tasks.

- ***Section B3: Environmental Factors***
  This section measured the level of influence of the environment on the successful execution of maintenance tasks.

- ***Section B4: Planning***
  This section measured the level of maintenance planning.

- ***Section B5: Spare Parts***
  This section measured the level of equipment support.

- ***Section B6:Maintainability***
  This section measured the level of plant equipment maintainability attributes.

- ***Section B7: Procedures***
  This section measured the level of maintenance procedures use by personnel.

- ***Section B8: Training***
  This section measured the level of training received by personnel to successfully execute equipment maintenance.

The questionnaire was designed to solicit information that flowed from the body of knowledge in order to answer the research question. The question aimed to comprehensively support the design of the approach that will be used by the maintenance function to reduce the MTTR of operating equipment.

4.2.4 Questionnaire item scales

To reach the objectives of the research, a series of statements about each topic of the research were drawn to measure opinions in terms of the extent to which respondents agree with them. Item scales were scored on a five Likert-type rating scales (1= *strongly disagree* to 5 = *strongly agree*) Jamieson (2004). Macleod (2008) states that a Likert-type scales assume that the respondent's strength or intensity of experience is linear.

4.2.5 Data capturing

The questionnaires received from the respondents were captured in a Microsoft Excel spread sheet and statistically processed using statistical analysis tools for analysis.

4.2.6 Statistical analysis

The two software packages used for statistical analysis were STATISTICA (2009) and SPSS (2009) with the assistance of Statistical Consultation Services of the North-West University, South Africa.

4.3 Presentation of results

This section will present the results and findings of the questionnaire on demographics variables, reliability, mean factor scores, correlations, t-test, Cohen's d-values and ANOVA as introduced in *chapter 3* of this research.

4.3.1 Demographics

Ninety four percent (94%) of the eighty six (86) questionnaires distributed were completed and returned. Respondents of the survey were of different ages. The summary of each age group that participated in the research is given in Table 4.3.1.

Table 4.3.1: Age group of respondents

Item	Age group (years)	Percentage (%)
1	18 – 29	31
2	30 – 39	22
3	40 – 49	31
4	50 - 59	14
5	60+	1

The respondents comprised of males and no females were found to have participated in the survey. The 18–29 and 40–49 years age groups contributed thirty one percent (31%) each to the total sample. The lowest percentage was of sixty plus (60+) year age group which was one percent (1%).

4.3.2 Education level of respondents

The summary of education level of participants is given in Table 4.3.2 below. For education levels, respondents with national certificate, national diploma, 3-year degree, post graduate qualification and other qualifications were seventy percent (75%), seven percent (7%), six percent (6%), five percent (5%) and seven percent (7%) respectively.

Table 4.3.2: Education level of respondents

Item	Education level	Percentage (%)
1	National certificate	75
2	National diploma	7
3	3-year degree	6
4	Post graduate qualification	5
5	Other	7

Respondents with national certificate comprised of mainly of tradesmen, followed by technicians and engineers. Such a spread was expected because of the work distribution and the cost of having a highly skilled and competent workforce in the maintenance function. Competency of maintenance personnel in maintenance procedures is also an important characteristic that can contribute to achieving a lower MTTR and for them to identify maintainability attributes and other factors that that are hindering the realization of this objective.

It is expected that maintenance personnel who have qualifications other than the national certificate to fully comprehend the approach and its components in answering the research problem will and to assist other maintenance personnel with its execution without additional human resources.

4.3.3 Reliability analysis

In order to be able to calculate and work with average scores of all the individual items of the questionnaire, the items in a section should be related to each other. To test consistency and accuracy of representation of the total population under study, a reliability test must be performed for each item of the questionnaire for reliability before deciding on the use of an average score for each respondent. In other words, the items per section could be summed or aggregated if the subscale (i.e. the section) turns out to be reliable.

The Cronbach's alpha (α) coefficient of reliability is chosen for this purpose. A cut-off point of 0.7 for the coefficient is used to indicate a reliable subscale (Nunnally &

Bernstein, 1994). Thus conclusions can be drawn on an item as a result of its reliability.

Since the questionnaire contained some reversely phrased questions that would have resulted to poor reliability results, reversely phrased items scores were reversed for the purpose of performing the reliability test. These items are given in Table 4.3.3 below.

Table 4.3.3: Reversely phrased items of the questionnaire

Item	Statement
16	The noise level in the plant prevents me from executing equipment maintenance effectively.
17	Working near high temperatures prevents me from executing equipment maintenance effectively.
18	Working in a dusty area prevents me from executing equipment maintenance effectively.
45	Equipment requires special tools to execute maintenance.

- For ***Equipment Performance Measures***, α was 0.786, which indicates that it was a reliable subscale and therefore an average score can be calculated for each respondent.

- For ***Human Factors***, α was 0.414, when all the items were included, with item 9 and 14 reversed. Item 9 and 14 turned out to be negatively correlated with the other items of this section. After removing item 9 and 14, α increased to 0.707. Therefore the average score of this section was calculated with only items 8, 10, 11, 12 and 13.

- For ***Environmental Factors***, α was 0.477, when all the items were included, with item 16, 17 and 18 reversed. Item 15 turned out to be negatively correlated with the other items of this section. After removing item 15, α

increased to 0.698. Therefore the average score of this section was calculated with only items 16, 17 and 18.

- For ***Planning***, α was 0.682, which indicates that it was a reliable subscale and therefore an average score can be calculated for each respondent.

- For ***Spare Parts***, α was 0.734, which indicates that it was a reliable subscale and therefore an average score can be calculated for each respondent.

- For ***Maintainability***, α was 0.875, which indicates that it was a reliable subscale and therefore an average score can be calculated for each respondent.

- For ***Procedures***, α was 0.836, which indicates that it was a reliable subscale and therefore an average score can be calculated for each respondent.

- For ***Training***, α was 0.856, which indicates that it was a reliable subscale and therefore an average score can be calculated for each respondent.

4.3.4 Mean factor scores of subsections

The results of frequencies for Section B of the questionnaire are attached in Appendix C *(Frequencies for Section B of Questionnaire)*. The results of the mean factors of each section are given below in Table 4.3.4.

Table 4.3.4: Mean factors of subsections

Item	Section	Mean	Standard deviation
1	Equipment Performance Measures	3.73	0.58
2	Human Factors	3.86	0.58
3	Environmental Factors	2.99	0.73
4	Planning	2.59	0.54
5	Spare Parts	2.64	0.60
6	Maintainability	3.11	0.49
7	Procedures	3.51	0.58
8	Training	2.99	0.89

A factor analysis method which is used to examine how underlying constructs influences the responses on a number of measured variables should have been used to determine the validity of the questionnaire. However Tabachnick and Fidell (2001: 613) state that it is comforting to have at least 300 cases for factor analysis. Since the population for this research consists of only 83 respondents, it was not possible to conduct a validity analysis and only a reliability analysis could be done.

4.3.5 Correlation between subsections

Pearson's correlation coefficient (*r*) which gives an indication of the degree of a linear relationship between two variables was used for the research to determine the relation between the items. However *r* does not characterize the relationship between the two variables of interest. A linear relationship is a relationship between variables in which change in one variable brings about a constant rate of change for another variable Nevarez (2011).

A guideline given by Field (2009) for interpreting *r* is given below:

r = |0.1| small effect no practically significant correlation

r = |0.3|	medium effect	practically visible correlation
r = |0.5|	large effect	practically significant correlation

Furthermore a negative *r* indicates a negative linear relationship between variables and a positive *r* indicates a positive linear relationship between variables. Table 4.3.5.1 below gives *r* between the sections of the questionnaire.

4.3.5.1 Practically significant correlation results

For Section B of the questionnaire, practically significant correlations were observed for the following sections:

- ***Equipment Performance Measures***: practically significant correlations were observed with *Human Factors and Maintainability*.

- ***Human Factors***: practically significant correlation observed with *Maintainability*.

- ***Spare Parts****:* practically significant correlation observed with *Maintainability*.

The interpretation of the results and findings is discussed in detail in *chapter 5*.

Table 4.3.5.1: Pearson's correlation coefficients between subsections

	Equipment Performance Measures	Human Factors	Environmental Factors	Planning	Spare Parts	Maintainability	Procedures	Training
Equipment Performance Measures	1	0.608**	0.147	0.313**	0.230*	0.481**	0.287**	0.310**
Human Factors		1	0.076	0.342**	0.458**	0.499**	0.303**	0.376**
Environmental Factors			1	0.142	0.084	0.101	0.087	0.180
Planning				1	0.399**	0.370**	0.108	0.086
Spare Parts					1	0.556**	0.240*	0.286**
Maintainability						1	0.258*	0.322**
Procedures							1	0.425**
Training								1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

4.3.5.2 Practically visible correlation results

For Section B of the questionnaire, practically visible correlations results were observed for the following sections:

- ***Equipment Performance Measures***: practically visible correlations were observed with *Planning, Maintainability and Training*.

- ***Human Factors***: practically visible correlations were observed with *Planning, Spare Parts, Procedures and Training*.

- ***Planning***: practically visible correlations were observed with *Spare Parts and Maintainability*.

- ***Maintainability***: practically visible correlation observed with *Training*.

- ***Procedures***: practically visible correlation observed with *Training*.

From the flow of the literature review in *chapter 2*, it was important for the research to determine the degree of relationship between variables to ensure that the these relations are known for the purpose of adding value in resolving the research problem and also in delivering a usable and practical approach in reducing the MTTR. The interpretation of the results and findings is discussed in detail in *chapter 5*.

4.3.6 Significant results analysis

4.3.6.1 Introduction

The research aimed at explaining certain observations or facts about maintenance personnel demographics for the purpose of establishing a construct that will enable or contribute in answering the research question guided by the body of knowledge.

The research in the following paragraphs will use the family of multivariate statistical technique for helping to infer whether there are real differences between the means of three or more groups or variables in a population, based on sample data Wikiversity (2011).

The different test methods of significance including *t*-test, ANOVA test, effect sizes and Cohen's *d*-value will be used to methodically determine practical significant

results, which can be understood as a large enough difference to have an effect in practice.

4.3.6.1.1 Introduction to t-Test

When the means between two groups is to be compared, the independent t-test is used for the evaluation. The *t*-test can only be used to test differences between two means. Statistical significance (*p*) of a result simply means that the researcher is in a position of being sure that the statistic is reliable StatPac (2011b). When $p<0.05$ for the t-test, one can conclude that the difference between the two groups is statistically significant i.e. the measured relationship between variables is unlikely to have occurred by chance alone.

4.3.6.1.2 Introduction to ANOVA test

The reason for doing an ANOVA test is to determine if there is any difference between groups on some variable Cerg (2011). It is used to compare the means of more than two samples. For the ANOVA test, an omnibus test is conducted first to determine if there are significant differences between two groups. The omnibus test indicates that there are statistically significant differences for $p<0.05$. If statistically significant differences were shown in the omnibus test, post-hoc tests are conducted to pairwise compare the groups and determine between which groups the difference lay.

4.3.6.1.3 Introduction to Cohen's d-value

Ellis and Steyn (2003) explain that when a sample is not a random sample from the population, *p*-values and statistical inference to the population are not relevant. Instead, the sample should be considered as a small population for which effect sizes can be determined. An effect size is the size of the relationship between two variables and is usually defined as the difference in mean outcomes between the treatment and control group and it is also an indicator of the strength of the difference between two groups Braunstein (2007).

Large effect sizes indicate practical significance, which can be understood as a large enough difference to have an effect in practice. Therefore, for the effect of size, Cohen's *d*-value is determined to indicate if differences are practically significant i.e. the research finding is practically important or useful in real life. The guideline for interpreting Cohen's *d*-value is as follows:

$d = \|0.2\|$	small effect	no practically significant difference
$d = \|0.5\|$	medium effect	practically visible difference
$d = \|0.8\|$	large effect	practically significant difference

For the sake of completeness *p*-values will be reported as stated Snijders (2001) by that it is more conducive to the advance of science to report *p*-values than merely whether the proposition was rejected at the conventional 0.05 level of significance, however emphasis will be placed on Cohen's *d*-value.

4.3.6.2 Age group variable

The omnibus tests did not show any significantly difference except for *Procedures*, where the *p*-value was 0.08, which is significant at ten percent (10%) level. For the post-hoc tests, it was observed that none of the pairwise comparisons showed practically significant difference with small *p*-values with the exception of the fifty-plus age group which differed practically significant from the others. The results are given below in Table 4.3.6.2.

Table 4.3.6.2: Age group variable and Cohen's d-values

Item	Age group (years)	Mean	Standard deviation	p-value	Cohen's d-value
1	18 – 29	3.65	0.62	0.14	0.79
2	30 – 39	3.59	0.64	0.22	0.68
3	40 – 49	3.48	0.53	0.47	0.61

For the other sections there were no differences found based on age.

4.3.6.3 Education level variable

The results of *p*-values and Cohen's d-values for the sections for respondents who have acquired a national certificate compared with grouped (national diploma, three (3) year degree and post graduate qualification) respondents are given in Table 4.3.6.3 below.

Table 4.3.6.3: Results of education level and Cohen's d-values

Item	Section	Mean		Standard deviation		p-value	Cohen's d-value
		National certificate	Other	National certificate	Other		
1	Equipment Performance Measures	3.74	3.75	0.63	0.54	0.91	-0.02
2	Human Factors	3.91	3.86	0.59	0.547	0.70	0.09
3	Environmental Factors	3.13	2.89	0.77	0.70	0.18	0.32
4	Planning	2.62	2.52	0.54	0.54	0.48	0.18
5	Spare Parts	2.70	2.58	0.56	0.63	0.44	0.19
6	Maintainability	3.05	3.29	0.42	0.60	0.09	-0.40
7	Procedures	3.57	3.47	0.67	0.45	0.45	0.15
8	Training	3.05	2.89	0.96	0.71	0.45	0.16

No practically significant differences were noted between the Sections and the grouped level of education of respondents.

4.3.6.4 Designation variable

t-Tests were done with the designation variable of supervisor, technician, engineer and other grouped together. Significantly differences between respondents and *Environmental Factors, Spare parts and Training* sections were observed. The results of *p*-values and Cohen's d-values for the sections for respondents are given in Table 4.3.6.4 below.

Table 4.3.6.4: Results of Cohen's d-values for designation variable

Item	Section	Mean		Standard deviation		p-value	Cohen's d-value
		Tradesmen	Others	Tradesmen	Others		
1	Equipment Performance Measures	3.72	3.77	0.62	0.44	0.72	-0.08
2	Human Factors	3.88	3.80	0.60	0.43	0.56	0.13
3	Environmental Factors	3.08	2.71	0.76	0.60	0.05	0.48
4	Planning	2.60	2.48	0.56	0.47	0.40	0.21
5	Spare Parts	2.70	2.32	0.60	0.49	0.02	0.63
6	Maintainability	3.12	2.99	0.50	0.52	0.39	0.24
7	Procedures	3.52	3.42	0.62	0.42	0.48	0.15
8	Training	3.17	2.21	0.85	0.76	<0.001	1.12

The interpretation of the finding is discussed in detail in *section 5.8.3 of chapter 5*.

4.3.6.5 Experience in current designation variable

The omnibus tests did not show any significantly difference except for Section B7, where the *p*-value *was* 0.09. For the post-hoc tests, it was observed that none of the pairwise comparisons showed practically significantly difference with small *p*-values. The exception was respondents with more than ten years' experience, which differed practically significantly from the others. The results are given in given in Table 4.3.6.5 below.

Table 4.3.6.5: Results of Cohen's d-values for experience in current designation

Item	Experience	Mean	Standard deviation	p-value	Cohen's d-value
1	≤ 2 years	3.70	0.67	0.11	0.59
2	2–5 years	3.66	0.54	0.53	0.63
3	6–10 years	3.51	0.57	0.66	0.35
4	10+ years	3.31	0.49		

The interpretation of the finding is discussed in detail in *section 5.2.7.3 of chapter 5*.

The *t*-test and ANOVA test enabled the researcher to determine the effect size and significance amongst the variables that have been measured to gain an understanding of respondents variances based on age, education, designation and experience on each item of the questionnaire. The result is of importance for the design of the approach for reducing the MTTR of the plant in ensuring that it encompasses elements that might not have been considered or that were not visible to the maintenance function and management for productive corrective actions.

4.4 CHAPTER SUMMARY

In this chapter the results of the research work focusing on descriptive statistics were presented. Chapter 5 of this research will discuss the findings of the research and derive interpretations guided by relevant literature review, with respect to the results of the research.

CHAPTER 5: DISCUSSION AND INTERPRETATION

The previous chapter of the research focused on case studies, descriptive statistics and correlations between the variables of Section A and B of the questionnaire. Chapter 5 of this research will discuss the findings of the research and derive interpretations guided by relevant literature review, with respect to the results of the research.

5.1 Analysis of case studies

5.1.1 Maintenance job card

The maintenance job card issued enables maintenance personnel to give feedback on actions taken when equipment was repaired but not on what can be done better to improve the execution of repairs timeously. Thus an opportunity of capturing observations and recommendations made by personnel who were involved with the execution of the task is lost.

This may be as a result of a lack of what information can be included in the feedback section of the job card. A proposal of information that can be included in a standard maintenance job card is presented and discussed in *section 5.2.1.2*.

Feedback information will ensure that the reduction of the MTTR is not seen as a static or once off event but a continuous process that is entrenched within the maintenance function.

5.1.2 Training of maintenance personnel

The result of a number of maintenance personnel leaving the organization has resulted in a loss of equipment maintenance skill and knowledge. This has resulted in new entrants entering the organization with no plant experience and inadequate training. This has had negative consequences on maintenance execution especially its effectiveness.

However new employees are being trained according to a developed individual development plan (IDP) to ensure that they are competent on the equipment that they must maintain.

The lack of documenting and managing knowledge does not allow the maintenance function to be a learning function because it is likely that personnel re-invent the wheel instead of tapping on what has been learnt by others. Knowledge will need to be shared amongst maintenance personnel in a structured way.

5.1.3 Equipment maintainability

The lack of proper equipment accessibility design for the plant is an issue that maintenance personnel are aware of. This was caused by the failure of consultation and implementation of suggestions made by maintenance personnel to the project team. As a result of no action taken to correct the situation the current status has been accepted because the process of getting funds to implement corrective actions is difficult.

Handling of equipment is also a challenge which causes tasks that can be done by one individual to be assigned to more than one person to ensure that there are more hands to assist with lifting of equipment. Thus the installation of handling equipment in the plant will improve the time taken for executing corrective maintenance.

5.1.4 Fault localization and isolation

Correct fault localization and isolation is critical for corrective maintenance tasks to avoid unnecessary delays. Maintenance personnel are aware that their experience gained over the years on fault finding is better than what is included in OEM manuals. The failure to document these failures and corrective actions of resolving them is not contributing to better fault localization and isolation.

Although other plant areas have advance fault diagnosis equipment, this has not been transferred to other areas where gaps have been identified. This may be

attributed to the fact that such information is not shared amongst maintenance personnel who are operating in “silos”.

The approach presented in this dissertation will assist with the identification of fault localization and isolation needs for the plant equipment so that the time spent on fault finding can be improved. It is expected that the sharing of best practices with regard to localization and isolation will be improved because of the multidiscipline team composition approach that is required for performing the analysis proposed by this dissertation.

5.2 Analysis of questionnaire

The findings of the survey are discussed in the following paragraphs. To address issues uncovered by the survey, included with this dissertation is feedback information that can be included in a maintenance job card feedback section to capture information about factors that can be improved to lower the MTTR. Included also is a spare part development and management procedure that can be used by the maintenance function.

5.2.1 Equipment performance measures

5.2.1.1 Human factors

The measurement of the MTTR for the purpose of analysing corrective maintenance tasks durations is of importance for continuous improvement. The finding of a linear relationship between the understanding of *Equipment Performance Measures* by maintenance personnel and *Human Factors* in section *4.3.5.1 of chapter 4* highlights the importance of the role and influence that maintenance personnel can have on the successful execution of maintenance tasks.

It is safe to assume that communicating equipment performance measures to maintenance personnel can deliver positive results for the reduction of the MTTR of the plant if maintenance personnel are knowledgeable on the plant’s MTTR. Thus care must be taken in ensuring that performance measures are clearly defined and

explained to maintenance personnel so that confusion does not result on what is actually measured.

Such information can be communicated to personnel by posting the plant's performance measures at the entrance of the maintenance workshop and form part of discussions during communication forums which are held every morning. Feedback by the maintenance manager of monthly performance measures will cause maintenance personnel to be aware of the importance of achieving and exceeding the set MTTR target.

5.2.1.2 Maintainability

Although Pearson's correlation coefficient of 0.481 between *Equipment Performance Measures* and *Maintainability* was not greater than 0.5 for this relationship to be practically significant, it points to the level of influence that plant equipment maintainability attributes have on equipment performance. This also supports the body of knowledge on maintainability as discussed in *chapter 2* of this dissertation.

It is encouraging to find that respondents have an understanding of the relationship between equipment performanceand its maintainability.

To obtain valuable information on the effects of maintainability of plant equipment, changes can be made on the maintenance job card feedback section which is issued for every maintenance task that has to be executed. The feedback captured must be focused on maintainability factors that when addressed will have a positive impact on the reduction of the MTTR. The proposed information that must be included in the job card is presented in Figure 5.2.1.2.

Maintenance personnel will have to be trained on the subject of equipment maintainability as a practically visible correlation was observed with *Training* so that value can be derived on the content and suggestions that will be noted on the job card returned to the supervisor after task completion. The supervisor must then ask

enough questions for problems that require immediate attention so that they can be clearly explained for corrective actions to be a success.



Figure 5.2.1.2: Proposed feedback information to be included in a standard maintenance job card

5.2.2 Human factors

The practically significant correlation observed between *Human Factors and Maintainability* indicates that the execution of tasks by maintenance personnel is strongly influenced by equipment maintainability. A small degree improvement of equipment maintainability will bear positive results for the reduction of the MTTR. Neglected maintainability of plant equipment will in the same degree negatively impact the MTTR. Thus it is important that maintenance personnel are engaged in the quest for improving the MTTR.

The finding of practically visible correlations between *Human Factors* and *Planning, Spare Parts, Procedures and Training* as shown in Figure 5.2.2 below shows that the execution of maintenance tasks is also influenced by spare parts, planning, procedures and training that must be taken into consideration when an attempt is made in reducing the MTTR of the plant.

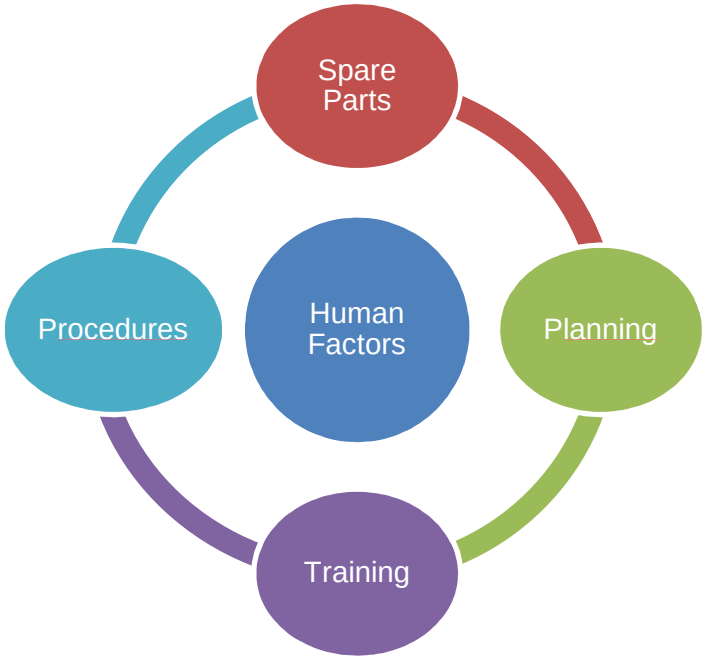


Figure 5.2.2: Relationship of spare parts, planning, training and procedures with human factors

Form the finding it is apparent that *Human Factors* cannot exist in isolation but need to be integrated with the other elements. These elements are discussed in detail in the following sections.

5.2.3 Spare parts

A mean of 2.64 was observed for *Spare Parts* as indicated in Table 4.3.4 of section *4.3 of chapter 4*, which was the lowest in magnitude when compared to the other sections. A practically significant correlation of 0.556 was also observed with *Maintainability*. Timely availability of spare parts affects the duration of maintenance tasks. Without proper support of equipment when required, executing maintenance becomes difficult for maintenance personnel. The lack of spare parts and knowledge of where to find them negatively affects the MTTR when maintenance has to be performed. Figure 5.2.3 gives the steps for developing and managing spare parts of equipment.

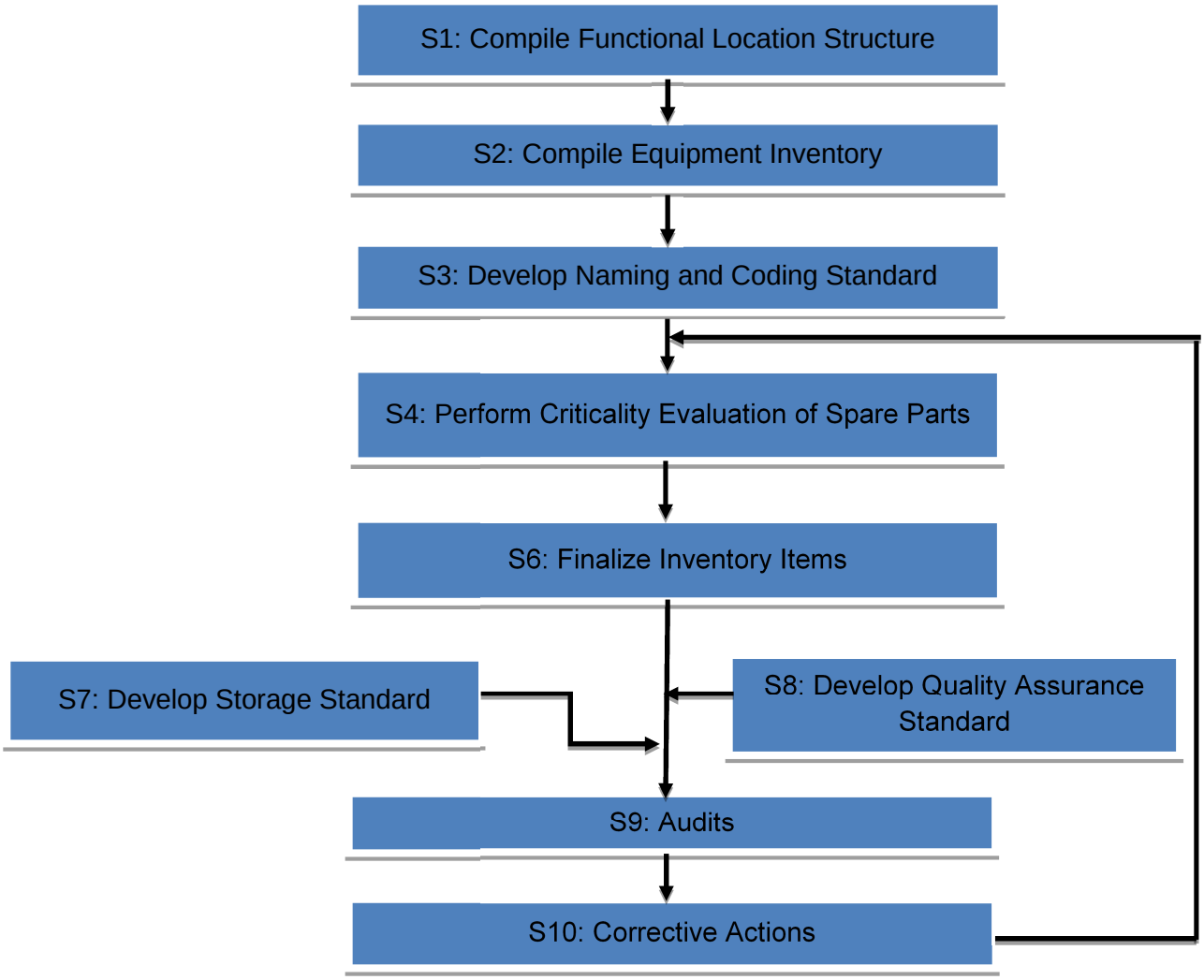


Figure 5.2.3: Proposed approach for maintenance store spare parts development and management

An explanation of the proposed approach is given in the following paragraphs.

S1: Compile Functional Location Structure

This activity involves the compilation of the equipment in the plant according to the location or the place at which a maintenance task is to be performed according to a hierarchy.

S2: Compile Equipment Inventory

An inventory of the equipment is a result of data and other information according the design of the plant. The purpose of this activity is to ensure that equipment in the plant is known and inventoried.

S3: Develop Naming and Coding Standard

For maintenance personnel to be able to locate and maintain stock, a standard for naming and coding storage areas must be designed. This eliminates confusion and ensures that every time the correct spare parts are ordered and stored correctly. Time will be saved if the exact location and identification of items is known by maintenance personnel.

A standard desktop PC running a standard spread sheet program which is approved by the organization will be able to perform this task without additional investment on a special software package.

S4: Perform Criticality Evaluation of Spare Parts

Each spare item that is carried in the local maintenance store must be evaluated in terms of its criticality in supporting the maintenance strategy chosen for that particular equipment. It suffices to say that this will not be the only criteria that will be used for evaluation. However an assumption is made that the main store of the works caters for other items that are in its inventory.

S5: Finalize Inventory Items

Once the actions of the previous steps have been completed, the inventory items of spare parts can be finalized. This inventory must be made available to all by keeping a hard copy in the store for maintenance personnel to access it when needed. The store person can be the keeper of the inventory and thus communicate any needs of its further development to the planners at ad-hoc or during an audit.

S6: Develop Storage Standard

To ensure that the quality of spare parts does not deteriorate, storage standards must be developed. The implementation of the original equipment manufacturer (OEM) recommendations is of importance. Any additional strict storage standards known based on experience of handling the spare parts is of value and should be implemented if the OEM's recommendations are deemed to be inadequate.

S7: Develop Quality Assurance

Items that have not been checked by the requester can be stored in a separate storage bay if there is an adequate storage area to ensure that items are of the correct standard before they are stored.

Items that are returned to the store must also be checked to ensure that before they are put in their respective storage areas; their qualities have not been compromised. This will eliminate occurrences whereby an item is taken to the plant only to find out that its quality has been compromised.

S8: Audits

The purpose of performing audits will establish if the system is working properly and adding value without being a burden. The audit team can consist of the store person, maintenance supervisors, planners and tradesmen. Facts behind any problem need to be established and recommendations that will result in

improvements being made to correct problems with the current inventory or system of managing the spare parts in the local store.

S9: Corrective Actions

Implementation of corrective actions is crucial for the success of an effective and productive spare parts management system for continuous improvement and elimination of any problems that might have been experienced in the past that resulted in prolonged maintenance durations.

Changes made on the feedback section of the maintenance job card and recorded by maintenance personnel as discussed in *section 5.2.1.2* on maintainability, will serve as valuable input for continuous improvement of the process suggested.

5.2.4 Environmental factors

No correlation was found between *Environmental Factors* and any other measured variable in Section B. This may be due to these factors being enforced by other laws of the country. This finding does not mean that environmental factors should not be taken into consideration in an attempt of reducing the MTTR of equipment installed plant.

5.2.5 Planning

Thelevel of maintenance planningmeasured in Section B4 was found to have a mean of 2.59 as indicated in Table 4.3.4. The finding in section *4.3.5.2 of chapter 4* of a practically visible correlation observed between *Planning*, *Spare Parts and Maintainability* highlights the relationship and impact that these three variables have on the MTTR of the plant**.**

To ensure that planning as a process achieves its outcomes, the maintenance function must see *Planning* as encompassing of maintainability, line management, tradesmen, planner, training, maintenance strategy, purchasing and procedures as shown in Figure 5.2.5 below.

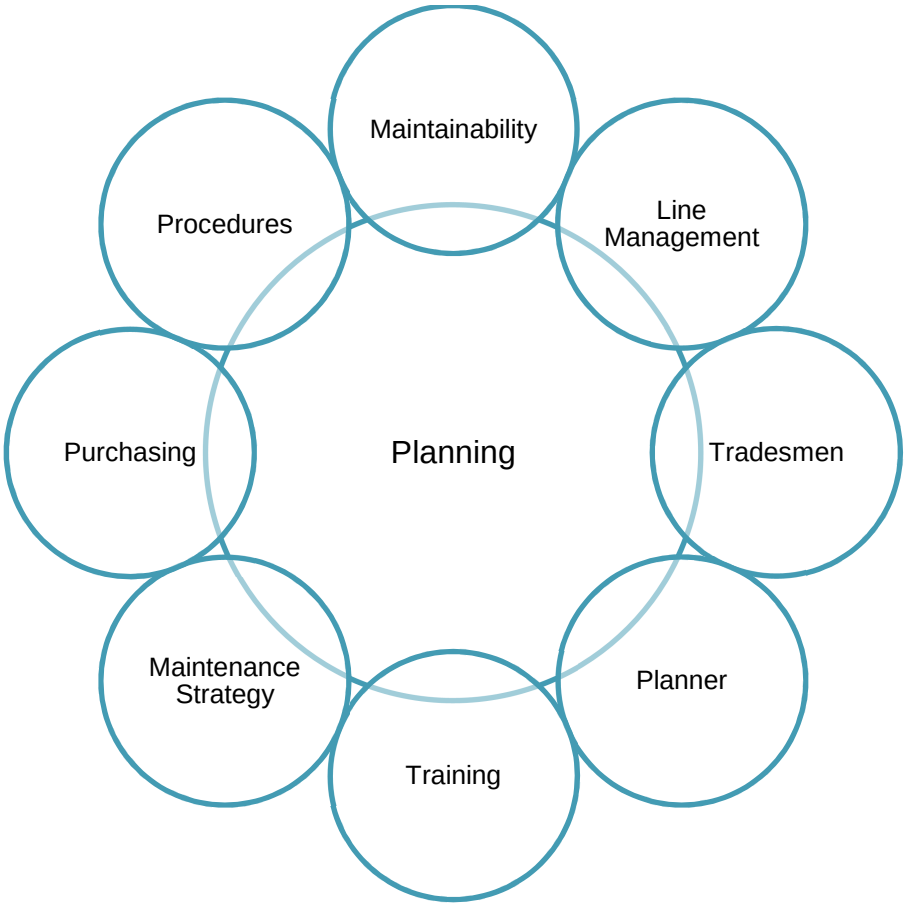


Figure 5.2.5: Relationship of planning with other support elements

When maintenance planning is being done, it is very important that the influence of technical and non-technical elements be considered because their impact may negatively impact the MTTR.

5.2.6 Procedures

The practically visible correlation observed between *Procedures and Training* of 0.425 in *section 4.3.5.2 of chapter 4,* points out that this relationship can influence the outcome in attaining the desired MTTR of plant equipment.

Detailed written procedures must be developed and followed to the letter by maintenance personnel. When procedures are followed, the risk of trial and error on the maintainer's side is mitigated. Procedures give a structured sequence of actions

that when followed eliminate prolonged maintenance tasks durations and eliminate substandard work.

Although OEM maintenance procedures are useful, they need to be adapted for the environment in which equipment is installed. Thus the use of the approach proposed will serve as a viable tool not only for deriving the maintenance actions for a procedure but also in decision making for maintenance strategies for the equipment in the blast furnace environment.

It is necessary that effort be put to ensure that the maintenance procedures are of a standard that can be interpreted, understood and implemented by maintenance personnel. If this is attained, personnel will be encouraged to give their input in further development of the maintenance procedures.

5.2.7 Demographics

5.2.7.1 Age group

The age groups 18–29 years, 30–39 years and 40–49 years had a mean of 3.65, 3.59 and 3.48 respectively. When the Cohen's value was determined, the finding for the 18–29 years age group was 0.79 as reported in Table 4.3.6.2, *section 4.3.6.2 of chapter 4*. This finding was a large effect and the difference practically significant. This age group responded favourably on the section of *Procedures* which measured the level of utilization of maintenance procedures by maintenance personnel.

The use of maintenance procedures seems to be least favoured by the other age groups, especially by maintenance personnel above fifty years old. Maintenance personnel in this age group surely must be depending on experience for executing maintenance. This is of concern as it can imply that maintenance is executed based on intuition. The MTTR and the quality of work are certain to be affected by the lack of procedure used as trial and error will likely waste valuable time.

5.2.7.2 Education level

No practically significant differences were noted between the Sections and the grouped level of education of respondents as reported in Table 4.3.6.3, *section 4.3.6.3 of chapter 4.*

5.2.7.3 Designation

A finding of notable practically significant differences was noted between respondents who are by designation tradesmen, supervisors, technicians and engineers. For the research, supervisors, technicians and engineers were grouped under line management for analysis purposes. Cohen's d-values for *Environmental Factors*, *Spare Parts* and *Training* were 0.48, 0.63 and 1.12 respectively as reported in Table 4.3.6.5, *section 4.3.6.5 of chapter 4* when tradesmen responses were compared to that of line management.

The difference in these categories of designations is expected as each designate has different duties with regards to plant maintenance. However this can also be interrupted as a lack of appreciation by line management of the challenges that tradesmen face daily when it comes to the maintenance of plant equipment which ultimately influence the MTTR.

It is important for supervisors, technicians and engineers to become actively involved with tradesmen in corrective actions of the FMEA output process suggested in *section 5.6* of this chapter.

The technical team that conducts the FMEA should consist of a supervisor, technician, engineer, tradesmen and a planner.

Under normal circumstances during faultfinding, tradesmen contact line management if they are not in a position to diagnose a fault. If the competency of line management is not at a level that will result in the correct diagnosis and corrective action required to resolve a fault, the time it takes to repair that particular equipment is further prolonged. It is important that tradesmen and line management

be trained on equipment installed in the plant rather than receiving generic training. The benefit of such action will result in an improved MTTR of the plant.

Line management is expected to be sensitive to factors that negatively affect the MTTR because of their all compassing view of the plant compared to tradesmen whose focus is usually on the area of responsibility. Plant walks that line management is expected to conduct as part of their function should also constitute looking at installed plant equipment from its accessibility, installation, environment of operation, diagnostic capability etc. for the purpose of improving the time it takes to conduct maintenance.

5.2.7.4 Experience in current designation

The results on the experience in current designation of maintenance personnel presented in Table 4.3.6.5 show respondents with more than ten years working experience in the plant differed practically significant from theothers. Personnel in the ≤ 2 years, 2–5 years and 6–10 years, showed a positive like-mindedness on the use of maintenance procedures than the ten years plus respondents.

Experienced maintenance personnel are valuable to any organization as they are important for transferring knowledge that has been acquired through experiences over the years to new personnel. However failure of theten years plus personnel to use maintenanceprocedures has the potential of not impacting positively to the maintenance function's quest of reducing MTTR.

5.2.8 Training

To reduce the MTTR, it is important that plant specific equipment knowledge, skills, and competencies required for the successful execution of maintenance tasks are obtained by maintenance personnel.

The practical skills and knowledge will result in the timely execution of maintenance tasks when done according to prescribed procedures. A combination of on-the-job training which takes place in a normal working situation and off-the-job training which

takes place away from normal work situation, will improve the competency of personnel and result in the reduction of the MTTR.

Maintenance personnel will have to be trained on the importance of the feedback they record on a job card and its correct completion.

5.3 CHAPTER SUMMARY

In this chapter the results of the research work focusing on case studies, descriptive statistics and correlations between the variables were presented. Chapter 6 of this research will present and discuss elements of the structured approach that answers the research question based on the findings of this research. The validation and test results of the approach are also discussed.

CHAPTER 6: STRUCTURED APPROACH DISCUSSION

In chapter 5 of this research the findings of the research and derived interpretations guided by a relevant literature review with respect to the results of the research were discussed. This chapter will propose and discuss an approach that answers the research question based on the findings of this research.

6.1 Structured approach introduction

The approach starts by asking if the current MTTR of the equipment can be improved. It then follows with the identification of potential failures and their effects on the equipment being analysed. These steps take on from the FMEA process discussed in *chapter 2, section 2.4* of literature review. The maintainability attributes of the equipment as installed in the plant are uncovered and evaluated on the basis of their impact on the corrective maintenance and times.

Failure diagnosis which includes fault localization and isolation is taken to a higher level in terms of analysis as a result of the research findings on case studies. The new corrective maintenance times are then computed as a result of identified corrective actions that flow from the process. New corrective maintenance times are computed.

The approach takes into consideration experience and competency of maintenance personnel responsible for maintaining the equipment by assigning factors in the final calculation of a new MTTR. If the new MTTR is better than the previous MTTR, recommended corrective actions that flow from the process are evaluated against the cost of implementation. The approach is discussed in detail in the following paragraphs.

6.2 Structured approach presentation and discussion

The approach briefly introduced in *section 6.1* is presented in Figure 6.2.

The steps that need to be completed by the team that conducts the analysis of equipment identified are discussed in detail in the following paragraphs.

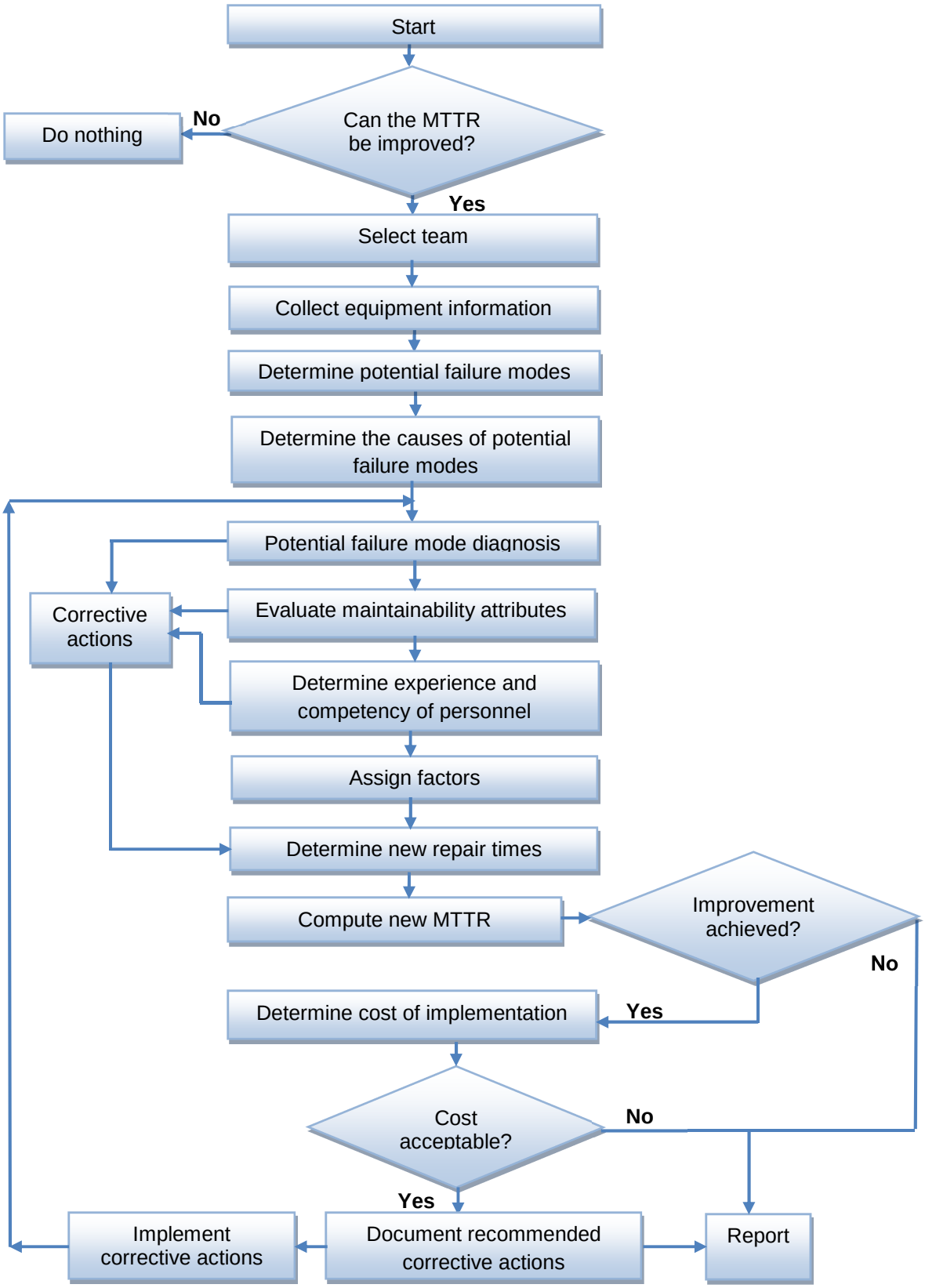


Figure 6.2: Proposed approach for the reduction of the MTTR of plant equipment

Step 1: Can the corrective maintenance repair times of the equipment be improved?

Since maintenance resources must be committed to ensure that the analysis is thorough and productive. It is vital to ask this question from the onset to ensure that scarce resources are not wasted. This question serves as a gate keeper of the approach.

However care must be taken in that the existing state of affairs within the maintenance function does not hinder an opportunity of investigating the reduction of the MTTR. Thus experience, maturity and leadership are required in answering the question.

Step 2: Team selection and composition

The team approach is chosen because it improves the likelihood of yielding good results and it embeds a paradigm shift for all participants involved with the execution of the analysis. Another advantage is that a group of personnel responsible for the maintenance of the plant equipment at different designations are exposed to the principles and practices contained within the approach.

A team leader responsible for coordinating activities of the process and ensuring that all the steps of the approach are undertaken must be assigned. It is essential that the team includes the following personnel that will challenge the status quo; engineer, technician, supervisor, tradesmen and a planner.

Participants in the analysis must know the working of the equipment and above all see room for improvement that this process offers.

Step 3: Collect equipment information

The equipment information may be obtained through previous investigation reports, item repair histories, OEMs, vendors, drawings and the knowledge of maintenance personnel is valuable information that must be utilised. It is always a challenge to

obtain information from OEMs timely, thus if accurate data cannot be obtained, educated engineering assumptions can be made about the equipment and its components.

The importance of a physical audit of the equipment cannot be overemphasised because it enables the team to see things that might be missed unless the equipment is touched and felt.

Step 4: Determine potential failure modes

The potential failure modes of the equipment must be documented to ensure that all possible failures are considered. Attention should be given to failure modes that are likely to happen in the operating environment of the equipment. Equipment failure mode should include the following:

1. Failures that have been experienced before by the equipment in their current or other location in the plant.
2. Failures that have not happened but are likely to happen and
3. Failures that have not happened and are unlikely to occur but can have severe consequences on the corrective maintenance times of the equipment.

Step 5: Determine the causes of potential failure modes

It is important to know what caused a failure to occur in order to diagnose the failure. This will reduce fault finding time.

Step 6: Potential failure mode diagnosis

The goal of fault detection, localization and isolation is to effectively detect faults and accurately isolate them to a failed component in the shortest time possible. The means for ensuring that the shortest time possible is achieved all the time need to be identified and improved upon to match the goal. The following questions must be asked and answered by the team:

- Can the failure be localized and isolated at the first instance i.e. without the use of test equipment?
- What level of competency is required for a person to localize and isolate failures of maintainable components?
- Can the person performing fault finding interpret the fault without the assistance of a special tool?
- Does each maintainable component have the means to detect all the identified failures within it?
- What is required to be in place to ensure that fault localization and isolation can be done without the use of tools?
- Can each potential failure mode be detected, localized and isolated by automatic, semi-automatic or manual means?
- Are current tools and methods used for diagnosis useful in diagnosing faults?
- Are tools and methods used for diagnosis out-dated and no longer relevant?

The team must generate ideas according to its knowledge and experience that when implemented will reduce the time of fault localization and isolation and the attainment of a lower MTTR. These ideas form part of corrective actions.

Step 7: Determine equipment maintainability attributes

The maintainability attributes of the equipment are evaluated based on the current location in the plant. The purpose of this step is to ensure that the outcome of the recommendations of corrective actions encompasses both inherent and operational attributes.

The handling of the equipment and its components must also be taken into consideration. All equipment installed in its current position was taken from somewhere, transported to the plant and installed in its position. This equipment had to be handled. The following questions must be asked and answered by the team:

- How easy is it to access the equipment?

- What are the design weaknesses of the equipment that make it to require special handling equipment?
- Can the faulty component be handled by one person?
- Can the faulty equipment be handled better to prevent a loss of time when a failure occurs?
- What can be improved to ensure ease of handling the equipment (e.g. electric hoists, handling trolleys, pallet truck)?

Step 8: Determine experience and competency of personnel

The propensity of experienced personnel not to use maintenance procedures is of concern and need to be managed properly to ensure that the corrective maintenance actions are executed effectively. This is very important for the enforcement of the use of maintenance procedures.

Step 9: Assign experience and competency factors

Ideally all maintenance personnel are supposed to be in a position of executing corrective maintenance at the same time based on their experience, training and skill level. However this is not always true in reality. To compensate for this variation, a factor is used based on the average experience and competency of maintenance personnel to calculate the revised MTTR. Table 6.2a and 6.2b give the factors used for calculating the MTTR based on the average maintenance team experience and competency respectively.

Table 6.2a: Average experience factor of team

Item	Average experience of team	Experience factor (k1)
1	≤ 2 years	1.2
2	2 – 5 years	1.15
3	6 – 10 years	1.1

Table 6.2b: Average competency factor team

Item	Average competency of team	Competency factor (k2)
1	81-100%	1.1
2	51-80%	1.2
3	less than 50%	1.3

The work of other researchers in this field had failed to acknowledge that not only competency influences the MTTR but also the experience of maintenance personnel as established by the research. The average maintenance team experience and competency factors allow for the variations that occur as a result of different persons that perform maintenance on equipment at different times during its life cycle.

Step 10: Compute new corrective maintenance times

Compute new corrective maintenance repair times that will be achieved based on the implementation of corrective actions identified. The estimation of corrective maintenance times of the equipment is guided by the step that identified the repairable components of the equipment. The repair actions must be described clearly so that it would be easy to determine the sequence of repairs.

Estimates can be made guided by experience at the first instance until accurate figures are obtained or needed for accuracy. The corrective maintenance actions times for each failure mode must be quantified. The experience of the team is very important for this step of the process as it might affect the decision of whether to commit additional resources to implement the corrective actions.

Step 11: Compute new MTTR

The improved MTTR that can be achieved by implementing corrective actions that flowed from the process must be quantified and evaluated. The purpose of calculating the availability of the equipment or component is to make visible the impact of the MTTR on the availability of the equipment or component at constant

failure rate. The failure rate of the equipment or component must be kept unchanged for consistency of evaluation.

Step 12: Determine cost of implementation

In an ideal world there are inexhaustible resources available. However in business, there is a competition for resources. Thus the cost of implementing the corrective actions must be determined to ensure that financial resources are invested where value will be derived. At this stage it is acceptable that the cost will not be accurate but for analysis purposes experience must be used in estimating the costs.

Step 13: Cost evaluation

The cost of implementing the recommended corrective actions must be evaluated against the cost of not doing anything. The LCC must be taken into consideration rather than the cost of just implementing the corrective actions of reducing the MTTR. The evaluation might include a simple pay back calculation to the net present value (NPV) method or any method that the organization uses for financial evaluation.

Step 14: Document recommended corrective actions

Recommended corrective actions that will result in the reduction of the MTTR must be documented so that in an event that a need arises to re-valuate them, the information will be available for maintenance personnel or other person interested in the information.

Step 15: Corrective actions implementation

The recommended corrective actions must be implemented to ultimately derive the benefits that were determined and quantified.

Step 16: Report

A report must be compiled to communicate all information pertaining to the process followed. Problems that were identified but could not be corrected must also be documented.

6.3 Validation and testing of approach

The approach was validated by conducting two cases identified together with supervisors of the plant. The case studies included the Stock house and the Furnace top of the plant. Included in *Appendix D and E* are samples of completed worksheets that were used to perform an analysis of equipment installed in the plant areas mentioned above.

The equipment installed in the Stock house was chosen because the supervisor's knowledge that the historic MTTR of 0.67 hours captured in the CMMS SAP (System, Applications and Products) platform did not reflect the true MTTR due to human error when logging maintenance requests. Thus it was important to establish a baseline MTTR.

The historic MTTR of 2.03 hours for the tilting gearbox installed at the Furnace top was used for the second case study. The new MTTR and plant availability calculated after the analysis was 1.25 hours and 99.982% respectively.

6.3.1 Data collection

Plant equipment known to be critical for the operation of the furnace was chosen for the analysis. The criticality approach for initiating the process of analysing the MTTR of equipment was also suggested by Case Study A.

The criticality result of the plant equipment was obtained from the archives of the maintenance function. The marrying of both technical and non-technical elements important for improving the MTTR of the plant by the approach enables a wider view of what needs to be thought of through for achieving improvement.

Obtaining information at the system level on the MTTR and availability was not a problem as it was readily available on the CMMS. Information on component level was not available because not all the functional locations on the CMMS were designed for capturing data at that level.

6.3.2 Maintainability attributes

The lack of equipment maintainability knowledge and its impact on the execution of maintenance by some of the team members resulted in taking valuable time during the case study. This was because of an explanation that had to be given to address this gap. Since the procedure enables personnel to have in depth knowledge of the performance of plant equipment, it can also serve as a valuable tool for reliability studies.

6.3.3 Experience and competency factors

The average team experience and competency factors used were deemed by the team to be too strict. This was expected because of each person's sensitivity towards the deviation from the new MTTR which becomes a baseline.

6.3.4 Cost of implementation

The cost of corrective actions was based on historical prices that were previously charged or are known to be standard. These prices were escalated to ensure that they are not less than what would eventually be charged by vendors. Care was also taken in ensuring that these estimated prices were not too high and result in a higher cost of implementation.

6.3.5 Cost of implementation evaluation

In the organization it is best to evaluate a benefit with respect to the availability that will be derived because it is easy to compute and not difficult to understand.

The need to evaluate the cost of implementation became apparent as team members asked about the benefits of the approach if it does not enable maintenance personnel to prove to decision makers that the investment of resources will improve the competitiveness of the organization.

The consideration of the cost of implementation of corrective actions was noted by all that it is a valuable element of the approach as it offers a complete delivery especially as it is needed by decision makers whose role is to ensure that resources are used productively.

It became apparent during the testing of the approach that the process requires commitment from the team appointed to perform an analysis. At a glance it looks as though the steps can be completed without much effort until a physical audit of the equipment is conducted where valuable information is revealed.

6.4 CHAPTER SUMMARY

This chapter discussed the approach that has been developed to enable maintenance personnel to systematically reduce the MTTR of equipment installed at BFD. The approach was tested and validated to ensure that it delivers on the research objectives.

Chapter 7 will present a summary of the research based on a comprehensive scientific methodology that considered factors derived from the body of knowledge, results and findings. Recommendations will be made and conclusions drawn.

CHAPTER7: RECOMMENDATIONS AND CONCLUSIONS

The previous chapter of the research focused on the designed structured approach for reducing the MTTR, descriptive statistics and correlations between the variables of Section A and B of the questionnaire.

Chapter 7 of this research will present a summary of the research based on its findings and make recommendations and conclude.

7.1 Conclusions

The research had as its main purpose the development of an approach or methodology founded on scientific grounds that can be used by the maintenance function to reduce the MTTR of equipment installed at Blast Furnace D. The approach had to assist maintenance personnel in their different capacities with the identification, recording, evaluation and implementation of corrective actions that will contribute to the reduction of the MTTR.

The approach proposed in this dissertation was derived from the existing body of knowledge, questionnaire survey and observations and has demonstrated that the reduction of the MTTR of plant equipment can be achieved. The results also indicated that through the use of the designed approach a regular pattern of repair or replacement times can be followed well in advance and that it is practical, user friendly and it also delivers on its objective of offering a structure for analysis and decision making aimed at reducing the MTTR.

It is envisaged that the approach will benefit and improve the competitiveness position of the organization.

7.2 Additional factors for MTTR reduction

Four factors that were also identified by the research to be critical for the reduction of the MTTR were;

- Feedback by maintenance personnel on maintainability attributes of plant equipment.
- Training of maintenance personnel.
- Maintenance procedures use by maintenance personnel and
- Spare parts which entail the level of equipment support.

Addressing these factors has the potential of reducing breakdown durations, improve plant availability and add value to the organization's bottom line, and improve the company's competitiveness through the maintenance function according to the maintenance strategies adopted for plant equipment.

7.2.1 Recommendations on maintainability

Recommendations on the FMEA process developed and discussed in *section 5.2.1.2 of chapter 5* of this research are highlighted as follows:

- Revise the job card feedback section to capture maintainability information of equipment.
- Train maintenance personnel on maintainability attributes of equipment so that the correct and quality of information adds value.

7.2.2 Recommendations on training of maintenance personnel

Recommendations on the training of maintenance personnel as a result of findings discussed in *section 5.2.8 of chapter 5* of this research are highlighted as follows:

- Maintenance personnel must be trained on maintenance procedures for them to execute them effectively within the prescribed time after the FMEA process has been completed for the plant.
- Training needs of individuals must be assessed to determine their alignment with the goal of reducing the MTTR of the plant.

- The training needs both internal and external must be allocated for in the budget and its impact measured to determine its benefits if any.

7.2.3 Recommendations on maintenance procedures

Recommendations on the use of maintenance procedures by maintenance personnel as a result of findings discussed in *section 5.2.6 of chapter 5* of this research are highlighted as follows:

- Considering the level of education of the majority of maintenance personnel, it is recommended that effort be put in ensuring that maintenance procedures are of a standard that can be interpreted, understood and implemented by maintenance personnel through the use schematics, photos, flow diagrams, and warnings etc.
- Input on the development of maintenance procedures by tradesmen must be encouraged because of their eagerness of contributing to the development as and their interaction with plant equipment more than line management.
- Attention should be given to experienced maintenance personnel who seemed not to be eager on the use of maintenance procedures to ensure that they understand the importance of using procedures.
- Experienced personnel should become part of the team that develops and evaluate maintenance procedures for them to appreciate the importance of executing maintenance tasks according to predefined steps.

7.2.4 Recommendations on spare parts

Recommendations on the level of equipment support as a result of findings discussed in *section 5.2.3 of chapter 5* of this research are highlighted as follows:

- The orientation of new employees on the management of spare parts in the plant's local store of the maintenance function will ensure that employees are familiar with the systems used for managing spare parts.
- An inventory of critical spare parts must be compiled with an input of line managers and managed by the planner and a supervisor.

- Planners must liaison with purchasing to ensure that at any given time spare parts are available when needed.

7.3 Future research

Further research must be done to determine the optimum cost benefit of equipment availability that can be derived when the mean time between failures and the mean time to repair of plant equipment are simultaneously improved.

7.4 Limitations of the study

This research was limited to a structured approach for the reduction of the MTTR of equipment installed at Blast Furnace D. The research finding may not be accurate for other blast furnaces because of cultural differences and competency levels of maintenance personnel. However commonalities are likely to be found and the sample used for the research survey provides a good representation of common challenges that are faced by maintenance functions with regards to the restoration of equipment as quickly as possible after a failure.

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ANNEXURE

Appendix A: Questionnaire Letter

ACADEMIC RESEARCH PURPOSES ONLY
(PRIVATE & CONFIDENTIAL)

Note: All responses are confidential and neither the individual nor the organisation will be identified in any report or release.

ACADEMIC RESEARCH PURPOSES ONLY
(PRIVATE & CONFIDENTIAL)

Dear Sir or Madam,

SUBJECT: A STRUCTURED APPROACH FOR THE REDUCTION OF THE MEAN TIME TO REPAIR

I am presently registered for the degree Masters of Engineering in Development and Management at the North West University, Potchefstroom, South Africa. I intend to complete my studies at the end of the year 2011.

I kindly request your support for the completion of the questionnaire for my dissertation. My chosen field of study is on 'A Structured Approach for the Reduction of the Mean Time To Repair of Blast Furnace D, ArcelorMittal South Africa, Vanderbijlpark.

The research has its main purpose the development of an approach or methodology that can be used by the maintenance function to reduce the mean time to repair (MTTR) of equipment installed in your plant.An approach which aims at improving the performance of equipment maintenance and subsequent improved availability will be recommended.

Questionnaires must be completed and sealed in an envelope and returned to me on the 2nd of September 2011 at the latest. Please answer all questions as honestly and accurately as possible. I assure that data will be handled confidentially. Also kindly indicate if you would like to have details of my findings, once approved by the University.

Your opinions through this questionnaire are highly appreciated. I thank you for spending your valuable time in completing this questionnaire. For any questions or comments, please contact Alex Madonsela at 082 298 7401 or alex.madonsela@arcelormittal.com.

It should take no longer than 15 minutes of your time to complete this questionnaire.

Thank you for your cooperation.
Sincerely,

AT Madonsela
016 889 4001 or 082 298 7401

Appendix B: Questionnaire

SECTION A

BACKGROUND INFORMATION

The following information is needed to help with statistical analysis of data. All your responses will be treated confidentially. Your assistance in providing this important information is appreciated. **Please mark the applicable block with a cross (X).**

AO1	**Indicate your age group**	18 – 29	30 – 39	40 – 49	50 - 59	60+
		1	2	3	4	5

AO2	**Indicate your gender**	Male	Female
		1	2

AO3	**Indicate your highest education level**	National certificate	National diploma	3-year degree	Post graduate qualification	Other
		1	2	3	4	5

AO4	**Indicate your designation**	Tradesman	Supervisor	Technician	Engineer	Other
		1	2	3	4	5

AO5	**Indicate your experience in your current designation**	≤ 2 years	2 – 5 years	6 – 10 years	11 – 15 years	16+ years
		1	2	3	4	5

SECTION B

A STRUCTURED APPROACH FOR THE REDUCTION OF THE MEAN TIME TO REPAIR QUESTIONNAIRE

This section consists of **62** statements. Please indicate to what extent you agree or disagree with each statement. **Please mark the applicable block with a cross (X)**

SECTION B1

	STATEMENT	SCALE				
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
1	I know the maintenance performance measures set for the plant.	1	2	3	4	5
2	The maintenance performance measures set for the plant have been communicated to me.	1	2	3	4	5
3	Actions for improving the maintenance performance measures have been communicated to me.	1	2	3	4	5
4	I support the maintenance performance measures set by my function for the plant.	1	2	3	4	5
5	I aim to positively contribute to the achievement of the plant's maintenance performance measures.	1	2	3	4	5

6	I feel that effective execution of equipment maintenance is my responsibility.	**1**	**2**	**3**	**4**	**5**
7	I feel that well maintained equipment contributes to business objectives.	**1**	**2**	**3**	**4**	**5**

SECTION B2

	STATEMENT	**SCALE**				
		Strongly disagree	**Disagree**	**Neutral**	**Agree**	**Strongly agree**
8	I aim to conduct maintenance activities/tasks in a shortest time possible.	**1**	**2**	**3**	**4**	**5**
9	I consider my work stressful as a result of time allocated for each maintenance activity.	**1**	**2**	**3**	**4**	**5**
10	I aim to take less time to execute equipment maintenance compared to the time allocated.	**1**	**2**	**3**	**4**	**5**
11	I aim to execute equipment maintenance the first time right.	**1**	**2**	**3**	**4**	**5**
12	I receive clear maintenance instructions.	**1**	**2**	**3**	**4**	**5**
13	I feel that equipment is adequately designed for me to execute maintenance successfully.	**1**	**2**	**3**	**4**	**5**
14	I feel that too much effort is required from me to execute maintenance.	**1**	**2**	**3**	**4**	**5**

SECTION B3

	STATEMENT	SCALE				
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
15	I feel that lighting around plant equipment is adequate for me to execute maintenance work.	**1**	**2**	**3**	**4**	**5**
16	The noise level in the plant prevents me from executing equipment maintenance effectively.	**1**	**2**	**3**	**4**	**5**
17	Working near high temperatures prevents me from executing equipment maintenance effectively.	**1**	**2**	**3**	**4**	**5**
18	Working in a dusty area prevents me from executing equipment maintenance effectively.	**1**	**2**	**3**	**4**	**5**

SECTION B4

	STATEMENT	SCALE			
		Never	Sometimes	Often	Always
19	I know what work I will perform the next day before the end of shift.	1	2	3	4
20	I plan my work in advance before going to the plant to perform maintenance.	1	2	3	4
21	I wait for a job card to be issued to me before I execute equipment maintenance.	1	2	3	4
22	I have the necessary spares required to successfully execute equipment maintenance.	1	2	3	4
23	I decide myself when to start equipment maintenance.	1	2	3	4
24	I execute maintenance of equipment timeously.	1	2	3	4
25	I know what tools to take along before going to the plant to perform maintenance work.	1	2	3	4

SECTION B5

	STATEMENT	SCALE			
		Never	Sometimes	Often	Always
26	I know where to look for spare parts when I need them.	1	2	3	4
27	The spare parts storage area is organized.	1	2	3	4
28	Spare parts are stored in their unique identifiable racks.	1	2	3	4

29	I am never in doubt of what spare part to use.	**1**	**2**	**3**	**4**
30	Spare parts issued always fit the first time and do not require any modification.	**1**	**2**	**3**	**4**
31	I am able to locate spare parts in the store without the support of the store assistant.	**1**	**2**	**3**	**4**

SECTION B6

	STATEMENT	**SCALE**				
		Strongly disagree	**Disagree**	**Neutral**	**Agree**	**Strongly agree**
32	Equipment service points (e.g. grease points) are visible.	**1**	**2**	**3**	**4**	**5**
33	Equipment service points (e.g. grease points) are fully accessible.	**1**	**2**	**3**	**4**	**5**
34	Equipment service points are at arm-reach.	**1**	**2**	**3**	**4**	**5**
35	Equipment components are directly and easily accessible for maintenance.	**1**	**2**	**3**	**4**	**5**
36	Equipment is designed for line-of-sight to be able perform visual inspection.	**1**	**2**	**3**	**4**	**5**
37	Equipment is designed for line-of-sight to be able perform servicing.	**1**	**2**	**3**	**4**	**5**
38	Equipment is designed for line-of-sight to perform adjustment.	**1**	**2**	**3**	**4**	**5**

39	Equipment is designed for line-of-sight to perform alignment.	**1**	**2**	**3**	**4**	**5**
40	Equipment is designed for line-of-sight to perform in-place repair.	**1**	**2**	**3**	**4**	**5**
41	Equipment consists of detachable modules, which can be manufactured, assembled, and serviced separately.	**1**	**2**	**3**	**4**	**5**
42	Equipment allows me to test, detect, diagnose or isolate faults without special testing tools.	**1**	**2**	**3**	**4**	**5**
43	Equipment has gauges, built-in-test function etc. which assist me with faultfinding.	**1**	**2**	**3**	**4**	**5**
44	Equipment can self-test to identify all the causes of malfunctioning.	**1**	**2**	**3**	**4**	**5**
45	Equipment requires special tools to execute maintenance.	**1**	**2**	**3**	**4**	**5**

SECTION B7

	STATEMENT	SCALE				
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
46	I feel that equipment must be maintained according to set maintenance procedures.	**1**	**2**	**3**	**4**	**5**
47	I think the use of maintenance procedures will improve the quality of my work.	**1**	**2**	**3**	**4**	**5**
48	There are standard maintenance procedures that are followed for maintenance.	**1**	**2**	**3**	**4**	**5**
49	I usually have a procedure with me when I perform maintenance work.	**1**	**2**	**3**	**4**	**5**
50	I know where to find a procedure when I need it.	**1**	**2**	**3**	**4**	**5**
51	I know how to access a procedure when I need it.	**1**	**2**	**3**	**4**	**5**
52	Procedures are written in such a way that they are easy to understand and execute.	**1**	**2**	**3**	**4**	**5**
53	Procedures contain schematics, photos, flow diagrams, and warnings etc. which enable me to effectively execute equipment maintenance.	**1**	**2**	**3**	**4**	**5**
54	My input on maintenance procedures can eliminate recurrent equipment failures.	**1**	**2**	**3**	**4**	**5**
55	My input on maintenance procedures can reduce the	**1**	**2**	**3**	**4**	**5**

	time taken for performing maintenance.					
56	I am empowered to contribute ideas towards continued improvement of maintenance procedures.	**1**	**2**	**3**	**4**	**5**
57	I am committed to the use of maintenance procedures.	**1**	**2**	**3**	**4**	**5**

SECTION B8

	STATEMENT	**SCALE**				
		Strongly disagree	**Disagree**	**Neutral**	**Agree**	**Strongly agree**
58	I have been trained on plant specific maintenance procedures.	**1**	**2**	**3**	**4**	**5**
59	I have been trained on plant specific maintenance procedures for equipment trouble shooting/faultfinding.	**1**	**2**	**3**	**4**	**5**
60	I know what training I must undertake to be effective in the execution of equipment maintenance.	**1**	**2**	**3**	**4**	**5**
61	I have received plant specific maintenance “refresher” training in the last 12 months.	**1**	**2**	**3**	**4**	**5**
62	I have reduced the time it takes me to execute equipment maintenance as a result of training received.	**1**	**2**	**3**	**4**	**5**

Appendix C: Frequencies for Section B of Questionnaire

SECTION B1								
STATEMENT		**SCALE**						
		Strongly disagree 1 (%)	**Disagree 2 (%)**	**Neutral 3 (%)**	**Agree4 (%)**	**Strongly agree 5 (%)**	**Mean**	**Standard deviation**
1	I know the maintenance performance measures set for the plant.	6.0	13.3	27.7	47.0	6.0	3.34	0.991
2	The maintenance performance measures set for the plant have been communicated to me.	4.8	21.7	30.1	32.5	10.8	3.23	1.063
3	Actions for improving the maintenance performance measures have been communicated to me.	7.2	28.9	28.9	30.1	4.8	2.96	1.041
4	I support the	2.4	10.8	33.7	39.8	13.3	3.51	0.942

	maintenance performance measures set by my function for the plant.							
5	I aim to positively contribute to the achievement of the plant's maintenance performance measures.	1.2	2.4	3.6	57.8	34.9	4.23	0.738
6	I feel that effective execution of equipment maintenance is my responsibility.	0	0	7.2	54.2	38.6	4.31	0.603
7	I feel that well maintained equipment contributes to business objectives.	0	0	4.8	33.7	61.4	4.57	0.588

SECTION B2

STATEMENT		SCALE						
		Strongly disagree 1 (%)	Disagree 2 (%)	Neutral 3 (%)	Agree4 (%)	Strongly agree 5 (%)	Mean	Standard deviation
8	I aim to conduct maintenance activities/tasks in a shortest time possible.	0	2.4	18.1	48.2	31.3	4.08	0.768
9	I consider my work stressful as a result of time allocated for each maintenance activity.	0	16.9	27.7	34.9	20.5	3.59	1.000
10	I aim to take less time to execute equipment maintenance compared to the time allocated.	1.2	8.4	15.7	54.2	20.5	3.84	0.890
11	I aim to execute equipment maintenance the first time right.	0	0	7.2	45.8	47.0	4.40	.624
12	I receive clear maintenance	0	12.0	22.9	50.6	14.5	3.67	.871

	instructions.							
13	I feel that equipment is adequately designed for me to execute maintenance successfully.	0	4.8	16.9	36.1	28.9	3.29	1.054
14	I feel that too much effort is required from me to execute maintenance.	3.6	15.7	32.5	30.1	18.1	3.43	1.073

SECTION B3								
STATEMENT		**SCALE**						
		Strongly disagree 1 (%)	**Disagree 2 (%)**	**Neutral 3 (%)**	**Agree4 (%)**	**Strongly agree**	**Mean**	**Standard deviation**
15	I feel that lighting around plant equipment is adequate for me to execute maintenance work.	9.6	36.1	25.3	26.5	2.4	2.76	1.031
16	The noise level in the plant prevents me from executing equipment maintenance effectively.	7.2	51.8	24.1	16.9	0	2.51	0.861

17	Working near high temperatures prevents me from executing equipment maintenance effectively.	2.4	37.3	27.7	25.3	7.2	2.98	1.012
18	Working in a dusty area prevents me from executing equipment maintenance effectively.	1.2	13.3	30.1	45.8	9.6	3.49	0.889

SECTION B4

	STATEMENT	**SCALE**					
		Never 1 (%)	**Sometimes 2 (%)**	**Often 3 (%)**	**Always 4 (%)**	**Mean**	**Standard deviation**
19	I know what work I will perform the next day before the end of shift.	22.9	59.0	16.9	1.2	1.96	0.671
20	I plan my work in advance before going to the plant to perform maintenance.	7.2	21.7	34.9	36.1	3.00	0.937
21	I wait for a job card	30.1	30.1	9.6	30.1	2.40	1.209

	to be issued to me before I execute equipment maintenance.						
22	I have the necessary spares required to successfully execute equipment maintenance.	7.2	47.0	34.9	10.8	2.49	.787
23	I decide myself when to start equipment maintenance.	32.5	24.1	27.7	15.7	2.27	1.083
24	I execute maintenance of equipment timeously.	7.2	32.5	39.8	20.5	2.73	0.871
25	I know what tools to take along before going to the plant to perform maintenance work.	2.4	14.5	36.1	47.0	3.28	0.801

SECTION B5						
STATEMENT	**SCALE**					
	Never 1 (%)	**Sometimes 2 (%)**	**Often 3 (%)**	**Always 4 (%)**	**Mean**	**Standard deviation**

26	I know where to look for spare parts when I need them.	1.2	26.5	30.1	42.2	3.13	0.852
27	The spare parts storage area is organized.	24.1	28.9	26.5	20.5	2.43	1.073
28	Spare parts are stored in their unique identifiable racks.	26.5	22.9	30.1	20.5	2.45	1.096
29	I am never in doubt of what spare part to use.	8.4	34.9	30.1	26.5	2.75	0.948
30	Spare parts issued always fit the first time and do not require any modification.	2.4	50.6	37.3	9.6	2.54	0.704
31	I am able to locate spare parts in the store without the support of the store assistant.	3.6	50.6	31.3	14.5	2.57	0.784

SECTION B6								
STATEMENT		**SCALE**						
		Strongly disagree 1 (%)	**Disagree 2 (%)**	**Neutral 3 (%)**	**Agree 4 (%)**	**Strongly agree 5 (%)**	**Mean**	**Standard deviation**
32	Equipment service points (e.g. grease points) are visible.	2.4	10.8	41.0	39.8	6.0	3.36	0.849
33	Equipment service points (e.g. grease points) are fully accessible.	0	18.1	48.2	31.3	2.4	3.18	0.751
34	Equipment service points are at arm-reach.	1.2	20.5	49.4	24.1	4.8	3.11	0.827
35	Equipment components are directly and easily accessible for maintenance.	1.2	26.5	43.4	25.3	3.6	3.04	0.847
36	Equipment is designed for line-of-sight to be able perform visual inspection.	0	22.9	43.4	28.9	4.8	3.16	0.833
37	Equipment is	0	20.5	47.0	28.9	3.6	3.16	0.788

	designed for line-of-sight to be able perform servicing.							
38	Equipment is designed for line-of-sight to perform adjustment.	0	18.1	48.2	30.1	3.6	3.19	0.772
39	Equipment is designed for line-of-sight to perform alignment.	0	12.0	48.2	36.1	3.6	3.31	0.731
40	Equipment is designed for line-of-sight to perform in-place repair.	1.2	13.3	55.4	25.3	4.8	3.19	0.772
41	Equipment consists of detachable modules, which can be manufactured, assembled, and serviced separately.	0	9.6	47.0	38.6	4.8	3.39	0.730
42	Equipment allows me to test, detect, diagnose or isolate faults	0	28.9	33.7	36.1	1.2	3.10	0.835

	without special testing tools.							
43	Equipment has gauges, built-in-test function etc. which assist me with faultfinding.	3.6	22.9	47.0	25.3	1.2	2.98	0.826
44	Equipment can self-test to identify all the causes of malfunctioning.	7.2	42.2	39.8	9.6	1.2	2.55	0.815
45	Equipment requires special tools to execute maintenance.	0	18.1	45.8	31.3	4.8	3.23	0.801

SECTION B7

STATEMENT		**SCALE**						
		Strongly disagreed 1 (%)	**Disagree 2 (%)**	**Neutral 3 (%)**	**Agree 4 (%)**	**Strongly agree 5 (%)**	**Mean**	**Standard deviation**
46	I feel that equipment must be maintained according to set maintenance procedures.	0	3.6	7.2	44.6	44.6	4.30	0.761
47	I think the use of maintenance procedures will improve the	0	2.4	6.0	48.2	43.4	4.33	0.700

	quality of my work.							
48	There are standard maintenance procedures that are followed for maintenance.	2.4	9.6	21.7	48.2	18.1	3.70	0.959
49	I usually have a procedure with me when I perform maintenance work.	12.0	33.7	25.3	20.5	8.4	2.80	1.156
50	I know where to find a procedure when I need it.	16.9	20.5	26.5	27.7	8.4	2.90	1.226
51	I know how to access a procedure when I need it.	16.9	21.7	30.1	26.5	4.8	2.81	1.152
52	Procedures are written in such a way that they are easy to understand and execute.	10.8	13.3	31.3	33.7	10.8	3.20	1.145
53	Procedures contain schematics, photos, flow diagrams, and warnings etc.	14.5	22.9	36.1	22.9	3.6	2.78	1.071

	which enable me to effectively execute equipment maintenance.							
54	My input on maintenance procedures can eliminate recurrent equipment failures.	1.2	4.8	22.9	51.8	19.3	3.83	0.838
55	My input on maintenance procedures can reduce the time taken for performing maintenance.	1.2	0	18.1	59.0	21.7	4.00	0.716
56	I am empowered to contribute ideas towards continued improvement of maintenance procedures.	3.6	14.5	24.1	45.8	12.0	3.48	1.004
57	I am committed to the use of maintenance procedures.	1.2	1.2	21.7	48.2	27.7	4.00	0.812

SECTION B8								
STATEMENT		**SCALE**						
		Strongly disagreed 1 (%)	**Disagree 2 (%)**	**Neutral 3 (%)**	**Agree 4 (%)**	**Strongly agree 5 (%)**	**Mean**	**Standard deviation**
58	I have been trained on plant specific maintenance procedures.	7.2	25.3	25.3	32.5	9.6	3.12	1.120
59	I have been trained on plant specific maintenance procedures for equipment trouble shooting/faultfinding.	10.8	22.9	30.1	28.9	7.2	2.99	1.121
60	I know what training I must undertake to be effective in the execution of equipment maintenance.	4.8	18.1	31.3	34.9	10.8	3.29	1.042
61	I have received plant specific maintenance “refresher” training in the	19.3	32.5	22.9	14.5	10.8	2.65	1.254

	last 12 months.							
62	I have reduced the time it takes me to execute equipment maintenance as a result of training received.	8.4	30.1	31.3	25.3	4.8	2.88	1.041

Appendix D: MTTR Reduction Approach Worksheet – Stock house equipment

The Mean Time To Repair (MTTR) Reduction Approach Worksheet							
1. CMT = Corrective Maintenance Time 2. MTTR = Mean Time To Repair 3. MTBF = Mean Time Between Failures 4. COI = Cost of Implementation							
Task no. *SHA-001*		**Team:** *ATM, LWS, LY, TD, TVM, AM*		**Date:***31 October 2011*		**Revision:00**	
Plant location: *Stock house*		**Functional location:** *03-S-FBD-DSH-0030*		**Equipment:** *Screen*		**Component:** *Motor*	
Failure:	*To drive the vibration unit*	**Mode:**	*Loss of vibration and feeding*	**Cause:**	*Overloading due to frequent starting under load, insulation damage, dust and vibration*		
Effects:	*Loss of charging to furnace leading to possible production losses depending on type of material being loaded.*						
Failures mode diagnosis	*1. Insulation test*						
	2. Ammeter mounted on the panel						
	3. Motor not turning						
	4. Overload trip in the motor control centre						

Corrective maintenance sequence description	*1. Isolate and lockout motor*
	2. Remove guard
	3. Disconnect motor
	4. Remove v-belts and pulley
	5. Remove motor holding down bolts from frame
	6. Rig motor from current position
Maintainability attributes (Accessibility, logistics, standardization, inter-changeability, environmental factors, human factors etc.)	*1. Improve lighting to ensure compliance with SANS*
	2. Improve de-duster availability to curb dust emissions in the area
	3. Specific equipment training required
	4.

Experience of maintenance personnel		**Competency of maintenance personnel**	
Average experience	Experience factor (k1)	Average Competency	Competency factor (k2)
less than 2 years	1.2	85-100%	1.05
2 - 5 years	1.15	50-75%	1.1
6 - 10 years	1.1	less than 50%	1.2

Recommended corrective actions	*1. Install crawl complete with electrical hoist to enable personnel to handle motor*
	2. Train personnel on basic rigging

	3. *Ensure that a spare unit is available and on good condition at the Main Store to minimize standing time*		
	4. *Motor must be complete with pulley installed on shaft*		
	5. *Mark settings on adjusting bracket rod to reduce adjustment times*		
	6. *Compile a maintenance procedure for the removal and installation of the motor, adjusting of bracket rod, testing*		
New CMT (hours) = ∑CMT×k1×k2	**New MTTR (hours)**	**New availability (%) = MTBF/(MTBF +MTTR)**	**COI**
2.53	*2.53*	*99.94*	*R86 000.00*

Appendix E: MTTR Reduction Approach Worksheet – Furnace top equipment

The Mean Time To Repair (MTTR) Reduction Approach Worksheet							
2. CMT = Corrective Maintenance Time 2. MTTR = Mean Time To Repair 3. MTBF = Mean Time Between Failures *4. COI = Cost of Implementation*							
Task no. *FTA-001*		**Team:** *ATM, LWS, LY, DP, TVM, AM*		**Date:***15 March 2012*		**Revision:00**	
Plant location: *Furnace top*		**Functional location:** *03-S-FBD-DFT-0030-0030*		**Equipment:** *Tilting gearbox*		**Component:** *Coupling*	
Failure:	*To drive the tilting gearbox*	**Mode:**	*Loss of tilting*	**Cause:**	*Damaged spider coupling*		
Effects:		*Loss of charging to furnace leading to possible production losses.*					
Failures mode diagnosis		*1. Chute not tilting*					
		2. Localized temperature rise in the furnace					
		3. Unstable furnace conditions					
Corrective maintenance sequence description		*1. Isolate and lockout motor*					
		2. Unplug motor cables (feedback, power and control)					

	3. *Disconnect motor flange bolts from tilting gearbox*
	4. *Remove coupling*
	5. *Install new coupling*
	6. *Repeat step 4 to 1*
Maintainability attributes (Accessibility, logistics, standardization, inter-changeability, environmental factors, human factors etc.)	1. *Improve lighting to ensure compliance with SANS*
	2. *Install a hoist to improve handling*
	3. *Specific equipment training required*

Experience of maintenance personnel		**Competency of maintenance personnel**	
Average experience	Experience factor (k1)	Average Competency	Competency factor (k2)
less than 2 years	1.2	85-100%	1.05
2 - 5 years	1.15	50-75%	1.1
6 - 10 years	1.1	less than 50%	1.2

Recommended corrective actions	1. *Install a hoist to improve handling*
	2. *Train personnel on basic rigging*
	3. *Keep a spare coupling in the maintenance workshop store*
	4. *Compile a maintenance procedure for the removal and installation of the motor and*

	coupling		
New CMT (hours) = ∑CMT×k1×k2	**New MTTR (hours)**	**New availability (%) = MTBF/(MTBF +MTTR)**	**COI**
1.25	*1.25*	*99.982*	*R23 000.00*