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RELIABILITY MONITORING TECHNIQUES APPLIED TO A HOT STRIP STEEL MILL

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Engineering Doctorate. 2011

Reliability Monitoring Techniques applied to a Hot Strip Steel Mill

By

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September 2011

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This work has not previously been accepted in substance for any degree and is not currently submitted for candidature for any degree

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This Thesis is being submitted in partial fulfilment of the requirements for the degree of Engineering Doctorate

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Candidate for degree of: Engineering Doctorate**.**

Full Title of Thesis: Reliability Improvement Techniques in a Hot Strip Steel Mill

Institute of study: School of Engineering

Summary:

Reliability engineering techniques have been used in the manufacturing environment for many years. However the reliability analysis of repairable systems is not so widely practised in the steel manufacturing environment. Many different analysis methods have been proposed for the modelling of repairable systems, most of these have had limited application in the manufacturing environment.

The current reliability analysis techniques are predominantly used by engineers to construct a "snapshot" in time of a manufacturing system's reliability status. There are no readily identifiable applications of reliability modelling techniques being applied to repairable systems over a long time period within the manufacturing environment

The aim of this work is to construct a method which can analyse and monitor the reliability status of multiple repairable systems within the steel plant over an extended operating period.

The developed analysis method is predominantly automated and is facilitated by applying standard reliability analysis techniques to all of the repairable systems failure data sets under review. This Thesis illuminates the methodology used to fulfil the remit of this research by the following sequential steps:

Developing a new methodology for the application of reliability analysis techniques to repairable systems within a steel manufacturing facility

Utilised an innovative step of combining three reliability analysis methods as complimentary activities

Constructed an automated reliability analysis model which fulfils the project remit. In addition the model is capable of the long term monitoring of repairable system reliability

The new reliability analysis method has been delivered to Tata Steel and is installed in the Port Talbot Technology Group with a direct link to the Hot Strip Mill (HSM) monitoring database.

This reliability analysis method has been tested with four years operational data from the Hot Strip Mill manufacturing area and the analysis has shown that changes and trends in all systems reliability status can be easily identified.

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List of Symbols

β	shape factor in Weibull and Power Law analysis and Beta with “hat” is unbiased beta in Cramer von Mises test
μ	failure intensity function in HPP, Weibull,
λ	Failure rate function in Weibull and Power Law
η	scale parameter, (eta) in HPP
τ	time length parameter
P	probability factor
L	log likelihood function in General Renewal Process
υ	ageing function in General Renewal Process
p	repair effectiveness factor in General Renewal Process
U	Non dimensional test statistic in Laplace test
Y	Non dimensional test statistic in Cramer von Mises test
e_i:	expected number of data points in cell i. Chi^2 test
o_i:	observed number of data points in cell i. Chi^2 test
χ^2_γ:	is the Chi^2 distribution table with degrees of freedom (DF) = y.

Abbreviations

ABAO – As Bad as Old
AGAN – AS Good As New
AMF – Asset Management Framework
ANN - Artificial Neural Network
ARA – Arithmetic Reduction of Age
ARI – Arithmetic Reduction of Intensity
ARIMA – Arithmetic Reduction in Moving Average
CDF – Cumulative Distribution Function
CMBL- Combined Lifecycle Distribution Model
CvM – Cramer von Mises Test
DST – Dempster Schafer Theory
EM – Estimation Method
ERP – Enterprise Resource Planning
FRACAS – Failure Reporting and Corrective Action System
FTA – Fault Tree Analysis
F5 – Mill Stand F5
F6 – Mill Stand F6
F7 – Mill Stand F7
F8 – Mill Stand F8
F9 – Mill Stand F9
F10 – Mill Stand F10
F11 – Mill Stand F11
GA - Genetic Algorithm
GRP - General Renewal process
HPP – Homogeneous Poisson Process
HSB - Horizontal scale breaker
HSM – Hot Strip Mill
IEEE – Institute of Electronic and Electrical Engineers
IID - Identical and independently Distributed
IMTBF – Instantaneous Mean Time Between Failures
InMTBF – Incremental Mean Time Between Failures

LSE – Least Squares Estimator

MLE – Maximum Likelihood Estimator

MPLP – Modified Power Law Process

MSS – Multi State System

MTBF – Mean Time Between Failures

MTTF - Mean Time to Failure

MTTR - Mean Time to Repair

NHPP – Non- Homogeneous Poisson Process

OEE – Operational Equipment Efficiency

PDF – Probability Density Function

PEXP – Piece Wise Exponential Process

PLP – Power Law Process

RBD – Reliability Block Diagram

RCM – Reliability Centred Maintenance

RP – Renewal Process

SARIMA - Seasonal Arithmetic Regression of Integrated Moving Average

SoSAT – System of Systems Analysis Toolkit

SPC - Statistical Process Control

SQL – Structured Query Language

TRAM – Tata Reliability Analysis Model

TTT – Total Time on Test

VSB - Vertical Scale Breaker

YTD – Year to Date Spreadsheet

1 Introduction

The author of this research comes from a practical engineering background with considerable experience in the automotive and FMCG manufacturing areas, the author has had extensive experience of using statistical measurements and analysis techniques in these manufacturing areas, but does not have extensive knowledge of statistical theory. Therefore this thesis is aimed towards the practical application of reliability analysis techniques rather than an in depth investigation into the statistical theories behind the techniques. The research is aimed at using these analysis techniques as a practical engineering tool for use in the manufacturing environment. With this in mind the thesis focuses on standard reliability techniques which have been applied to machines and manufacturing systems. One of the main facets of reliability engineering is the statistical analysis of a system through the monitoring of its operational performance. Reliability engineers can construct mathematical models of systems, which can recognise trends and identify areas for improvement in operational performance. This analysis is important in identifying the most suitable maintenance regime for the system and can underpin other operational factors, which impinge upon system efficiency. The research is focused on the measurement of machine and system reliability which is primarily concerned with the quantification of machine or system failures in a time domain. This can be expressed as the number of machine failures over a specified period.

Reliability is an aspect of engineering uncertainty which can be expressed as a *Probability,* the usual definition of reliability is:

"*The Probability that an item will perform a required function without failure under stated conditions for a stated period of time".* [O'Conner, 2006]

In effect a machine, process or system, is expected to consistently operate for a set period before remedial actions or periodic maintenance are required. This consistency allows the process to be fully utilised and allows effective integration with other processes.

1.1 Reliability Analysis and Monitoring

Mathematical and statistical methods can be used for quantifying and analysing machine or system reliability through the analyses of failure data. However due to the high levels of uncertainty involved these analyses can seldom be applied with the level of precision that engineers are accustomed to [O’Conner 2006]. Practical engineering methods are required to support results obtained from statistical analysis methods when possible

This research is carried out from a mechanical engineering perspective scoped to derive an industrial application for reliability analysis and monitoring methods within the steel processing industry. The research is not intended to be an academic investigation into reliability analysis techniques or their relative merits, Therefore reliability monitoring in this research can be described as the repeated statistical analysis of the reliability performance of the Hot Strip mill Processes through the examination of the systems’ failure data.

This can assist in facilitating and verifying the construction of an analysis method which is suitable for the manufacturing system, which can recognise performance trends and identify areas for improvement in operational performance.

1.2 Repairable Systems

For the purpose of this research a *system* is defined as consisting of one or more machines (units) whilst a *process* consists of one or more systems.

A repairable system is one which can be restored to an operating condition by some repair process other than the replacement of the entire system, many real world systems such as automobiles, airplanes computers are repairable systems [Rigdon 2000]

The non repairable system is one which is discarded after failure; a typical example of a non repairable system is light bulb. However many electrical items are now non-repairable as they are more expensive to repair than replace, and are discarded after first failure.

It should be noted that the systems within the Hot strip Mill, (e.g. rolling mill stands) are primarily constructed of mechanical components which are powered by electrical or hydraulically drive systems. These systems are physically very large and can weigh many tonnes. Some of these systems are decades old, and can consist of components ranging from greater than twenty to less than one year old. These systems have been continually repaired and updated over their operating life. All of these systems are electronically controlled.

From this description it can be identified that the constituent systems within the Hot Strip Mill rolling mill are repairable systems.

1.3 Principal Research Aims and Thesis Introduction

This research has been derived from an earlier project which reviewed the descaling system installed at the Hot Strip Mill to identify an appropriate system upgrade.

During the construction of the business case for the descaling system upgrade it became part of the project remit to identify the current reliability status of the descaling system with a view to improving the system through the replacement of strategic operational sections. it was found that there was no easily recognisable way to achieve this due to the following reasons

- Inability to identify uniform data sources for use in the reliability analysis, this manufacturing operation is, monitored by several data logging systems, each focused on a particular area.
- Unable to identify a simplistic, practical method of identifying the current reliability characteristics of individual systems or processes at the Hot Strip Mill

Further details on this project are presented as a case study in Chapter 8 of this Thesis.

This research is into the application of reliability engineering principles in an industrial environment, namely the Hot Strip Mill with the aim of deriving a reliability analysis modelling technique which is suitable for this application. In addition the reliability analysis model will contain the following features:

- Be of a modular design which is capable of high level (system) analysis and low level (subsystem/machine) analysis.
- Produce an analysis model that is portable and capable of system analysis at alternative manufacturing facilities.

The reliability analysis model is expected to be simple to operate and require little technical input from the operator. It is intended that the analysis model utilises a mainstream software package and will not require the purchase of specialist software or additional hardware.

1.4 Thesis Construction

With the goal of constructing a simplistic reliability analysis method which could be used in the steel manufacturing industry in mind the author derived the Scope of this Thesis which is to:

"*Develop a reliability analysis method capable of monitoring and quantifying the reliability of all production systems in the Hot Strip Mill utilising current software and equipment"*

The sequential methodology used in the construction of this thesis is:

Research into the theory behind reliability analysis techniques, this research was used to expand the author's knowledge in reliability analysis techniques. The main analysis techniques used in this Thesis are described in Chapter 2

Research the current status of machine and system reliability analysis in the manufacturing environment through a literature review and identify if there are any reliability analysis methods which can be utilised in a steel manufacturing environment, this review is contained in Chapter 3.

The research manipulates the operating data accumulated from the Hot Strip Mill manufacturing process into systems failure data sets constructed in a format which is suitable for the application of reliability analysis techniques to these repairable systems . This process is described in Chapter 4.

The knowledge accrued in the preceding chapters allowed the construction of a prototype reliability analysis model for repairable systems based on the research into reliability analysis methods. This prototype reliability analysis model is trialled using the failure data sets obtained from the Hot Strip Mill monitoring process to perform proof of principle tests which are used to identify flaws in the prototype model methodology.

The prototype model is reconfigured into the development analysis model for repairable systems, which is again tested using the proof of principle methods to identify its suitability for this manufacturing application. The development of this reliability analysis models is described in Chapter 5.

The development reliability analysis model for repairable systems evolves into the Tata Reliability Analysis Model (TRAM) methodology. The TRAM methodology is explored and tested using the proof of principle testing in Chapter 6.

The TRAM model is constructed to operate in a semi automatic program, the programming and principles used to automate the constructed TRAM methodology are described in Chapter 7. The TRAM model is tested using the same criteria used for earlier versions of the reliability analysis model.

The Case file investigating the Hot Strip Mill descaling system is explored in Chapter 8, the Case file explores the initial reliability analysis into this system plus a comparison with the detail obtained from the later application of the TRAM methodology to the descaling systems failure data set.

Chapter 9 reviews methods of integrating the TRAM methodology into the overall steel plant operating control system.

The Thesis conclusions are presented in Chapter 9, this chapter contains an overall review of the Thesis plus on journal papers derived from the Thesis.

The Future work activities which will be applicable to the Thesis are explored in Chapter 10.

Each chapter of the Thesis is illustrated in the flow diagram provided as Figure 1.1. The Chapters relevant to the reliability analysis models technical development are referenced as Chapter 4 to Chapter 7.

The next Chapter, Chapter 2, is an overview of the theory of reliability. This was performed with the intention of identifying and grouping current analysis techniques and reviewing their statistical calculations and operating methods.

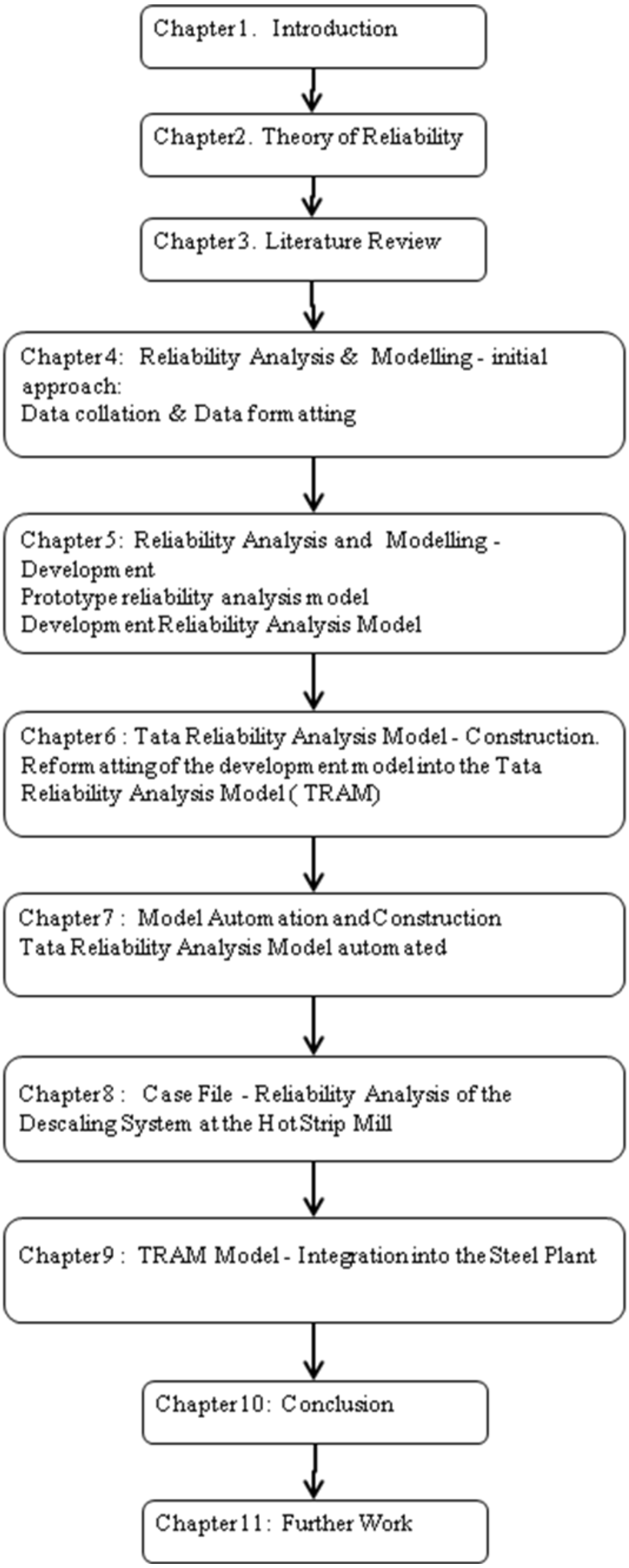


Figure 1-1 Process Flow Diagram of Thesis

2 Theory of Reliability

This Chapter explores the theory of reliability and the statistical methods used for reliability analysis. The chapter gives a short overview of reliability theory, leads into reliability analysis techniques and details the methods used for testing the statistical significance of reliability analysis techniques. The investigation was facilitated primarily using details obtained from Statistical Textbooks, [O'Conner] [Rigdon] [Ascher] [Dummer] [Smith].

This investigation is from a mechanical engineering perspective and is used to identify the most relevant analysis methods for repairable systems and the equations used to facilitate these methods. In addition this chapter is used as a development phase by the author to attain greater knowledge of statistical techniques which allows the author to become more effective in using these techniques. This investigation is not intended as a statistical investigation into the relative merits of these techniques

The Theory of Reliability relies heavily on the probability theory, the branch of mathematics which is concerned with the analysis of random phenomena. The probability theory is used for the descriptions of complex systems given partial knowledge of their state. In the probability theory probability distributions are used to determine the value of an unidentified random variable when the variable is discrete, or to assess the probability of the value falling within a particular interval when the variable is continuous. This methodology is aligned with the reliability analysis of repairable systems which are subject to operating constraints which are imposed by multiple variable parameters. There is variability in almost any value which can be measured in a population, and it is recognised that all measurements are subject to intrinsic errors. For this and other reasons, a simple number can be inadequate for describing a measured quantity and a probability distribution is often more appropriate. Probability theory covers the various probability distributions, including:

The Discrete probability distribution where the random values which form a finite or countable set whose Probability = 1 and whose cumulative distribution function increases in steps. These distributions are characterised by the probability mass function, *p* such that

$$\Pr[X = x] = p(x) \quad \text{Eqn. 2.1}$$

The Continuous probability distribution defined by one convention as continuous if its cumulative distribution function indicates that it belongs to a random variable *X* for which

$$\Pr[X = x] = 0 \quad \text{Eqn. 2.2}$$

2.1 Poisson Processes

The Poisson process is a stochastic process in which events occur continuously and independently of each other. This process is a collection of random variables, which can be represented by Equation 2.3

$$\{N(t) : t \geq 0\} \quad \text{Eqn. 2.3}$$

Where *N (t)* is the number of events which have occurred up to time *t* (starting at *t*=0)

The number of events between a time *a* and time *b* is denoted as *N (b)*-*N (a)*. These conform to a Poisson distribution, with each step of the process *N (t)* being a non-negative integer which acts as a step function. This can be thought of as the points in time between zero and infinity where an event occurs. The Poisson process is a continuous time process which possesses the following properties:

- $N(0) = 0$
- Independent increments.
- Stationary increments as the probability distribution of the number of event occurrences in an interval only depend on the length of the interval.
- No counted occurrences are simultaneous.

2.1.1 Homogeneous Poisson Process

One of the main types of Poisson process is the homogeneous Poisson process (HPP). This reliability analysis method can be described thus: If the number of events in a time interval (t, t +τ) (where τ is the time length parameter) follows a Poisson distribution with the associated parameter λτ then:

$$P[(N(t+\tau) - N(t)) = n] = \frac{e^{-\lambda\tau}(\lambda\tau)^n}{n!} \quad \textbf{Where } \boldsymbol{n} \textbf{ = 0,} \quad \text{Eqn. 2.4}$$

This is characterised by the failure rate parameter λ. In this reliability model the failure rate function is equal to the failure intensity function as shown in equation 2.5

$$\mu(t) = \lambda(t) \quad \text{Eqn. 2.5}$$

Manufacturing facilities often specify mean time between failure (MTBF Equation 2.6) figures when purchasing new machinery or constructing new processes. The manufacturing sites use these reliability indices as guide values to assess the processes efficiency. In addition these reliability indices assist in assessing the overall reliability of the manufacturing process

$$MTBF = \frac{1}{\lambda(t)} \quad \text{Eqn. 2.6}$$

Where $\mu(t) =$ Failure intensity function, $\lambda(t) =$ Failure rate = N/T, N = Number of Failures, T = total operating time and MTBF = Mean time between failures

It is generally the case that this analysis method is not regarded as suitable for the analysis of repairable systems. The main reason for the non-suitability is that the data sets required for the HPP analysis must be statistically independent and identically distributed (SIID).

Crow [Crow 2010(1)] reinforces the argument against using the HPP model to analyse repairable systems with the statement that in a repairable system the events (failures) are not independent and in most cases are not identically distributed. He elaborates that when a failure occurs in a repairable system the remaining components have a current age and the next event depends on this age. Thus the failure events at a system level are dependant.

2.1.2 Non-Homogeneous Poisson Process

In general the rate parameter λ may change over a period of time resulting in a non-homogeneous Poisson process (NHPP). In this case the generalised rate function is given as λ (*t*), with the expected number of events between time *a* and time *b* being:

$$\lambda_{a,b} = \int_a^b \lambda(t)dt \quad \text{Eqn. 2.7}$$

Thus the number of arrivals in the interval (a, b) are given as N (b) – N (a) and follow a Poisson distribution with the rate parameter $\lambda_{a,b}$ where

$$P[N(b) - N(a) = n] = \frac{e^{-\lambda a,b}\left(\lambda_{a,b}\right)^n}{n!} \quad \text{Eqn. 2.8}$$

Where $n = 0, 1\ldots$, It can be shown that the homogeneous poison process can be viewed as a special case with $\lambda\,(t) = \lambda$.

2.2 Lifetime Analysis Methods

One of the important topics in failure data analysis is to select and specify the most appropriate lifetime distribution that describes the times to failure of the system. There are two general approaches to fitting reliability distributions to failure data

- Derivation of an empirical reliability function directly from the data.
- Identify an appropriate parametric distribution, such as Weibull, Gamma and the exponential lognormal which can be used within the process method to estimate the unknown parameters

The second method is widely practised because of the ability to extrapolate data beyond the sample range and to apply more complex analysis methods to calculate properties such as hazard rates etc. There are several methods supporting this approach. They are included here for completeness but not considered in detail.

2.2.1 Exponential distribution

This is the simplest model for lifetime distributions and it is the only continuous distribution with a memory less property i.e. if the distribution has a memory less property then the probability that an old unit will survive one more day is equal to the probability that a new unit will survive one more day [Rigdon 2000]

2.2.2 Weibull Distribution and the "Bathtub Curve"

Reliability specialists often describe the lifetime of a population of products using a graphical representation called the bathtub curve. The bathtub curve consists of three periods: an Early Failure period with a decreasing failure rate followed by a normal life period (also known as the Intrinsic Failure period or "useful life") with a low, relatively constant failure rate and concluding with a Wear-out Failure period that exhibits an increasing failure rate.

The bathtub curve, displayed in Figure 1 is a failure rate vs. time plot above; this does *not* depict the failure rate of a single item, but describes the relative failure rate of an entire population of products.

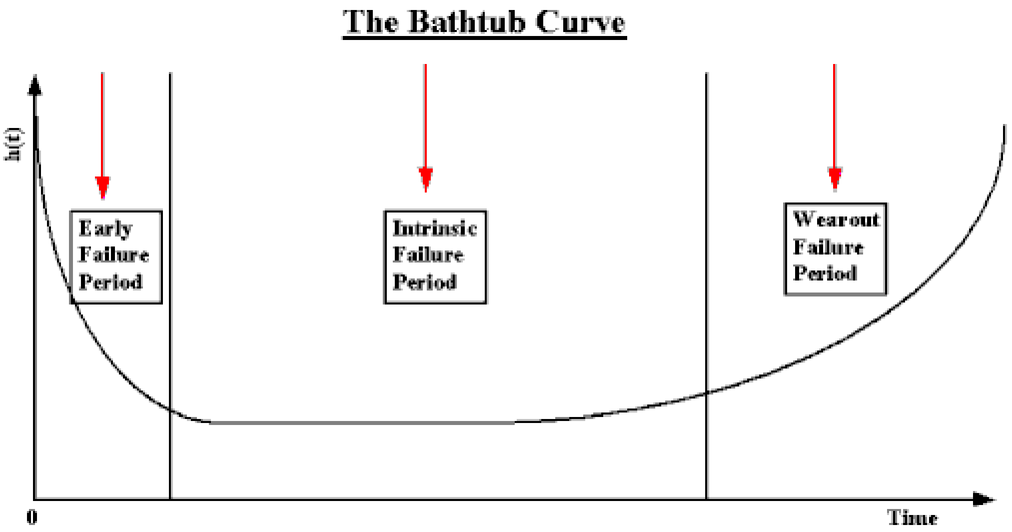


Figure 2-1 The Bathtub Curve

The Weibull distribution is a flexible life distribution model that can be used to characterize failure distributions in all three phases of the bathtub curve. The basic Weibull distribution has two parameters, a shape parameter, often termed beta (β), and a scale parameter, often termed eta (η). The scale parameter, eta, determines when, in time, a given portion of the population will fail. The shape parameter, beta, is the key feature of the Weibull distribution that enables it to be applied to any phase of the bathtub curve. A beta less than 1 models a failure rate that decreases with time. A beta equal to 1 models a constant failure rate. And a beta greater than 1 models an increasing failure rate. [Wilkins 2012]

The Weibull distribution is the one of the most commonly used analysis methods for lifetime distributions, and is widely applied in non-repairable systems analysis. The Weibull distribution is directly related to the Power Law process [Ascher et al. 1984, Rigdon 2000]. And the two and three parameter Weibull distributions are amongst the most common distributions used. They can be manipulated to support accurate representations using their shape (β) and scale (θ) parameters and can thus model a wide variety of data and life characteristics. Since the form of a life distribution is often composed of more than one shape the application of a mixed distribution pattern becomes a natural alternative. Bucar et al. [Bucar et al 2004] postulates that the application of a mixed distribution Weibull methodology is always possible for the reliability approximation of any arbitery system.

2.2.3 NHPP - Power Law Analysis

The Power Law analysis technique is widely used for the analysis of repairable systems due to its ability to analyse systems which are improving or deteriorating, this analysis method is a special case of the non homogeneous Poisson process with its intensity function proportional to the global time *t* raised to a power. [Basu. 2000]

The analysis method uses:

Failure intensity

$$\mu(t) = \lambda\beta t^{\beta-1} \quad \text{Eqn. 2.9}$$

Where Lambda (λ- failure rate) is depicted as

$$\lambda = \frac{N}{T^{\beta}} \qquad \text{Eqn. 2.10}$$

And Beta (β- shape factor) is classed as

$$\beta = \frac{N_q}{\sum_{i=1}^{N_q} Ln\left(\frac{T}{X_{iq}}\right)} \quad \text{Eqn. 2.11}$$

And instantaneous mean time between failures is defined as

$$IMTBF = \frac{1}{\mu(t)} \quad \text{Eqn. 2.12}$$

2.2.4 General Renewal Process

The General Renewal Process model is an adaptation of the Power Law process which contains an ageing factor υ.

$$\lambda_I(T) = \lambda\beta\upsilon_t^{\beta-1} \quad \text{Eqn. 2.13}$$

The General Renewal Process addresses the situation where the system falls between the two extremes of repair status, as good as new (AGAN), as bad as old (ABAO), by introducing a repair effectiveness factor, classed as *q* which is ranked between 0 and 1 where

- 0 = Homogeneous Poisson Process (AGAN).
- 1 = Non- Homogeneous Poisson Process.

The ageing factor υ (virtual age) takes into account the repair effectiveness q by considering it as a factor of time t through the equation

$$\begin{aligned} \upsilon_i &= \upsilon_{i-1} + qx_i = qt_i \\ \therefore \upsilon_{i-1} &= qt_i - qx_i \end{aligned}$$

Eqn. 2.14

A Monte Carlo simulation using the MLE calculated variables is used to derive the instantaneous failure intensity and its corresponding time between failures

This program uses two methods of calculating the “virtual age of the system

Type1: Where the last repair is returned to full operating status.

Type 2: Where all previous repairs are returned to full operating status.

Due to the operating parameters being examined in this Thesis the Type 1 system is considered for all analyses. Through the derivation of the partial derivatives from the natural log of the likelihood function L (Equation 2.15) and equating to a maximum:

$$\ln(L) = \Lambda = n(\ln\lambda + \ln\beta) - \lambda\left[(T - t_n + \upsilon_n)^\beta - \upsilon_n{}^\beta\right] - \lambda\sum_{i=1}^{n}[(x_i + \upsilon_{i-1})^\beta - \upsilon_i{}^\beta] + (\beta - 1)\sum_{i=1}^{n}\ln(x_i + \upsilon_{i-1})$$

Eqn. 2.15

The maximum likelihood estimation (MLE) of the three variables Beta (β) and Lambda (λ) and the virtual age υ which is obtained from the partial differential of the repair effectiveness factor *q*. (Equations 2.16 – 2.18):

$$\begin{aligned} \therefore \frac{\partial\Lambda}{\partial\beta} &= \frac{n}{\beta} - \lambda\left(T - t_n + qt_n\right)^\beta \ln\left(T - t_n + qt_n\right) + \lambda\,[(qt_n)^\beta \ln(qt_n)] \\ &- \lambda\sum_{i=1}^{n}\ [(x_i + qt_i - qx_i)^\beta \ln(x_i + qt_i - qx_i) - (qt_i)^\beta \ln(qt_i)\ ] + \sum_{i=1}^{n}\ \ln(x_i + qt_i - qx_i) \end{aligned}$$

Eqn. 2.16

$$\therefore \frac{\partial\Lambda}{\partial\lambda} = \frac{n}{\lambda} - \left(T - t_n + qt_n\right)^\beta + (qt_n)^\beta - \sum_{i=1}^{n}\ [(x_i + qt_i - qx_i)^\beta - (qt_i)^\beta]$$

Eqn. 2.17

$$\begin{aligned} \therefore \frac{\partial\Lambda}{\partial q} &= -\lambda\beta\, t_n\left(T - t_n + qt_n\right)^{\beta-1} + \lambda\beta\, t_n(qt_n)^{\beta-1} \\ &- \lambda\sum_{i=1}^{n}\ [\beta(t_i - x_i)(x_i + qt_i - qx_i)^{\beta-1} - \beta\, t_i(qt_i)^{\beta-1}] + (\beta - 1)\sum_{i=1}^{n}\frac{t_i - x_i}{[x_i + qt_i - qx_i]} \end{aligned}$$

Eqn. 2.18

2.3 Statistical Testing and Other Factors

Statistical testing is a method of qualifying a set of variable data through providing a mechanism for making a quantitative decision about a process or processes. With the intention of determining whether there is enough evidence to reject the null hypothesis (a condition that is doubted). [NIST, Engineering Statistics Handbook] To reject a hypothesis is to conclude that it is false. However, to accept a hypothesis does not mean that it is true merely that it displays a condition that is believed to be true. This form of hypothesis testing is used in the following test regimes

2.3.1 Laplace Test

One of the simplest trend testing methodologies in use for statistical analysis is the Laplace test. This test will be used in the analysis model to test the hypothesis that a trend does not exist within a system. The Laplace trend test can determine whether the reliability related performance of a system is improving, deteriorating or stationary. The test is implemented by calculating the non dimensional test statistic *U*, Equation 2.24:

$$U = \frac{\frac{\sum_{i=1}^{N} X_i}{N} - \frac{T}{2}}{T\sqrt{\frac{1}{12N}}} \quad \text{Eqn. 2.22}$$

Where T = total operating time, X_i = age of system at i^{th} failure, N = total number of failures.

The Test Statistic *U* is approximately a standard normal variable which can be standardised using the theoretical population mean and standard deviation. This parameter can then be compared to the standard normal distribution, whose critical value is read from the Standard Normal tables with the required significance level. This comparison allows the identification of any trends in the systems performance.

2.3.2 Chi^2 Testing

The Chi^2 goodness of fit test is a statistical procedure that is used to identify if the assumed underlying data distribution is correct. These tests are predominantly based on either of two basics distribution parameters [START 2004]

- The Cumulative Distribution Function (CDF) these are termed “distance tests”

- The Probability Density Function (PDF) these are termed as “area tests”

The Chi^2 test is an area test and is suitable for large data sets and follows a well defined path by:

- Assume that the data follows a specified distribution. e.g. Normal.
- Obtain the distribution parameters, e.g. mean and variance.

This process yields the “composite” distribution hypothesis (which has more than one element which must jointly be true) which is termed the Null Hypothesis (H_0). The negation of the null hypothesis (H_0) is called the alternative hypothesis (or H_1). The assumed (hypothesised) distribution is tested using the data set and finally the null hypothesis is rejected whenever any one (or more) of the elements in the hypothesis (H_0) is not supported by the data. The formula that explores the difference in expected and observed values follows a Chi^2 distribution pattern.

The procedure is summed up as follows

- Divide the data range of X into k subintervals.
- Count the number of data points in each subinterval (histogram).
- Superimpose the PDF of the assumed (theoretical) distribution.
- Compare the empirical histogram with the theoretical PDF.
- If the results agree (probabilistically) the distribution assumption is supported by the data.
- If they do not agree the assumption is most likely incorrect.

The formula for the Chi^2 statistic is

$$\chi^2 = \sum_{i=1}^{K} \frac{(e_i - o_i)^2}{e_i} - \chi^2_{k-1} \quad \text{Eqn. 2.23}$$

Where

e_i: expected number of data points in cell i.

o_i: observed number of data points in cell i.

k: total number of cells or subintervals in range.

n: sample size for implementing the Chi^2 test.

k-1- Number of Estimated Parameters (nep): Chi^2 degrees of freedom (DF>0).

χ^2_γ : is the Chi^2 distribution table with degrees of freedom (DF) = *y*.

2.3.3 Cramer von Mises Test

The Cramer von Mises test is the goodness of fit test which is stated as suitable for the Power Law Analysis (Reliasoft 2005) For a system with x_i successive failures which use the variable (M) values which are classed as:

M =N-1 for a failure terminated system and M=N for a time truncated system.

The non-dimensional Y values are obtained by dividing each successive failure of the system by the corresponding end time *T*.

$$Y_i = \frac{X_i}{T} \quad \text{Eqn. 2.24}$$

And calculating the unbiased estimate of Beta where:

$$\overline{\beta} = \frac{M-1}{\sum_{i=1}^{M} \ln\left(\frac{T}{X_i}\right)} \quad \text{Eqn. 2.25}$$

And by treating the Y_i values as one group and sequencing from the smallest to the largest gives the ordered Z values $Z_1, Z_2 \ldots Z_m$

This allows to calculation of the parametric Cramer von Mises statistic

$$C_M^2 = \frac{1}{12M} + \sum_{j=1}^{M}\left(Z_j^{\beta} - \frac{2j-i}{2M}\right)^2 \quad \text{Eqn. 2.26}$$

2.3.4 Conclusion

This chapter contains details on some of the analysis methods which are used for reliability analysis. After examining these analysis methods, the decision was taken to pick the most likely methods for use in building a reliability analyses method for the repairable systems in the steel manufacturing scenario, these are:

The homogeneous Poisson process, this method is stated by the reliability literature as not suitable for the reliability analysis of repairable systems, However it is the most simplistic of the reliability analysis methods available, and in the authors experience it is widely used in many manufacturing enterprises.

The Power Law method is widely used for the analysis of repairable system within the reliability community, and appears a practical choice for the steel manufacturing environment

The General Renewal Process is an extension of the Power Law process to accommodate an ageing factor; this could be a benefit in this application due to the wide rage off system ages employed.

It was further decided to run a series of statistical significance test on these methods and their applied failure data sets to see if they can comply with statistical significance requirements

Chapter 3 is dedicated to a literature review of the latest reliability analysis methods. This is performed with the intention of enhancing the author’s knowledge in reliability analysis techniques and identifying if there is a mainstream analysis method suitable for this application.

3 Literature Review

This Chapter is predominantly a review into the reliability analysis methods being used for manufacturing systems in all applications and identifying if there are any reliability analysis techniques currently in use which might be suitable for application into the Hot Strip Mill. The examination of the literature is structured in the following way.

Section 3.1: Repairable Systems Analysis: This section gives an overview of the reliability analysis methods used for these systems.

Section 3.2 Current Analysis methods: Is tailored towards the standard reliability analysis and latest reliability analysis methods used during the period 2000- 2010

Section 3.3: Lifetime Analysis Methods

Section 3.4: System Reliability Analysis and its complementary activities

The concept of reliability is being applied, with ever increasing importance, to the assessment of both qualitative and quantitative attributes in our industrial society. Machine reliability is a major contributor to efficient manufacturing; it has a direct relationship with machine availability and process efficiency. In addition indirect relationships are formed with product quality through inconsistency in the processes manufacturing capability. Reliability problems may also result in losses arising from disruption to upstream and downstream manufacturing processes. The definition of system and machine reliability has been aptly expressed as: "*The characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time*" [Dummer 1990].

This consistency allows the process to be fully utilised and allows effective integration with other processes. For the purpose of this paper a "system" is defined as consisting of one or more machines (units) whilst a "process" consists of one or more systems.

3.1 Repairable Systems Analysis

The reliability of repairable systems is regarded as a complex application. Reliability monitoring is widely practised throughout most of industry through its association with process availability, but the greater in depth analysis needed to consider the reliability of repairable systems is regarded as a specialist area. Numerous consultancies are available to carry out this task and commercial software is available for this application, but specialised knowledge is required for their efficient use.

Some further reasons for these limited applications are:

- Restricted data set availability; most systems are bespoke, therefore allowing limited application of testing regimes.
- Repairable systems can be large and can require breakdown into subsystems each with their own reliability characteristics.
- Many differing analysis models have been developed to cover all types of systems. Their application requires knowledge of statistical methods; often an iterative approach is required to identify the most suitable model.
- Deviations in the operating environment mean that in practice reliability life characteristics can change dependant on outside influences

This review is aimed at identifying the current “best practice” in the field of reliability analysis of repairable systems. Particular attention is paid to the newer analysis methods and their possible application to the Thesis main theme of constructing a reliability model suitable for this manufacturing environment. Practical applications of the reliability analyses methods have been identified where possible and the relationship between reliability and other major manufacturing parameters has been given consideration

3.1.1 Reliability Analysis Software

To date the reliability analysis of repairable systems is regarded as a specialism. There are several manufacturers of commercial reliability analysis software packages available. These software packages are normally broken down into modules which cover all aspects of manufacturing analyses and are biased towards non-repairable analysis methods. Consultants or specialist departments within larger industries normally use these packages. The most popular commercial packages are identified in Table 3.1; this table includes the sections of the packages which are claimed to be suitable for the analysis of reparable systems. Bespoke or in house packages are not considered in this review.

Table 3-1 Commercial Reliability Analysis Software

Reliability Analysis Software - Reference chart		
Manufacturer	Module	Analysis method
Reliasoft	Weibull ++ RGA	General Renewal Process Power Law
Isograph	MIL 217 Telecordia NEWSC (Mech) IEC 62380 BJB/Z299B	Power Law, and predictions made on standards (predominantly Power Law derivations)
Relex	Reliability prediction - team edition Reliability prediction calculation engine - team edition	Power Law, and predictions made on standards (predominantly Power Law derivations)

For the purpose of this Thesis modules of the Reliasoft software package were used to test and correlate the constructed reliability analysis method. This package is supported by Dr Larry Crow, regarded as the originator of the Power Law Process [Ascher et al 1984] and contains multiple examples of differing analysis applications.

3.2 Current Analysis Methods

Much of the work done on modelling repairable systems is concerned with modelling failure times and is predominantly based on the point process theory. The most common models used for repairable systems are renewal processes [Lindqvist 2006] which include the HPP and NHPP [Tan et al. 2008, Krivtsov. 2007 (1),] Within this class of models the HPP is recognised as the simplest since, if the failure process of a system is HPP, the system will be returned to as good as new after every failure, the times between failures are independent and identically distributed random variables for which the rate of change of failure λ is constant. Extensions and adaptations of this approach have been generated to support currently deployed analysis methods, some of which are now considered.

3.2.1 Renewal Processes

It is traditionally recognised that the HPP model is not suitable for analysing repairable systems, where events are generally not statistically independent and identically distributed. However it has become custom and practice in the manufacturing environment for the HPP mean time between failure (MTBF) parameter to be quoted as a measure of the reliability of repairable systems in the mistaken belief that it is a true measure of the reliability characteristics of these systems. The relevance of the HPP analysis to repairable systems can be proved by making the generalisation that the traditional "bathtub curve "is representative of a system's failure performance. The variations in the system's failure rate can be easily identified which indicates the non suitability of the HPP model, this model may be suitable only for examining the flat portion of the failure rate curve. Crow [Crow 2010(1)] reinforces this argument with the statement that in a repairable system the events (failures) are not independent and in most cases are not identically distributed. He elaborates that when a failure occurs in a repairable system the remaining components have a current age and the next event depends on this age. Thus the failure events at a system level are dependant.

Tan [Tan. 2008,] shows that it is possible to use the HPP process for the whole life cycle by subdividing the failure data into separate intervals and applying a HPP analysis to each interval. This is illustrated by an example using steam-generating equipment to which Laplace tests are applied to each data segment to demonstrate that the HPP is suitable for the analysis. This leads to the conclusion that this analysis method may be suitable, when the changes in failure rates are not too large, and the null hypothesis can confirm suitability. Crow [Crow 2010(2)] has used a similar approach in the Reliasoft software with the use of "Fielded Systems" in the RGA module. Using the assumption that the data set contains several modes, the A mode where a repair will not be applied, and the BD mode where a delayed fix will be applied. This assumption implies that the system is in a steady state and is neither wearing out nor exhibiting reliability growth [Crow 2010(2)]. Another general assumption that is made when using a point process methodology for the analysis of repairable systems is that the systems repair time is negligible compared to the overall operating time.

Krivtsov [Krivtsov. 2007 (1)] states that this is can be a reasonable assumption in some applications e.g. the case of an automobile breaking down for 3 days over an 18 month period. If upon failure the system is returned to as good as new condition and the time between failures can be treated as independent and identically distributed and the failure occurrence can be modelled as an ordinary renewal process which is a suitable HPP application. If the system is subject to minimal repair and returned to the same state that it was in before repair the repair is stated as a same as old state, and the appropriate model to describe the state will be the NHPP model. Krivtsov [Krivtsov. 2007(2)] states that the NHPP can be modelled as a renewal process with the "same as old" type of renewal upon each failure.

It may therefore be concluded that the ordinary renewal process has had limited application in repairable systems and that the generalised renewal process applications are relatively recent and have been targeted towards specific applications.

3.2.2 Imperfect Repair

The case for the imperfect repair model is based on the assumption that in reality a minimal repair to the system returns it too as bad as old condition, whilst a perfect repair returns it to as good as new condition. Most standard maintenance reduces the failure intensity but does not leave the system as good as new. This is known as imperfect or minimal repair. In reality it could be said that after repair the system will be between the two repair conditions. This is put forward as the Generalised Renewal Process (GRP) which introduces the notion of virtual age into the system.

Kaminskiy et al. [Kaminskiy. et al. 1998] has shown that the ordinary renewal process and NHPP are specific cases of the Generalised Renewal Process and proposes a Monte Carlo based approximation solution for certain applications. The key assumptions are made that the time to first failure and the repair quality can be estimated from the available data. The repair time is considered negligible and the failures are considered as a point process. Nagode et al. [Nagode et al. 2008] discusses the relative merits of the Monte Carlo and later maximum likelihood estimation methods for analysing the generalised renewal process parameters, with further discussion on the merits of using multi fold Weibull applications to derive the time to first failure of a system. The data set requirements for both methods are set out and the hypothesis is made, that in some circumstances the estimation method (EM) algorithm will be more suitable for deriving the generalised renewal process parameters. A further proposal is made that by using the Monte Carlo method to calculate the initial parameters for input into the estimation method algorithm speeds up its convergence. The General Renewal Process model has been examined by Zhao et al. [Zhao et al 2005] and Kajima [Kajima 2003]. Whilst [Crow 2010(3)] has addressed the problem of imperfect repair by the practical application of the General Renewal Process analysis method in the Reliasoft Weibull ++ module.

The NHPP family can support the majority of repairable systems analysis and the majority of publications consider two monotonic forms of the NHPP rate of change of failure. Krivtsov [Krivtsov 2007(2)] explains how to expand the NHPP analysis methods from the normal Weibull/Power Law distributions to incorporate other life data analysis methods including lognormal and normal, through several examples which show an imprint effect over estimation of the cumulative hazard function and the cumulative incidence function in these examples. The need for more complex analyses models than the NHPP is put forward by Lindqvist [Lindqvist 2006] in a comprehensive paper which identifies the need for trend testing to test if the failure process is a Poisson process. The pitfalls of treating failure times as independent and identically distributed if there is a trend between them have also been considered [Lindqvist 2006, Ascher et al. 1984]. The boundaries for defining the limits of the failure process were considered in the same work, with a renewal process classed as the perfect repair or an NHPP classed as a minimal repair. His paper leads on to an in depth examination of the renewal process models and the manipulation of these models through various mathematical iterations. The two “extreme” kinds of repair are represented as the first dimension of a repairable, model cube. The second dimension of this cube is the appearance of trends in the failure data, whilst the third dimension corresponds to unobserved heterogeneity in the system, this problem being relevant when several systems of the same kind are observed [Lindqvist 2006].

A later examination by Doyen et al.[Doyen. et al. 2004] introduces two new imperfect repair models The arithmetic reduction of intensity (ARI) models consider that each repair reduces the failure rate by an amount which is dependant on the past failure process. The reduction of age models that work on the principle that repair rejuvenates the system which therefore reduces the virtual age of the system by an amount proportional to its age before the repair. The paper shows these operators working in conjunction with the Power Law process and includes calculations for the maximum likelihood estimators. The conclusion is reached that further work is needed to investigate the probabilistic properties of the models through theoretical studies on parameter estimator properties with the proviso that a goodness of fit test should be devised to confirm the models validity.

3.2.3 Trend Renewal Process

Another class of alternative models to the renewal process (RP) and NHPP are the trend renewal processes (TRP). This model is a generalisation of Berman's gamma process [Lindqvist 2006] and works by generalising the following property of the NHPP. First the cumulative intensity function (CIF) corresponds to an intensity (λ). Then if T_1, T_2 is an NHPP process (λ (t)) the time transformed stochastic process Λ ($T_{1)}$, Λ ($T_{2)}$ is HPP. The TRP is defined by allowing the HPP to be any renewal process RP (F), with a specified distribution F for the inter-arrival times of this renewal process.

An example of this process is the replacement of a major part in a system (a tractor engine is used as an example); if the rest of the system is not subject to wear the RP would be a suitable model for the failure process, however if wear is present an increased replacement frequency could be expected. The TRP achieves this by accelerating the internal time of the renewal process which represents the cumulative wear. It can be seen that the TRP model has some similarities to the accelerated failure rate models [Lindqvist 2006].

Analysis of failure data associated with the operation of heterogeneous implementations must be approached with care. It can lead to an apparently decreasing failure rate, which can be counterintuitive due to the effects of wear and aging on the system. Proschan [Proschan 1963] demonstrated this fact statistically through using a result from Barlow et al. [Barlow et al. 1963] which implies that a mixture of exponential distributions has a decreasing failure rate. The connection between heterogeneity and the Poisson process was studied as early as 1920 [Greenwood et al. 1920] and it has been shown in biostatistics that neglecting individual heterogeneity may lead to severe bias in lifetime distributions through references in biostatistics literature by Aalen et al. [Aalen et al.1988], Hougaard et al. [Hougaard et al 1996] and Vaupel et al. [Vaupel et al. 1979]. Lindqvist [Lindqvist 2006] states that the presence of heterogeneity is often apparent from repairable systems data if there is a large variation in the number of events per system. In addition it is not really possible to distinguish between heterogeneity and the dependence of the intensity on past events for a single process. Heterogeneity can be modelled by including an unobservable multiplicative constant in the conditional intensity of the process. For systems with a single type of event the conditional intensity $\gamma(t)$ is replaced with $a\gamma(t)$ where a is a random variable that represents the *"frailty"* of the system. Since a is unobservable one needs to review its distribution in order to derive the likelihood function from the observed data. Lindqvist et al [Lindqvist et al. 2003] introduces heterogeneity into the TRP and other processes and use a three dimensional cube based approach [Lindqvist 2006] to facilitate the presentation of maximum log likelihood values and parameter estimations. Several examples are shown which appear to support the conclusions of Proschan [Proschan 1963] and conclusions are drawn that there is no significant heterogeneity present in the stated examples, however a slight time trend with a *p*- value of 0.022 is detected

In many repairable systems one of the main aims is to detect trends in failure data which occur over time. These trends may be monotonic indicating an improving or deteriorating system, or a non-monotonic such as a bathtub curve or a cyclic trend. In this context there are two main types of trend testing available; graphical and statistical trend testing. Graphical testing normally entails using the plot of the failure pattern to identify any trends present. Examples of this method include the Nelson Aalen plot and the total time on test (TTT) plots, each of which identifies deviation in the intensity function corresponding to system changes. Statistical trend testing is biased towards detecting the null hypothesis for the HPP or renewal process. This test is designed to detect if the failure process is stationary rather than displaying a trend. There are several tests available for this analysis including the Laplace test. These tests are predominantly biased towards detecting if the failure process is an HPP. Additional tests are available to identify if the process is a renewal process, these tests include the modified Laplace test and Lewis Robinson test [Ascher et al 1984, Lindqvist 2006]

Having reviewed the most commonly deployed analysis methods it is logical to consider next the manner in which these methods can be applied in reliability analysis and performance assessment.

3.3 Lifetime Analysis Methods

One of the important topics in failure data analysis is to select and specify the most appropriate lifetime distribution that describes the times to failure of the system. There are two general approaches to fitting reliability distributions to failure data. The first method involves the derivation of an empirical reliability function directly from the data. The second method identifies and adopts an appropriate parametric distribution, such as Weibull, Gamma and the exponential lognormal which can be used within the process method to estimate the unknown parameters The second method is widely practised because of the ability to extrapolate data beyond the sample range and to apply more complex analysis methods to calculate properties such as hazard rates and mean time to failure (MTTF). There are several analysis methods supporting this approach which have applications in mechanical system reliability analysis, including those considered below.

3.3.1 Power Law Process

In general most repairable systems are not returned to "as good as new" condition after the replacement of a single component. For example the replacement of a water pump in a car does not return the car to as good as new condition. This indicates that distribution theory does not apply to the failures of a complex system, such as a car and that the intervals for the following failures will not follow the same distribution pattern. Normally a distribution such as the Weibull cannot model this pattern and a process is often used instead of a distribution. The Power Law model is the most popular process model. It uses the Weibull distribution to model time to first failure and the Power Law process to model each successive failure. The Power Law process is easy to use and understand and lends itself to many practical applications [Ascher et al 1984, Rigdon 2000, and Crow 2008]. This model was introduced in 1974 [Crow 1974] and has formed a major part of this field with incorporation into military handbooks and other reference materials.

The majority of industrial applications of reliability analysis considered have been related to the NHPP family. Typical of this approach is one such analysis [Weckman et al 2001] which utilises the Power Law process in an approach to modelling jet engine life. The analysis includes predictions of a jet engine's operating pattern to illustrate how the model compares to actual events. The engine data is depicted in terms of the number of shop visits where the engine is removed from the aircraft and sent to the workshop for attention. This is measured as time to shop visits times between the removals. Duane growth models had previously been used to model design improvements [Duane 1964]. This example used data from two airlines and concluded that the Weibull model’s accuracy varied, depending upon the circumstances controlling the engine maintenance scheme. Deeper analysis identified that the shop visit counting process was significantly disrupted by a number of mandatory removals of the engine due to cycle limitations rather than engine deterioration or part failure. Suggestions were made that future methodologies could account for this distortion of the counting process and improve estimation of parametric values that could more accurately model the Weibull process. This does highlight the difficulties of identifying the true failure parameters of any system, and the relationships to maintenance strategies, operating policies and other associated factors.

Another analysis [Saldanha et al 2001] considers the performance of an ageing system in a case study investigating the reliability of service water pumps in a nuclear plant. This analysis works on the rate of change of failure of the pumps, and uses two NHPP models, the log linear and the Power Law process, as comparative methodologies. The conclusion is reached that the model adequately includes the variations in the failure occurrence rates due to periodic testing and maintenance activities performed on repairable systems. Thus it can be used to survey ageing mechanisms and to assess maintenance effectiveness.

The reliability of the major subassemblies of onshore wind turbines, including the gearbox, generator and converter, is considered by Spinato et al. [Spinato et al 2009]. The data is analysed and considered suitable for the application of a Power Law methodology. It is deduced from this long-term study lasting more than eleven years that wind turbine generators and converters both achieve reliabilities considerably below that of similar units deployed in other industries. This is a major concern in these times of rapid expansion in the wind turbine industry. The proposal is made that offshore wind turbines should be subject to a more rigorous testing regime.

Marshall et al. [Marshall et al 2010] investigates the methods of fitting models to failure data from a repairable system using the NHPP family. The paper's primary interest is in determining a methodology supporting the assessment of whether an NHPP is an appropriate model. It suggests the use of trend testing through either graphical or statistical approaches and considers the methods of ascertaining whether these tests are valid. After conformation that the NHPP model is an appropriate model for the failure process the paper indicates the various methods of estimating the intensity function of the Power Law and the log likelihood models by the application of several goodness of fit tests. The paper applies these methodologies to warranty data for two vehicles obtained from a major car manufacturer over a three-year period.

The conclusion is drawn that the NHPP model is an appropriate model for this data. It is noted that all of tests indicated focus on the Power Law and log linear intensity functions with few tests available for other types of intensity functions and suggests that further research might be directed towards this area. This Thesis illustrates the complexity of applying one of the (relatively) simple analysis methods for a repairable system and indicates the breadth of choices that has to be made to obtain a robust analysis methodology.

3.3.2 Bayesian Estimation

The classical approach to statistical inference treats parameters as fixed but unknown values. In contrast the Bayesian approach regards parameters as unobservable random variables. This approach leads to the implementation of a *prior distribution* before events are observed and a *posterior distribution* after the events is observed, allowing the construction of a combined lifecycle analysis model. The development of a new combined lifecycle distribution model (CMBL) which updates when new time to failure data becomes available have been outlined [Briand et al. 2008]. This provides an application friendly method of characterising a component's failure distribution. The CMBL distribution is used in two simulations; a system of systems analysis toolkit (SoSAT) and a real time consequence engine (RTCE). The primary use of SoSAT is to support systems analysis for the US Army's future combat system whilst the RTCE is a forward-looking development tool. Both methods use a bathtub shaped density hazard function. The distribution parameters are based on new time to failure data modelled as a Poisson process. A Bayesian change point methodology was used to return an updated CMBL when new time to failure data becomes available. In this process the change points are determined first through the Poisson process change point model using a Bayesian formulation. The process uses Markov chains and Monte Carlo methods to determine the change point's function. This relies heavily on the accurate prediction of the change points to determine the CMBL parameters.

Briand et al.[Briand et al. 2008] concludes that the CMBL parameters can be easily identified once the change points have been identified through the use of the Poisson process change point model (PPCM). The results were consistent with some over estimation of individual parameters, however it was noted that the Poisson process change point model accuracy is limited to data with well-defined distributions over the whole lifecycle. Additional research is recommended to confirm the models suitability for practical applications.

Sarhan et al [Sarhan et al 2003] examined the case of a "1 out of 2: G" repairable system with unknown parameters λ and μ. The paper investigates the use of the maximum likelihood estimator and Bayes estimates to calculate these unknown parameters and concludes that this methodology is superior to the moment estimator. It further concludes that the new method can be calculated for all observed failures and the method appears to have smaller percentage errors.

An approach to using a Bayesian estimation of piecewise constant failure rates under the proviso that the failure rate interval time is greater than the failure rate value in prior intervals is presented by Zequeira et al. [Zequeira et al. 2001]. This investigation considers how the ageing class of distributions including increasing failure rate, increasing failure rate average and new better than used has significance to most repairable systems. The increasing failure rate distribution patterns arise as a model for deteriorating systems. Complex systems like nuclear power plant electricity generating equipment could fall into this class. The new, better than used family is naturally considered in replacement policies for ageing plant. The specified prior distribution of the failure rate of each interval is specified through a Gamma distribution as is the posterior distribution failure intervals. This analysis approach is presented as a solution to different reliability problems such as determining the optimal age replacement policy for an infinite time span system or by estimating parameters in a model with missing information. It is noted that although this model is applied to estimating increasing piecewise failure rates the approach could be adopted for decreasing piecewise failure rates.

A Bayesian approach to maintenance applications by optimising a condition based maintenance policy is proposed by Grall et al. [Grall et al. 2008]. The paper tackles the problem of maintenance decision rules for a stochastically deteriorating system. The paper deals with a non-stationary deteriorating system where the mean deterioration rate can change during the life cycle. An adaptive online maintenance policy with an online Bayesian change detection algorithm optimised with respect to global maintenance costs is proposed. The goal of the paper is to apply an adequate change detection algorithm to the stochastically deteriorating system which is capable of detecting the optimal failure threshold. The use of online and offline maintenance policies is compared and the conclusion is drawn that the use of the online policy significantly decreases the maintenance costs.

3.3.3 Multi State Systems

Many real world systems can perform tasks with a degraded performance level. This is predominantly caused by component degradation or the failure of some elements which contribute to the overall lowering of the system's performance. Systems of this type are termed multi state systems (MSS).

Traditional binary reliability models only allow two states, perfect functionality or failure. Multi state system reliability analysis relates to systems which cannot formulate an all or nothing failure criteria. Lisnianski [Lisnianski 2007] presents a method of extending the classical reliability block diagram to a repairable multi state system. The straightforward stochastic processes are difficult to apply to this method due to the huge number of system states available. The method extends the reliability block diagram into the repairable MSS by an application of the universal generating function and random processes. The advantages of the proposed system are related to the simplification of the MSS model through building separate system models for elements rather than a complex overall model. It also provides a simplification of the modelling process by solving *n* lower order equations for separate elements rather than one high order overall model. These initial analysis measures reduce the model size and consequently reduce the number of operating states in the MSS which are available for analysis. In an elaboration on the previous case Lisnianski et al. [Lisnianski et al 2009] discusses the case of redundancy in the MSS. They consider two systems in a set-up where one system can satisfy its own demand and provide assistance to the other system in order to increase overall reliability. The application of a universal generating function and random processes takes into account multi-state models for all system components. The method proposed to accurately predict the short and long-term performance of the MSS with redundancy as the procedure is structured and is based on the natural decomposition of the entire interconnected systems.

Liu et al. [Liu et al. 2008] considers the case of a single multi state element with performance rates and transition intensities represented as fuzzy states in a MSS. It is recognised that it is difficult to identify individual multi state element parameters in the MSS because of inaccuracy and data fluctuation especially in continuously degrading elements. This fuzzy methodology is presented as an alternative MSS analysis method and is applied through the use of several fuzzy Markov models to modify and extend the fuzzy multi state element availability assessment through the use of a parametric programming algorithm.

Wang et al. [Wang et al. 2002] consider the case of a repairable system that does not evaluate the effectiveness of repairs. One can assume that the repairs follow a non-homogeneous Poisson process and in general the repair includes part replacement or periodic overhaul. The distribution characteristics of failures can shift gradually in relation to the number and time in repair from a normal (or Weibull) distribution to a mixed type distribution (Normal and Weibull) and finally become an exponential distribution. In this paper the cumulative failure data set is developed with fuzzy consideration to distinguish between repairable and non- repairable cases in the failure data. This identifies the system failure mode at the next failure interval. The fuzzy data sets are integrated with the cumulative damage to the system. This allows an equivalent dynamic reliability with repairs model to be constructed which allows for “jumps” in the system reliability between repairs. The results from the model are seen to be acceptable when compared to a Weibull distribution.

Komal et al [Komal et al. 2009] considers the case of complex industrial systems that often produce limited failure data and repair data, and considers the difficulty in assessing the reliability availability and maintainability parameters in such cases. The paper provides an idea of calculating these parameters using a genetic algorithm based "lambda tau" technique. The genetic algorithm is used to compute these parameters in the form of triangular fuzzy numbers. An example of a paper mill in India is used to illustrate this technique and the methodology is used to compute a reliability and maintainability index, which is used to rank the systems components on the basis of their performance. This methodology allowed the identification of several components with inferior performance, thus supporting the design upgrades required for the specified components.

3.4 Systems Reliability Analysis and Complementary Activities

System and machine reliability is an important consideration that must be made when attempting the optimisation of manufacturing capability; it has to be factored into the system design, layout and construction. Consideration has to be given to how reliability factors will influence the required availability of the system and the necessary level of system redundancy to comply with manufacturing and safety considerations. This consideration must be made when commissioning and operating the system, with specific attention paid to the associated maintenance requirements. These considerations and the effect that redundancy engineering can have upon them have been reviewed in the following section indicating the latest ideas on their implementation and improvement.

3.4.1 Availability, Optimisation and System Redundancy

System availability is a consideration which is of paramount importance in the design of an industrial system. As the system becomes more complicated the cost of improving reliability also increases. Redundancy is the main avenue of increasing system availability. Jiang et al. [Jiang et. al. 2005] proposes a genetic algorithm (GA) based optimisation model to improve the design efficiency whilst considering the design constraints. This is carried out through object orientated programming to develop a knowledge based system for the design of a series parallel system. This program becomes an effective tool to decide the related characteristics of each component. The conclusion is reached that the proposed system requires further study to optimise the GA parameters, including data entry and statistical analysis from the design knowledge base. Nourelfath et al. [Nourelfath et al 2007] discusses the redundancy optimisation problem from a different perspective by assuming that the design goal has achieved its required redundancy through the selection of discrete components available on the market. Nourelfath et al. examines redundancy optimisation of the minimal configuration and maintenance costs of a series parallel multi state systems when under reliability constraints. The maintenance policy specifies the priorities between the system components and the use of a shared maintenance team. The optimisation approach developed by Nourelfath et al. is analytical and uses the universal “z” transform and Markov chain techniques to develop a heuristic model. Future work is recommended in developing a direct optimisation method, which supports the whole maintenance structure

3.4.2 Reliability Analysis in Manufacturing

One of the main objectives for carrying out the literature review was to search for papers that have particular relevance to the Thesis topic of machine reliability in a Hot Strip Mill. One of the few documents in this field is a paper presented by Goode et al.[Goode et al 2000] which considers the operation of a Hot Strip Steel Mill. This is a manufacturing process in which unscheduled stoppages can critically affect plant availability, productivity and product quality. For many years steel companies have practised condition-based monitoring in strategically vital areas such as the Hot Strip Mill. These monitoring methods include vibration analysis, oil and wear debris analysis and performance measurement using numerous techniques to measure parameters such as electric current, temperature etc. The present methods allow maintenance personnel to detect and often diagnose pending equipment failure but they are not able to predict remaining equipment life with any certainty. The authors state that using historical data to predict future performance requires an assumption that historical and current performance is highly verified, in reality this is not the case. A predictive model is proposed which utilises a Weibull distribution to define the expression modelling the failure intervals. This equation is solved using a Monte Carlo approach with the time to failure (TTF) being predicted as a cumulative probability distribution. The paper defines the application of condition monitoring measurements as applied using two separate regimes, designated as the stable and failure zones. In the stable zone condition monitoring methods indicate that the operation is normal and a reliability monitoring method is used. In the failure zone the condition monitoring methods identify the existence of a problem and both reliability and condition monitoring information are combined to predict the remaining machine life. The paper investigated both simulated and case studies and concluded that the prediction model is highly dependent on both the quality and accuracy of the condition based measurements.

Xie et al. [Xie et al 2009] considers an important parameter in reliability engineering by examining the effects of ageing in a power generating system. The paper identifies that failures can be classified as either repairable random failures or non-repairable ageing “end of life” failures. Xie et al. state that only repairable failures have been considered in most power system’s reliability analysis and that a modelling concept for unavailability due to ageing must be developed. A Normal or Weibull distribution is suggested as the means to estimate the failure probability density function due to the ageing process and a combined model is proposed including calculations for repairable and ageing failures. An example using seven generating units is used to verify the correctness of the constructed model. The results indicate that ageing failures have significant impact on the unavailability of components particularly in the case of older systems.

3.5 Discussion

Reliability analysis in its various forms is a well-established tool used in many industrial applications. It impinges on many aspects of our lives from everyday issues such as domestic transport through to futuristic concepts such as space travel. The problems associated with quantifying reliability are aptly illustrated in a paper by Mendall et al. [Mendall et al 2004]. This paper indicates the significance of reliability in future space exploration by discussing the future requirement of human exploration of Mars, currently envisaged as a 500-day stay at the planets surface. This mission will be incapable of attaining an abort to Earth capability, which means that critical mission systems are specified to perform reliably for over three years. The required reliability level of 99% with a confidence limit of 0.95% would require a test regime for the systems to be operating for 149000 days, in space, without a single failure. This constraint is infeasible and the paper examines the problems of correlating the reliability requirements with current technologies. The conclusion reached is that a rigorous testing regime including additional Lunar exploration will be required to “prove out” equipment before undertaking the Mars Mission.

Ascher et al. [Ascher et .al. 1984] considers the current state of reliability analysis in respect of the misconceptions and misuse of the approaches he presented in his 1984 book. In a detailed paper Ascher [Ascher 2007] considers that the reliability community is still using widely disparate terminology and notation. These discrepancies primarily surround the conflicting use of failure rates and force of mortality. He strongly advocates added rigour in applied terminology and notation and the use of approaches that recognise the fundamental differences between parts and systems in their models and techniques. The paper stresses the importance of determining whether part or system failure data is being analysed and incorporating the basic differences between parts and systems into data interpretation and subsequent efforts to improve reliability. In reality this appears to be a major concern within the industry e.g. a motor can be system in its own right, but when taking into the context of a manufacturing process which could contain several hundred motors, it would be considered as a part.

Most statistical systems analysis methods referred to in this review are based on one or more of the above processes. The NHPP in its various forms (Power Law etc) accounting for the majority of reliability systems analysis usually with the assumption that the data set forms a stochastic (random) process. The various process derivations have been included for completeness. It can be seen that some of the later analysis methods identified in this review often use some, or several, of the above processes in their analysis.

3.6 Conclusion

The purpose of this review is to identify if there is a reliability engineering analysis method suitable for widespread application to mechanical systems operating in a manufacturing environment.

There is wealth of data available regarding statistical modelling on the reliability of repairable systems: However these are predominantly biased towards statistical investigations into:

- Identifying whether there is a reliability analysis system available for a particular system

- The relative merits of differing reliability analysis methods when applied to a particular system.
- Manufacturing either (a) a derivation of the current reliability analysis techniques or (b) a combination of several techniques in order to create a new reliability analysis technique.

These investigations have predominantly been performed as academic exercises and some have contributed towards the statistical understanding of systems operational behaviour

There is a lack of actual worked examples of complete system analysis. The search of databases for the 2000-2010 periods found less than ten examples. Many of the papers quoted use specific data sets from previous case files, some dating back several decades. However, the majority of the examples for the reliability analysis for repairable systems were based on the Power Law analysis method. This reaffirmed the author's opinion that the reliability analysis for repairable systems method under review for this application should contain the Power Law method.

As such this review must conclude that the development of a comprehensive approach to reliability engineering analysis suitable for widespread application to mechanical systems operating in a manufacturing environment is needed and that research effort to support this is justified.

The next Chapter identifies the methods used for machine or system failure monitoring currently in use at the Hot Strip Mill in Port Talbot. A spreadsheet application is proposed which can interrogate the failure data base and segregate the data into a format which is suitable for further analysis.

4 Reliability Analysis & Modelling – Initial Approach

This Chapter is a review into the operational monitoring methods being used for the manufacturing systems in this application and identifying if there is any systems failure monitoring methods currently in use which might be suitable for further analysis. The chapter identifies the most suitable database for use and identifies.

- The data to be derived from the main database
- The Excel workbook constructed to interrogate and compile thee failure data retrieved from the main database.

The Hot Strip Mill has multiple data logging systems which are derived from several locations and run concurrently. An audit of the data sources identified the databases which are the most suitable for reliability analysis. The main failure data methods at this plant are automated systems which are based on the "traffic light" monitoring method where an alarm is judged as:

Green: No issue
Orange: possible cause for concern
Red: Failure

The initial audit identified two of these databases applicable to the descaling system, the pump house monitoring system and the hydraulic pumps monitoring system

The alarm parameters can be modified to suit individual operating circumstances by plant engineers. In addition these failure records are logged on a rolling four week cycle due to the amount of failure data being recorded. Therefore the failure data from these data logging methods have been identified as not suitable for this application and have not been used for any of the following reliability analyses.

The main failure database at this plant is the generic failure monitoring system which is used for recording all process stoppages in the Hot Strip Mill. This is a high level database which is predominantly automated with one manual input relating to the reason for the plant stoppage. It was decided by the author that this process failure data base is the most suitable data source for the system reliability analysis.

4.1 Process Failure Monitoring Method

The main process stoppage recording medium at the Hot Strip Mill is the process (Pi) database; this stoppage data is automatically transferred onto a "year to date" spreadsheet which consists of approximately 5,000-recorded readings per annum. The stoppage data is automatically recorded by the operational control system which tracks the area or sensor which has stopped the line. This operation monitors the stoppage and records the time taken to restart the manufacturing process. The Line controller will add additional detail to the database once the reason for the stoppage has become apparent. The machine systems being monitored by the year to date spreadsheet are of indeterminate age. Most are decades old and have been upgraded with the latest technologies at various stages of their working lives. This means that there are systems in operation with machine ages ranging from under one year old to over forty years old. It was decided by the author that this year to date spreadsheet (in an Excel spreadsheet format) could act as a data manipulation document for any chosen reliability analysis method.

To aid software compatibility it has also been decided to maintain the analysis method in an Excel spreadsheet format. The year to date spreadsheet is renewed annually, by plant engineers and archived. This spreadsheet is automatically updated at an eight hourly interval during plant operation. The spreadsheet is located on the Tata Steel intranet website and is accessible to all plant engineers and managers. A typical set of recorded failure data is shown in Table 4.1

The spreadsheet draws its line stoppage data from the main automated data logging system, known locally as the "Pi" system, as it is named after the software's manufacturer. The data is automatically logged as date, start/stop times, duration of stoppage, area affected, and stoppage class. The manufacturing personnel manually input additional detail referring to the source and reason for the individual stoppages into the "Detail" column. This spreadsheet is used as the monitoring medium by the Hot Strip Mill engineers to construct reports and assist in formulating future maintenance strategies.

Table 4-1 Hot Strip Mill Year to Date Spreadsheet

DATE	SHIFT	START	END	LENGTH(Mins)	AREA	CLASS	DETAIL	COMBINED
01/01/2008	C	7:00:00 AM	7:00:00 PM	720	STRIP MILL	NM	Non required time	STRIP MILL-NM
01/01/2008	E	7:00:00 PM	9:15:00 PM	135	STRIP MILL	NM	Non required time	STRIP MILL-NM
01/01/2008	E	10:45:00 PM	10:49:00 PM	4	F11	ELEC	Shifting not going to position	F11-ELEC
01/01/2008	E	11:30:00 PM	11:37:00 PM	7	R/ROUGHER	RC	Tightening down screw down	R/ROUGHER-RC
01/01/2008	E	11:56:00 PM	12:02:00 AM	6	R/ROUGHER	MECH	Tightening down screw down	R/ROUGHER-MECH
01/01/2008	E	1:27:00 AM	1:36:00 AM	9	ROLLCHANGE	RC	G.r.c.13a	ROLLCHANGE-RC
01/01/2008	E	5:10:00 AM	5:19:00 AM	9	ROLLCHANGE	RC	G.r.c.21a	ROLLCHANGE-RC
02/01/2008	D	7:30:00 AM	7:50:00 AM	20	SLAB YARD	ELEC	charging from south (transfer car fault)	SLAB YARD-ELEC
02/01/2008	D	9:10:00 AM	9:23:00 AM	13	STRIP MILL	ELEC	hmi server fault	STRIP MILL-ELEC
02/01/2008	D	10:48:00 AM	10:59:00 AM	11	ROLLCHANGE	RC	grc	ROLLCHANGE-RC

The spreadsheet is populated with nine sections:

Section 1: DATE: The start date of the stoppage

Section 2: SHIFT: The shift in which the stoppage occurred, there are four shifts working at the plant, these are classified as B, C, D, E. Each shift works for twelve hours on a four day on – four day off working pattern The data set shown in Table 3.1 covers the transition from shifts C & E to shifts B & D.

Section 3: START: The start time of the stoppage

Section 4: END: The end time of the stoppage

Section 5: DURATION: The overall length of the stoppage

Section 6: AREA: The designation of the mill into twenty eight systems which cover all aspects of the process operations.

Section 7: CLASS: This is an abbreviated classification of the systemic operational stoppages seen in this manufacturing area.

Section 8: DETAIL additional detail on the root cause of the stoppage.

Section 9: COMBINED: The combined root cause of stoppage which includes area and class.

The main sections of failure database which are used in constructing the failure data set for reliability analysis modelling are now considered:

4.1.1 Section 6: AREA:

A condensed explanation of the areas designation and operation is contained in the following list:

1. A FURNACE ; reheat furnace A.
2. B FURNACE ; reheat furnace B.
3. COIL HANDLING ; Coil removal from end of process – no failure data.
4. COIL BOX ; Mid process area which coils unfinished strip.
5. COILER 4 ; End process which coils finished strip.
6. COILER 5 ; End process which coils finished strip.
7. COILERS ; End process which transports finished coils.
8. CRANES ; overhead gantry cranes.
9. CROP SHEAR *****; shearing process for trailing end of strip.
10. F5; rolling mill stand F5.
11. F6; rolling mill stand F6.
12. F7; rolling mill stand F7.
13. F8; rolling mill stand F8.
14. F9; rolling mill stand F9.
15. F10; rolling mill stand F10.
16. F11; rolling mill stand F11.
17. FINISHING; all coil transportation activities, packing etc.
18. FLUID POWER ; supply of all hydraulic systems.
19. FSB ; Finishing scale breaker, final part of Descaling process.
20. FURNACES ; control and supply systems for the reheat furnaces.
21. HSB ; horizontal scale breaker, part of Descaling system.
22. HSF; hot strip finishing, quality checks etc.
23. ROLL CHANGE**** change of work rolls normal process.
24. ROTS ; Run out table final cooling of hot strip.

25. R-ROUGHER ; reversing rougher, large mill performs major slab deformation.
26. SLAB YARD ; stockyard for all slabs at start of process.
27. STRIP MILL**** all control aspects of process, e.g. outside electricity supply.
28. VSB; vertical scale breaker, part of the descaling system.

The areas marked with **** are considered as part of the normal manufacturing process and no reference to these areas is considered in the reliability analysis model. This reduces the number of areas under investigation from the original twenty eight areas to a maximum of twenty five areas which can be considered for reliability analysis. These process areas are schematically depicted within Figure 4.1 in the form of a "Process Mimic" which was constructed by the author.

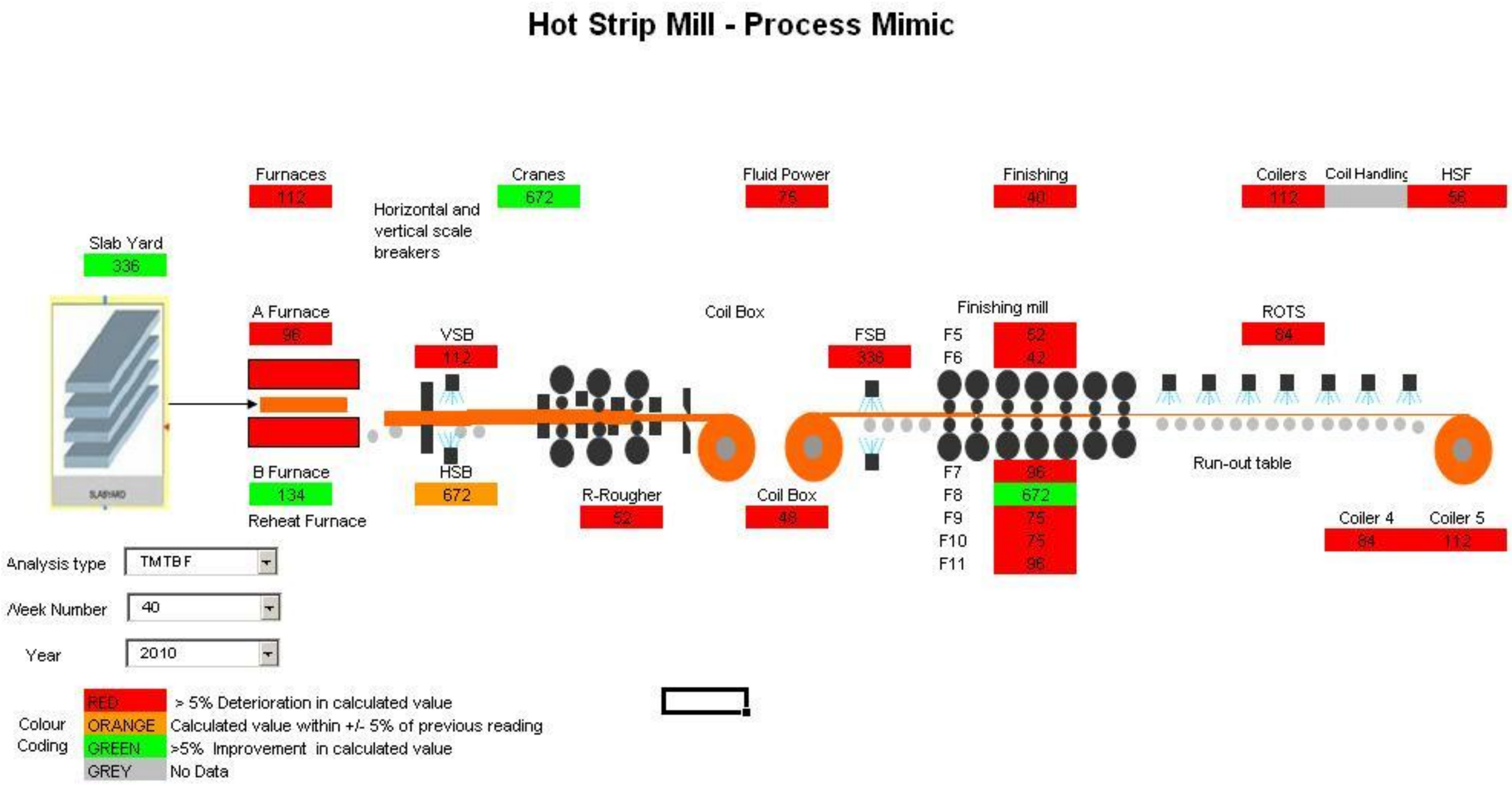
4.1.2 Section 7: CLASS:

There are nine classes in total which include planned and unplanned stoppages for operational requirements or process failures, these abbreviated designations are explained in the following table:

1. ELEC: Stoppage due to an electrical reason.
2. LM: Load management, balancing of work throughput.
3. MECH: Stoppage due to a mechanical reason.
4. NM: Non Mill – process time with no product available.
5. OP: Operational fault.
6. PM: Planned Maintenance.
7. QC: Quality Checks on product.
8. RC: Roll change- normal process change.
9. RS: Roll stoppage, no rolls available for process.

These areas are classified in the database to segregate the stoppage time attributable to the standard mill operation from all other operational influences. For the purpose of the reliability analysis the author has decided that there are two classes relevant which are relevant to actual operating machine or system failure, these are the MECH & ELEC classes.

During the course of this Thesis there were four year to date workbooks constructed by the author, these were copied from the original "year to date" spreadsheets and saved in a separate folder, they are named as: YTD_2007, YTD_2008, YTD_2009 and YTD_2010.



Hot Strip Mill - Process Mimic

Analysis type: TMTBF

Week Number: 40

Year: 2010

Colour Coding		
	RED	> 5% Deterioration in calculated value
	ORANGE	Calculated value within +/- 5% of previous reading
	GREEN	>5% Improvement in calculated value
	GREY	No Data

Figure 4-1 Process Mimic of the Hot Strip Mill

The reliability monitoring method produced was required to perform analyses over the short and long term operating periods. Therefore the year to date sheets 2007-2009 were used for the majority of analysis tests to identify long-term trends, the 2010 dataset was used to update and test the analysis model and to ensure smooth operation. The original database spreadsheet was changed for Year 2011 to a web based format. However the latest format is still compatible and similar to the year to date spreadsheets. There are no expected problems in accessing the latest database. This change and the ability of the developed analysis methods to accommodate it, is seen as further justification for the approach taken to construct the Tata Reliability Analysis Modelling method (TRAM) by the author.

4.2 Database Interrogation and SORTED Workbook Compilation

The automatic interrogation of the year to date spreadsheet constructs an intermediate spreadsheet known as the SORTED workbook. This workbook forms part of the Tata Reliability Analysis Model (TRAM) operating methodology. It is expected that technical specialists in conjunction with the mill engineers will use the TRAM method. These personnel although skilled in engineering functions are not expert in reliability analysis, therefore the proposed reliability analysis model is required to be user friendly, and will need minimal training to operate. As the analysis model is constructed in the Excel format the terminology applicable to the Excel program will be applied from this point forward.

> A worksheet is a single Excel sheet within the “workbook” file. Worksheet titles will be in normal text with parenthesis to indicate the application, (e.g. “Info Sheet”).
>
> A workbook is a compilation of Excel worksheets, all workbook names will be in block capitals (e.g. FRONT PANEL).

The adoption of this terminology allows the differentiation between worksheets and workbooks; these are predominantly named after their operating mediums and can have similar titles. A prime requisite for an effective reliability model analysis is an efficient method of data compilation. To facilitate this, the SORTED workbook was constructed to automatically interrogate the year to date spreadsheet and extract the data appertaining to each area. This will allow the compilation of minimal, focussed, failure data sets which will enable the TRAM methodology to work with maximum efficiency.

The initial investigation into the year to date spreadsheet by the author identified that twenty five AREAS in the data sheet are directly linked to the manufacturing process.

In addition only two out of the nine CLASS tags, “MECH” and “ELEC” are directly related to machine or system failure. These unplanned stoppages account for approximately 20% of all recorded stoppages in this manufacturing process per annum. The other 80% of stoppages are predominantly operational or scheduled stoppages. As this research is directly related to unplanned machine stoppages all other stoppages in the year to date spreadsheets were ignored. An additional benefit of the intermediate SORTED workbook is its ability to operate automatically and simplify the TRAM application to the additional manufacturing units within the steel manufacturing plant. The sequential operation of the SORTED workbook is depicted in Figure 4.2.

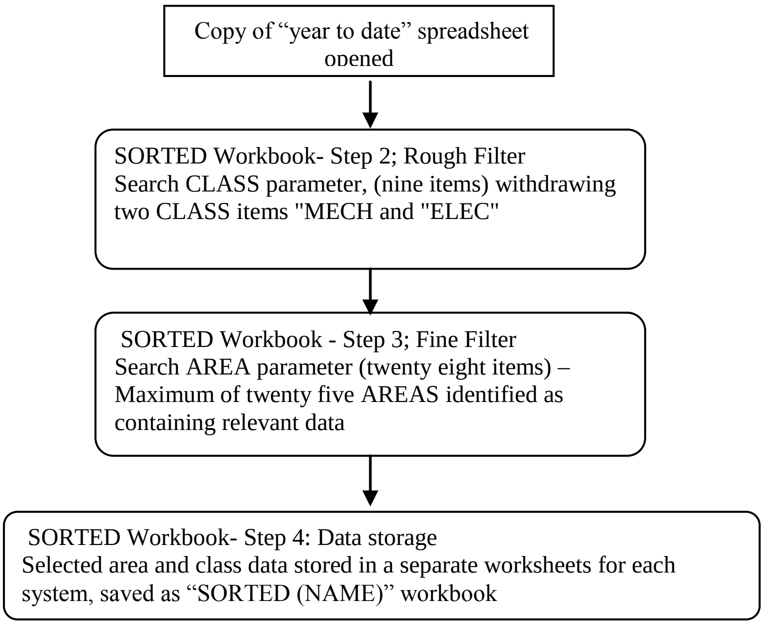


Figure 4-2 SORTED Workbook – Flow diagram

This workbook was designed to be initially compiled by the operator at the start of the analysis. An example of the SORTED workbook’s input data sheet populated with two class parameters and thirteen area parameters is portrayed in Table 4.2. The input sheet (“Info Sheet”) from the master SORTED workbook allows the modification of both the class and area parameters to minimise, or maximise, the analysis if required. This is the only sheet in this workbook which requires operator interaction.

Table 4-2 SORTED Workbook "Info Sheet"

SEARCH	31/12/2009	**CLASS**	MECH	**AREA**	A FURNACE	**PLANT**	Hot Strip Mill
		2	ELEC	13	B FURNACE	**ABBRV**	HSM
					COIL HANDLING		
					COIL BOX		
					COILER 4		
					COILER 5		
					COILERS		
					CRANES		
					F5		
					F6		
					F7		
					F8		
					F9		

Hot Strip Mill operational CLASSES, populated by operator

Hot Strip Mill operational AREAS, populated by operator

This sheet consists of several operating cells:

SEARCH: Consists of the year-end date from the data set being interrogated, this cell is automatically populated by a macro routine.

CLASS: Identifies the number of "Class" operators required, the name cells are populated by the operator, the number cell is populated by the "Sorted" macro.

AREA: Identifies the number of areas required for analysis, fifteen in this example. The title cells are populated by the operator, the number cell is populated by the macro.

PLANT: Cell populated by operator.

ABBRV: Cell populated by operator, the abbreviated name of the plant, is automatically transferred to the saved database e.g. SORTED HSM.

The example shown in Table 4.3 shows the vertical scale breaker (VSB) populated spreadsheet from the automatically saved "SORTED HSM" workbook for year 2007.

The saved SORTED workbook consists of a separate worksheet for each selected AREA, each worksheet is based on the year to date spreadsheet and uses the same headings. These are:

DATE: Start date of stoppage.

SHIFT: Shift pattern being worked at stoppage.

START: Start time of stoppage.

FINISH: Finish time of stoppage.

DURATION: Overall length of stoppage.

AREA: Stoppage area.

CLASS: Stoppage class.

DETAILS: Details on stoppage.

COMBINED: Combined “AREA” and “CLASS” of stoppage.

The SORTED workbook forms part of the TRAM operating method, it is purely a data collation and classification tool, and no analysis is performed within this workbook.

Table 4-3 SORTED HSM – Vertical Scale Breaker (VSB) Spreadsheet

DATE	SHIFT	START	FINISH	DURATION	AREA	CLASS	DETAIL	COMBINED
17/01/2007	D	7:30:00 AM	7:35:00 AM	5	VSB	ELEC	slab stalled on entry tables	VSB-ELEC
17/01/2007	D	10:35:00 AM	10:45:00 AM	10	VSB	ELEC	slab stalled on entry tables	VSB-ELEC
20/03/2007	B	3:58:00 AM	4:20:00 AM	22	VSB	ELEC	slab stuck on dead entry table rollers	VSB-ELEC
26/04/2007	E	4:02:00 AM	5:56:00 AM	114	VSB	MECH	Seized roller on vsb entry tables(slabs skidding)	VSB-MECH
27/04/2007	C	7:00:00 AM	7:20:00 AM	20	VSB	MECH	slab stuck on dead rollers	VSB-MECH
27/04/2007	C	7:30:00 AM	7:50:00 AM	20	VSB	MECH	slab stuck on dead rollers	VSB-MECH
27/04/2007	C	8:40:00 AM	10:15:00 AM	95	VSB	MECH	carrying out repairs to approach table rollers	VSB-MECH
27/04/2007	C	11:06:00 AM	11:12:00 AM	6	VSB	MECH	slab stuck on dead rollers	VSB-MECH
27/04/2007	C	12:00:00 PM	12:26:00 PM	26	VSB	MECH	carrying out repairs to approach table rollers	VSB-MECH
27/04/2007	C	12:48:00 PM	1:02:00 PM	14	VSB	MECH	slab stuck on dead rollers	VSB-MECH
27/04/2007	C	5:24:00 PM	5:32:00 PM	8	VSB	MECH	slab stuck on dead rollers	VSB-MECH
27/04/2007	C	5:45:00 PM	6:09:00 PM	24	VSB	MECH	carrying out repairs to approach table rollers	VSB-MECH
27/04/2007	C	9:46:00 PM	9:54:00 PM	8	VSB	MECH	slab stuck on dead rollers	VSB-MECH
27/04/2007	C	1:00:00 AM	1:06:00 AM	6	VSB	MECH	slab stuck on dead rollers	VSB-MECH
27/04/2007	C	3:50:00 AM	4:02:00 AM	12	VSB	MECH	slab stuck on dead rollers	VSB-MECH
24/05/2007	D	7:41:00 PM	7:47:00 PM	6	VSB	ELEC	ROLLERS NOT TURNING	VSB-ELEC
14/07/2007	B	10:43:00 PM	10:48:00 PM	5	VSB	MECH	entry table roller shaft sheared (no.4 roller)	VSB-MECH
14/07/2007	B	10:50:00 PM	10:59:00 PM	9	VSB	MECH	entry table roller shaft gear box end removed	VSB-MECH
14/07/2007	B	2:16:00 AM	2:20:00 AM	4	VSB	MECH	entry table roller shaft roller end removed	VSB-MECH

4.3 Data Set Manipulation

The construction of the SORTED workbook realised twenty five separate AREA worksheets out of the original twenty eight areas in the year to date spreadsheet. Three of the operating AREAS were identified by the author as not related to machine failure. Twenty four of these worksheets, formatted as in Table 4.3 contain all the relevant data required for the reliability analyses. The twenty fifth worksheet contains no useable data. However as the data sets are presented in a Date/Time format, further work was required to transpose the data into a format suitable for a reliability analysis application. The mathematical models applied to most reliability analyses use the defined data sets to returns the calculated values in several formats such as:

- Failure Intensity (non-dimensional).
- Failure Rates (non-dimensional).
- Time between failures (in various formats) (dimensional).

For practical use in this research it was decided that the “Time between failures” format and its derivatives would be the most suitable method to use. This format is well known in most engineering functions and returns the calculated time between failures recorded in “hours”. This allows the changes in time between failures to be readily identified. The current year to date spreadsheet relies on specific dates coupled with the start/stop time of each stoppage as the recording medium. The corresponding SORTED workbook is similarly constructed. This raises issues with a continual monitoring system, as this recording method is non-uniform requiring deviations to the analysis model to account for month length, leap year etc. For this reason it was decided to choose the operating “week number” as the recording medium. This is consistently logged as a 52 week year with monthly/annual time deviations catered for by adjusting the start date of week 0 of the following year.

The recorded data starts with the year to date 2007 spreadsheet and the 1st January 2007 was chosen as the origin time “0”. By applying the spreadsheets cell “number” format to the date 1/1/2007 returns a registered numerical value of 39083. Performing a similar action on the current date recorded in the Start cell returns a numerical value for this date. Therefore by subtract the origin number from the actual failure date value gives a numerical value for each day’s operation. This method allows any stoppage time to be measured relative to 1/1/2007.

4.4 Data Compilation – Statistical Significance

As described in Section 1.4 all statistical analyses are based on the laws of probability and are therefore not definitive, but rather a “best fit” scenario. They might have been caused by a pure statistical “accident”. Therefore establishing confidence in the calculated result requires the identification of the level of statistical significance of the result. This is determined by calculating the probability that a statistical accident has not happened through identifying the “P” value, which is an estimate of the probability that the result *has* occurred by statistical accident. Therefore a large value of P represents a small level of statistical significance and vice versa. In all statistical analysis it is proper procedure to define a significance level at which verification will be deemed to have been proven. It is important to realise that however small the P value is there is always a finite chance that the result is pure accident. A typical set value of P would be 0.01 means that there is a 1% chance that the result was accidental. This is characterised by the statement $P<0.01$. A significance level which is frequently quoted is $P< 0.05$ this means that there is a 1 in 20 chance that the result was accidental. There is no fixed ruling available regarding significance levels however a $P < 0.01$ value is generally considered significant and a $P < 0.001$ value would be considered highly significant.

Through custom and practise in practical applications it appears that the most widely used significance level is $P< 0.05$ (a 95% confidence level or a 1:20 chance of a statistical accident). The philosophy behind the data compilation exercise is to identify if the failure data sets which are constructed for each manufacturing area (system) are statistically significant. This will assist in choosing the correct analysis methods and verifying that the results obtained are statistically stable. All the analyses in this investigation are tested against the $P<0.05$ criteria.

4.5 Data Compilation – Trend Testing

There are several trend testing methodologies in use for statistical analysis; one of the simplest is the “Laplace test”. This test will be used in the analysis model to test the hypothesis that a trend does not exist within a system. The test can determine whether the reliability related performance of a system is improving, deteriorating or stationary.

The test is implemented by calculating the non dimensional test statistic U, which is approximately a standard normal variable (www.weibull.com//Appendix_

B_Laplace_ Trend_Test.htm). The random variable (test statistic *U*) can be standardised using the theoretical population mean and standard deviation. This parameter can then be compared to the Standard Normal distribution, whose critical value is read from the Standard Normal tables with the required significance level (α). This comparison allows the identification of any trends in the systems performance. (all equations relating to this test were presented in Chapter 2)

4.6 Data Compilation -Goodness of Fit Tests

Most statistical analysis methods assume that there is an underlying distribution to the data set under examination [START 2004] and the assumption that a data set follows a specific distribution can incur serious risk; if the assumed distribution is not correct then the required statistical confidence levels will not be met. In addition the results obtained from any hypothesis testing being implemented could be spurious. There are two ways to check the distribution assumptions:

> Empirical procedures – based on intuitive or graphical properties of the distribution.
>
> Goodness of Fit tests, these tests are described by Walpole [Walpole 2001] as formal procedures to assess the underlying distribution of a data set. The tests are based on statistical theory and can be numerically convoluted. These often require specific software to operate but the results are quantifiable and thus more reliable than empirical procedures It is intended that goodness of fit tests will be implemented for the analysis methods used in the final reliability model. Details on these tests are presented in Chapter 2 and Chapter 5.

4.7 Further Work on Data Compilation

It has been identified by the author that the current data logging method in the Hot Strip Mill is not fully compatible with the demands of a robust system reliability analysis. There are two aspects of the data logging which could require further attention, These aspects are detailed in the following sections, and the issues have been reported to the mill engineers for further investigation.

4.7.1 Duplication of failure events

Upon investigation it has been identified that the year to date data logging methodology at the Hot Strip Mill is not optimal. It is the current accepted working practice for a system to be rebooted after failure and restarted if the reboot is successful. This is regarded as the first “trial” in identifying if the system has failed for a spurious reason or not. This action can allow an individual failure breakdown to be logged more than once in quick succession. This means that the accumulated data set attributed to the system can be perceived as operating more inefficiently than it actually is and means that the data set should be treated with caution. It is realised that it would be difficult to remove this working practise, but it is suggested that all data sets with multiple failures attributed to a single root cause should have duplicated entries removed or an allowance made for multiple entries.

4.7.2 Area data set compilation

As explained in Chapter 4.1 the current database has the manufacturing process derived into twenty five operating areas of which twenty four areas have recorded failure data. These areas are indicated in the reliability block diagram shown in Figure 4.3. This reliability block diagram was constructed as the initial review of the Hot Strip Mill process. The diagram was constructed using the failure data compiled in the SORTED workbook to perform a manual reliability analysis on each area. This initial analysis was carried out using the homogeneous Poisson process to calculate MTBF figures for each area. Whilst performing the initial system reliability analysis it was noted that these areas are primarily allocated to their geographical layout which does not always tally with their process operation. Most are classed as a specific process area, for example area “F5” is dedicated to the mill stand F5.

Support services in the Hot Strip Mill are classed as separate areas, for example Fluid Power is classed as a separate area even though its discrete systems are dedicated to all fluid pumping elements contained in most areas in the mill.

When viewed in a reliability block diagram (RBD) format it can be seen that the method of logging failure data in the Hot Strip Mill regards Fluid Power as a separate area which operates in parallel to the manufacturing process. This can lead to difficulties in deriving the required data for individual systems analysis. In reality it is preferable for Fluid Power, and other similar areas to be broken down into their constituent systems, with each system allocated to their related operational areas.

The next chapter continues the investigation into identifying a suitable reliability analysis methodology for this manufacturing unit and constructing a prototype analysis model for the application.

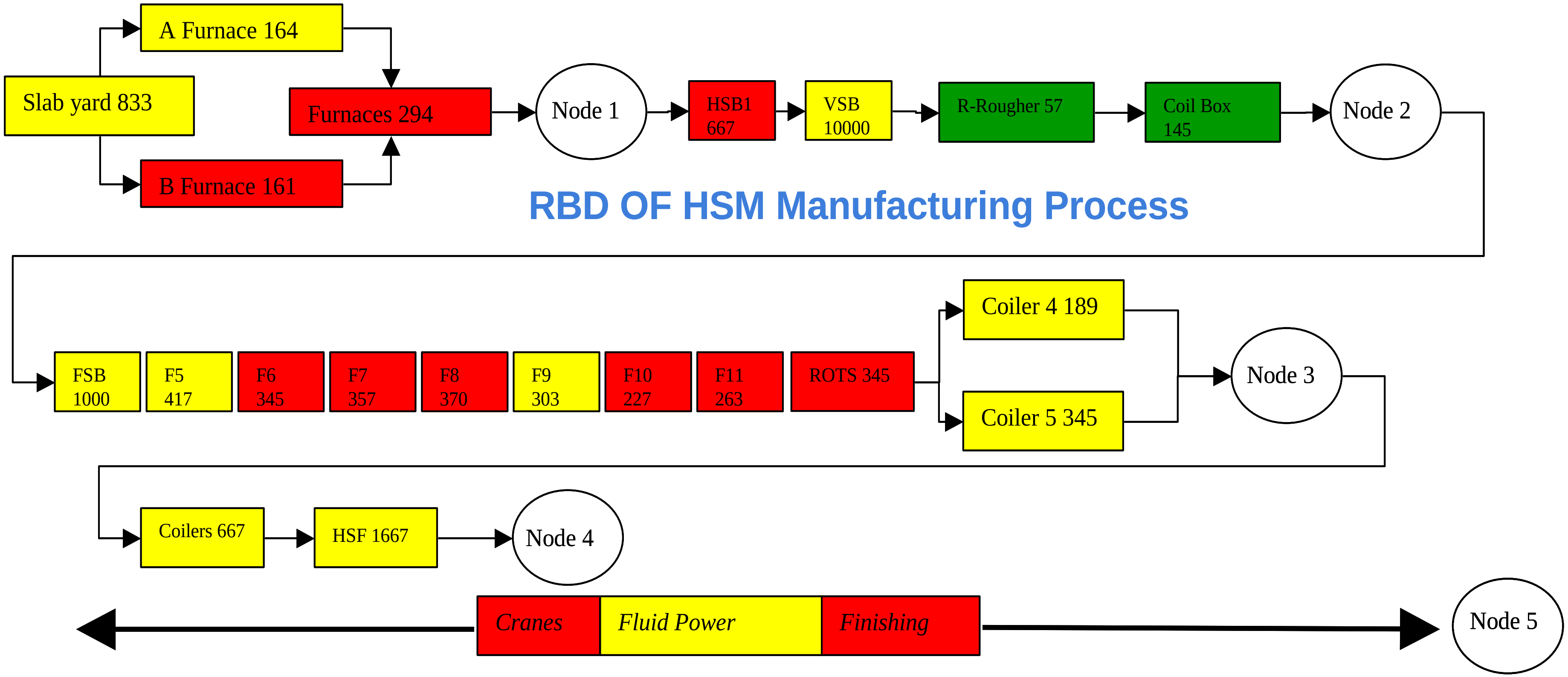


Figure 4-3 Hot Strip Mill – Reliability Block Diagram – all MTBF values are in Hours

5 Reliability Analysis & Modelling - Development

This Chapter describes the construction of the prototype reliability analysis model leading onto a further development reliability analysis model. In addition the statistical testing regime is applied to both models to establish the veracity of the analysis results,

The initial reliability analysis at the Hot Strip Mill was aimed at calculating the reliability indices for the descaling prior to its upgrade. This analysis demonstrated that there was no readily available “reliability calculation” method currently operational anywhere in the Hot Strip Mill. Further research led to the conclusion that calculation of the reliability of repairable systems (i.e. units not replaced upon first failure) is not widely used in the steel manufacturing environment. Rather this analysis area is regarded as a specialism, accessed primarily by experts (consultants) and used for specialised reviews of manufacturing industries. One of the requirements of the descaling system upgrade was to prove that the system’s reliability has improved after the upgrade. This led to the requirement for an analysis model which could compare the system’s reliability pre and post upgrade. The following remit was constructed by the author for the model:

- Construct a reliability analysis model that allows the comparison of different systems through continuously monitoring their reliability performances.
- The reliability analysis model should be portable and transferable to all plant operating areas, making it possible to compare systems on a “plant wide” basis.
- The reliability analysis model must utilise widely available software, require no additional expenditure and require minimal expertise to operate.

5.1 Modelling Techniques for the Analysis of Reparable Systems

The methods suitable for the analysis of repairable systems were reported in the literature review which forms Chapter 3 of this Thesis. Most analysis methods for repairable systems are based on “Poisson” processes but there are many alternatives including basic Monte Carlo methods through to the latest methods using Artificial Neural Networks (ANN). The detailed review identified several practical examples of the analysis of repairable systems in manufacturing industry, these are:

- Weckman et al [Weckman et al 2001] uses a Power Law analysis to model jet engine lifecycle.

- Saldanha et al [Saldanha et al 2001] uses a NHPP model to analyse water pumps in a nuclear power station.
- Garcia et al [Garcia Escudero et al 2005] using a Duane plot (NHPP) for analysing railway aerial networks.
- Tan [Tan 2008] uses a HPP model for a whole life cycle analysis.
- Spinato et al [Spinato et al 2009] uses the Power Law analysis to monitor onshore wind turbines.
- Komal et al [Komal et al 2009] uses a Genetic Algorithm analysis in an Paper mill.
- Marshall et al [Marshall et al 2010] uses a NHPP (Power Law) analysis to monitor the warranty data on several motor vehicles.

This led the author to the conclusion that the Poisson processes HPP, NHPP (Power Law) are the most applicable reliability analysis methods currently being used in this field. A review of the specialist software previously summarised in Table 3.1 identified that the main analysis method used for repairable systems is the NHPP (specifically the "Power Law"). An additional analysis method which has been identified in this review is the General Renewal Process (GRP), which is again predominantly based on the "Power Law" method. From this investigation it was decided that the Poisson processes in general and specifically the HPP, NHPP (Power Law), General Renewal Process have been identified as the most feasible analysis methods available at present. From this review the decision was made to construct a prototype analysis model in a standard operating package based upon these methods.

5.2 Prototype Reliability Analysis Model

The initial stage of the development of a reliability analysis method for this application was to construct a prototype model as a basis for exploring the concept and requirements of reliability analysis at this manufacturing unit. One of the requirements of the model is not to use any additional or bespoke software for the construction or application of the analysis model. There are several fundamental reasons for this decision, these are:

- All of the commercial analysis packages require specialised training to operate, in addition to requiring the operator to have knowledge of reliability analysis techniques. It is envisaged that the reliability analysis operators will be drawn from several areas including technical and maintenance departments. These engineers, whilst having considerable expertise in their relative areas have limited knowledge of reliability analysis techniques. By default the analysis model must be simple to operate and require minimal operator training.

- Thee are multiple databases I n operation at this steel plant, there may be issues with software compatibility

The bespoke software packages require specialist knowledge in order to integrate with, and maintain, a link to the Tata operational databases. The Tata databases are structured to use the software applications in the Microsoft Office program as their reporting mediums and there is limited opportunity to integrate bespoke software packages.

Therefore the decision was taken by the author to construct the prototype model in Microsoft Excel, 2003 version. The program uses a standard file format consisting of several worksheets which can be linked in numerous configurations. After several attempts at model construction the worksheet format depicted in Table 5.1 was chosen as the format for the Power Law analysis method. This worksheet contains all the required formula with links to additional worksheets where required. A separate worksheet similar to Table 5.1 was constructed for each reliability analysis method used. These worksheets were combined to construct the prototype analysis model indicated in Figure 5.1. This model was based on the HPP, Power Law and General Renewal process analysis methods. The methodology of this prototype model was to:

- Perform the HPP analysis as a background check.
- Perform the Power law analysis, if data set proved not suitable through statistical testing.
- Transfer to General Renewal Process, perform statistical testing – if the analysis method was found not suitable refer for further analysis.

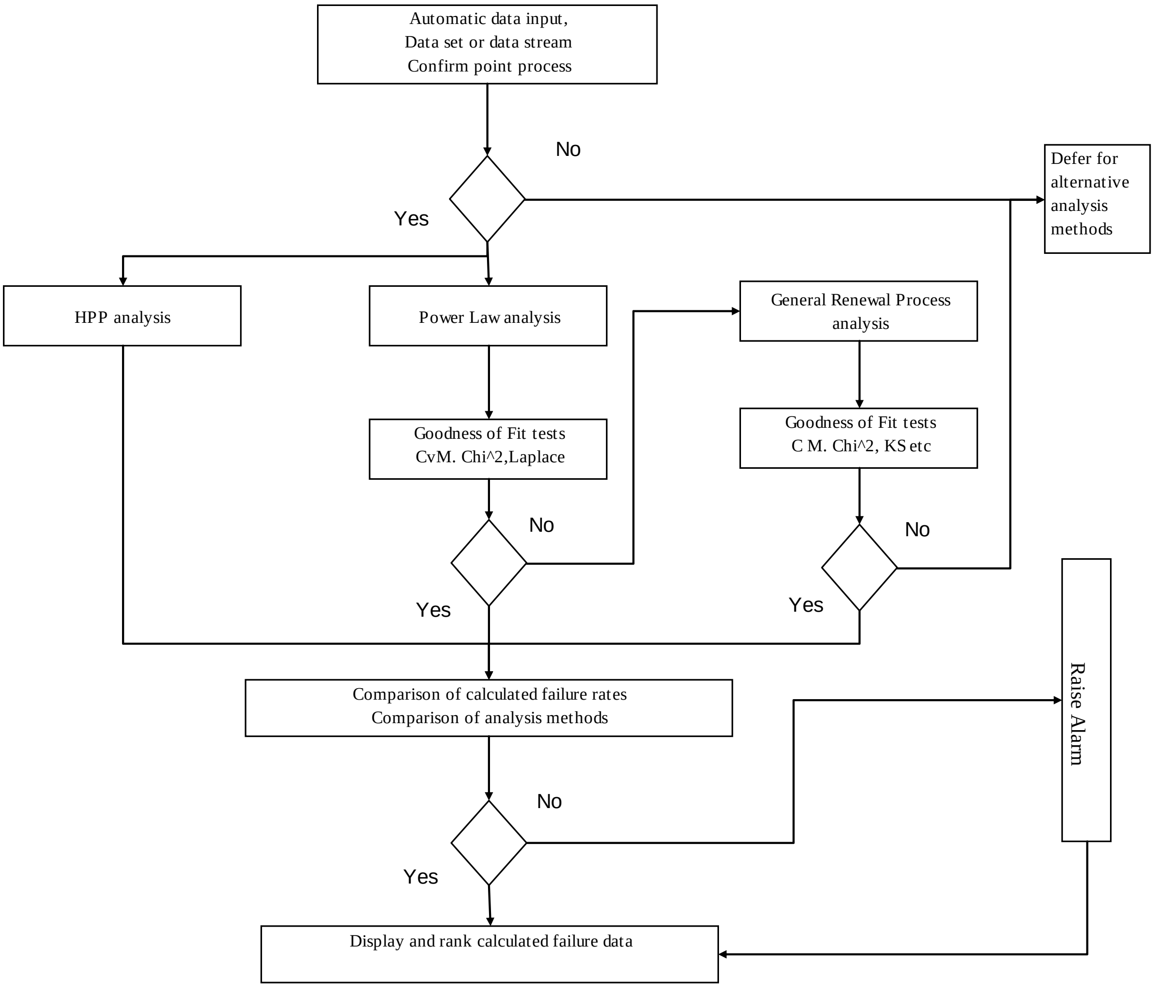


Figure 5-1 Prototype Reliability Analysis Model

5.2.1 Worksheet 1: Homogeneous Poisson Process. (HPP)

Manufacturing facilities often specify MTBF figures when purchasing new machinery or constructing new processes. The manufacturing sites use these reliability indices as guide values when these processes are progressing through their working lives, not realising that technically, these indices are relevant only to processes which are returned to as good as new condition after repair. This has led to the widespread misuse of the MTBF reliability indices in manufacturing, often in the mistaken assumption that the MTBF figure is a calculated value suitable for all applications. It is generally the case that this analysis method is not regarded as suitable for the analysis of repairable systems. The main reason for non-suitability is that the data sets required for the HPP analysis must be statistically independent and identically distributed (SIID). As the repairable system is linked, there must be a statistical inference between the relative systems. Therefore this method was introduced as a comparator for the non-homogeneous Poisson process and a worksheet similar to Table 5.1 which utilised equation 2.6 was constructed for the prototype model.

5.2.2 Worksheet 2: Power Law Analysis

As stated in Section 5.1 this analysis technique is widely used for the analysis of reparable systems, a further examination of Table 3.1 shows that this analysis method is indeed used in most commercial reliability analysis packages. All calculations were formatted into the worksheets (Figure 5.1) and these were run as stand alone applications. A test regime was carried out using data from the year to date data set for years 2007-2009 by manually constructing an additional worksheet similar to Figure 5.1 for each area. In addition a supplementary test regime was carried out using a data set supplied by [Zhao et al 2005] this test regime returned the calculated values of Beta (β) at 0.9298 and Lambda (λ) at 0.2156 from both the prototype model and the commercial software. This test regime confirmed that the prototype analysis model was returning the expected values. After the initial trials with the prototype model were concluded it was identified that this model should be expanded further into the development model.

During the construction of these, worksheet a testing regime was carried out to ensure that the goodness of fit tests was returning the required results. It was found that in the vast majority of cases the data sets were not compliant to the statistical testing regimes thereby negating the possibility that the data set could be transferred from one analysis method to the next until a suitable analysis method is found. The results from these analyses are contained in Table 5.4. This caused a major review on the operating methodology required for the Tata reliability analysis model. This feature along with the correlation of the analysis model has been expanded upon in the Development model discussed in the next section model.

Table 5-1 Analysis worksheet for the NHPP (Power Law) method

Beta > 1 failure rate increasing, Beta = 1 HPP , Beta< 1 Failure rate decreasing
Details taken from Weibull.com Reparable systems- parameter estimation - Power Law models - Data taken from 2007 - 2008 HSM breakdown data supplied by S -Evans

Equations from www.reliasoft.com-practical methods for analysing the reliability of repairable systems										
File	project\Reliabili	**?Ln(*Tq/Xi*)**	26.76849458							
N1+N2+N3	30.0	**N =**	30.0							
time *Tq*	17520.0	**Run Time**	17520							
failure Time -d	*Xi* (hrs)*q*	Ln(*Tq/Xi*)	**b**	1.120720477	Days	Hours	Failure intensity μ-eqn1		Weibull Density	IMTBF
51	1224.0	2.661218901	**λ**	0.000526388	0.041666667	1	0.000589933	0.999473751	0.000589623	1695.10654
52	1248.0	2.641800816	**Tq^β**	56992.2183	7	168	0.001095074	0.848610074	0.000929291	913.180444
55	1320.0	2.585711349			14	336	0.001190649	0.699796866	0.000833213	839.8778307
149	3576.0	1.589098228			28	672	0.001294567	0.460132604	0.000595672	772.4593481
76	1824.0	2.262311194	2007 YTD B Down data		56	1344	0.001407553	0.184892978	0.000260247	710.4526667
79	1896.0	2.223596682	2008 YTD B Down data		84	2016	0.001478164	0.070019253	0.0001035	676.5148404
179	4296.0	1.405658728			112	2688	0.001530401	0.025461139	3.89658E-05	653.4233715
179	4296.0	1.405658728			140	3360	0.001572188	0.008973042	1.41073E-05	636.056421
179	4296.0	1.405658728			168	4032	0.001607175	0.003082204	4.95364E-06	622.2097947
217	5208.0	1.213147181			196	4704	0.001637363	0.00103588	1.69611E-06	610.7380738
241	5784.0	1.108247601			224	5376	0.001663971	0.00034158	5.6838E-07	600.9719189
384	9216.0	0.642401982			252	6048	0.0016878	0.000110747	1.86919E-07	592.4872687
384	9216.0	0.642401982			280	6720	0.001709405	3.53634E-05	6.04503E-08	584.9990443
419	10056.0	0.555173614			308	7392	0.001729186	1.11364E-05	1.92569E-08	578.3066841
424	10176.0	0.543311079			336	8064	0.001747446	3.4625E-06	6.05053E-09	572.2639113
444	10656.0	0.497219972			364	8736	0.001764413	1.0639E-06	1.87716E-09	566.7608733
481	11544.0	0.417177264			392	9408	0.001780268	3.23314E-07	5.75586E-10	561.7130458
481	11544.0	0.417177264			420	10080	0.001795158	9.72447E-08	1.7457E-10	557.0540498
481	11544.0	0.417177264			448	10752	0.001809199	2.8966E-08	5.24052E-11	552.7308375
493	11832.0	0.39253536			476	11424	0.001822488	8.54918E-09	1.55808E-11	548.7003699
556	13344.0	0.27227624			504	12096	0.001835107	2.50139E-09	4.59033E-12	544.9272651
556	13344.0	0.27227624			532	12768	0.001847124	7.25849E-10	1.34073E-12	541.3820959
568	13632.0	0.250923115			560	13440	0.001858597	2.0897E-10	3.88391E-13	538.0401338
586	14064.0	0.219724745			588	14112	0.001869577	5.97099E-11	1.11632E-13	534.8804071
619	14856.0	0.164939261			616	14784	0.001880106	1.69383E-11	3.18459E-14	531.8849812
621	14904.0	0.161713452			644	15456	0.001890222	4.77182E-12	9.0198E-15	529.0384044
628	15072.0	0.150504368			672	16128	0.001899959	1.33537E-12	2.53714E-15	526.3272725
647	15528.0	0.12069824			700	16800	0.001909345	3.71302E-13	7.08944E-16	523.7398857
680	16320.0	0.070951736			728	17472	0.001918406	1.02604E-13	1.96836E-16	521.2659731
689	16536.0	0.057803263			756	18144	0.001927167	2.81838E-14	5.43148E-17	518.8964714
					784	18816	0.001935646	7.69696E-15	1.48986E-17	516.6233437

$$\text{Eqn 3:}\beta = \frac{\sum_{q=1}^{K} Nq}{\sum_{q=1}^{K}\sum_{i=1}^{Nq} Ln\left(\frac{T}{X_{iq}}\right)}$$

$$\text{Eqn 2}: \lambda = \frac{\sum_{q=1}^{K} Nq}{KT^{\beta}}$$

$$IMTBF = \frac{1}{\mu}$$

$$\text{Eqn1: } \mu(t) = \lambda\beta t^{\beta-1}$$

5.3 Development Analysis Model

The development model which followed on from the prototype model contained several additional features such as the automation of all analyses. In addition the model was capable of automatically deploying the goodness of fit tests such as Cramer von Mises and Chi^2 tests. For this model all analysis methods are arranged in parallel and operate simultaneously

The development model consisted of four worksheets similar to Figure 5.1; these were constructed separately due to the significant amount of data that will be worked on. The largest data set to date shows an average of approximately 250 readings per annum. As this analysis method is expected to record up to ten years data it was realised that using a single data sheet would be unwieldy. Therefore a worksheet for each of the following analyses; homogeneous Poisson process, Power Law, General Renewal Process and the Goodness of fit tests was constructed. Each worksheet based upon the prototype model template. The goodness of fit tests, which are required to identify if the data set was statistically significant, were run on a separate worksheet to ensure data integrity. The model was constructed with the HPP and Power Law worksheets directly carried over from the prototype model with some reformatting of the sheet layout. The calculation methodology remained the same and the model was checked after all modifications to ensure that the calculated result remained consistent with the prototype models results. The Flow Diagram for the development model is depicted in Figure 5.2. It is intended for this analysis model to be permanently installed into a manufacturing facilities data management system.

Therefore it was deemed prudent to undertake a period of experimentation to choose the most promising analysis methods available. It was decided to use a bespoke software package to verify the constructed analysis models as the most suitable course of action. After identifying several mainstream reliability software manufacturers (See Table 3.1) it was decided to use the “Reliasoft” programs as the verification tool.

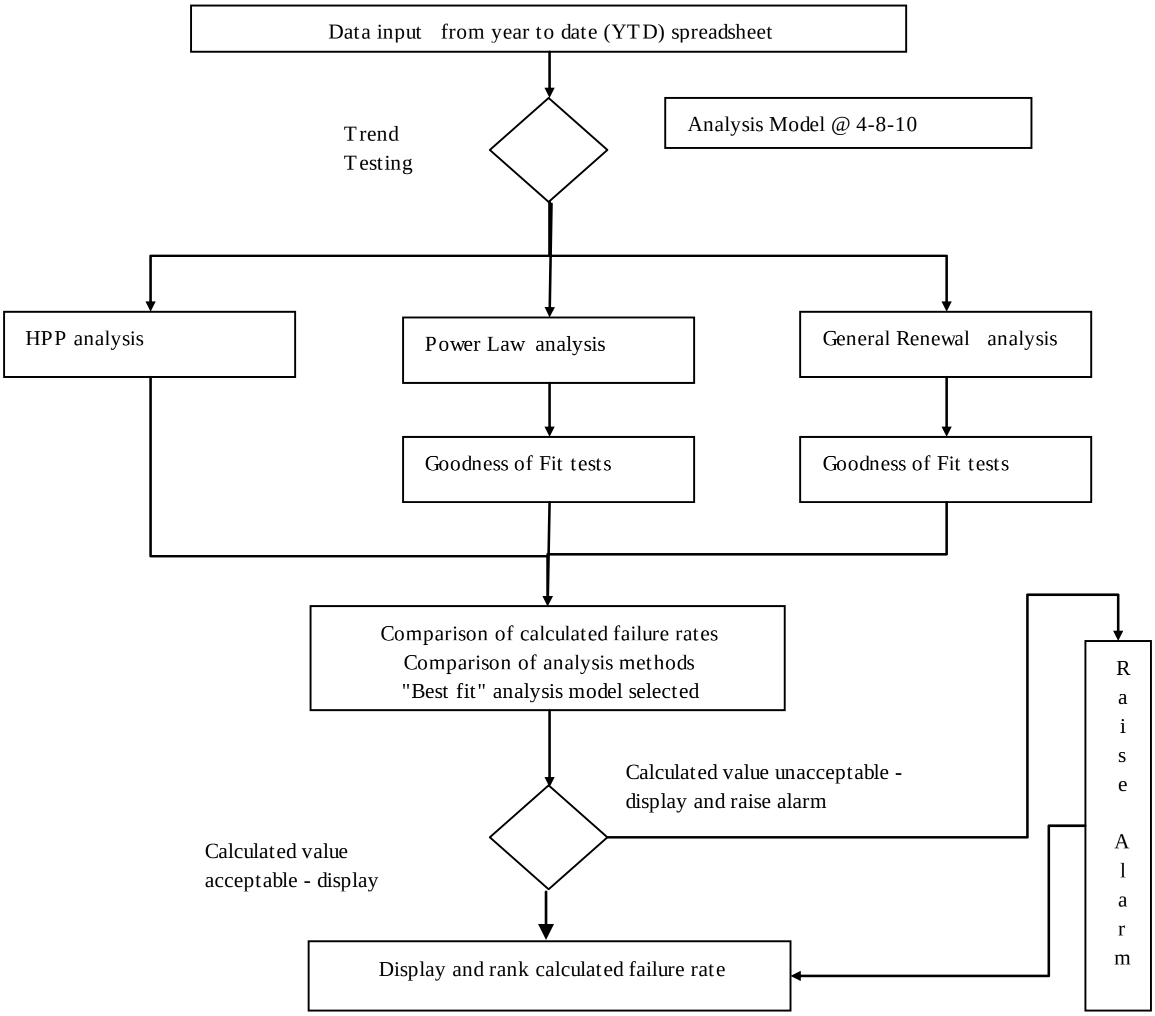


Figure 5-2 Development Reliability Analysis Model

5.4 Power Law Verification Testing – Worksheet 2

The Reliasoft software manufacturer has presented the Power Law analysis method as an analysis tool for repairable systems; the method is represented by Equations 2.9 – 2.12. This analysis method is contained in the “Reliability Growth Analysis” (RGA7) module from the Reliasoft Corporation. This module contained numerous additional features which were not intended for the analysis of repairable systems and a trial version of the module was downloaded to test relevant data sets.

An analysis model was constructed in the format shown in Table 5.2.which depicts the reliability analysis for year 2008 on stand F5. The failure times are taken from the SORTED workbook’s interrogation of the 2008 year to date spreadsheet.

Table 5-2 Development Reliability Analysis Model - Power Law worksheet

Power Law Analysis - Stand F5 year 2008									
			?Ln(*Tq/Xi*)	12.3					
	N1+N2+N3	23	**N =**	23					
	time *Tq*	8760	**Run Time**	8760		Days	Hours	Failure intensity μ	IMTBF
Failure no.	Failure Time - days	*Xi* (hrs)*q*	Ln(*Tq/Xi*)	**β**	1.88				
1	58	1392	1.84	**λ**	9.14E-07	0.04	1	1.7E-06	583016
2	60	1440	1.81	**Tq^β**	25172226	7	168	1.5E-04	6510
3	63	1512	1.76			14	336	2.8E-04	3544
4	124	2976	1.08			28	672	5.2E-04	1930
5	172	4128	0.75			56	1344	9.5E-04	1051
6	172	4128	0.75			84	2016	1.4E-03	736
7	221	5304	0.50			112	2688	1.7E-03	572
8	221	5304	0.50	Start Day		140	3360	2.1E-03	470
9	232	5568	0.45	01/01/2008		168	4032	2.5E-03	401
10	247	5928	0.39			196	4704	2.9E-03	350
11	248	5952	0.39			224	5376	3.2E-03	311
12	285	6840	0.25			252	6048	3.6E-03	281
13	305	7320	0.18			280	6720	3.9E-03	256
14	305	7320	0.18			308	7392	4.2E-03	235
15	305	7320	0.18			336	8064	4.6E-03	218
16	305	7320	0.18			364	8736	4.9E-03	203
17	305	7320	0.18			392	9408	5.2E-03	191
18	305	7320	0.18			420	10080	5.6E-03	179
19	306	7344	0.18			448	10752	5.9E-03	170
20	308	7392	0.17			476	11424	6.2E-03	161
21	313	7512	0.15			504	12096	6.5E-03	153
22	329	7896	0.10			532	12768	6.9E-03	146
23	329	7896	0.10			560	13440	7.2E-03	139

All equations used in the model were extracted from Ascher [Ascher et al. 1984] and cross checked against the Power Law equations provided on the Reliasoft website [www.reliasoft.com-Practical methods for analysing the reliability of repairable systems]. A separate worksheet similar to Table 5.2 was manually constructed for each area. These worksheets were used to compare the twenty-five sets of failure data withdrawn from the year to date spreadsheet's for years 2007-2009 against the Reliasoft commercial software. All failure data sets were run through the development TRAM method and the Reliasoft RGA7 analysis model. As expected, the calculated values obtained for the Beta (β) and Lambda (λ) parameters for all failure data sets are identical.

An additional verification check was made on the instantaneous mean time between failures (IMTBF) calculated values for week 52-2009 on a selection of areas to ensure that this section of the analysis model was operating correctly. The analysis results for these areas were:

A Furnace: IMTBF verified @ 95.85 hrs
B Furnace: IMTBF verified @ 77.74 hrs
Coil Box: Verified @ 96.80 hrs
Coiler 4: Verified @ 81.76 hrs
Coiler 5: Verified @ 152.12 hrs

In conclusion it can be stated that the development TRAM method gave excellent verification with the results obtained from the Reliasoft (RGA7) commercial software module and it is considered that the TRAM method will perform a robust Power Law analysis

5.5 Power Law Analysis – Goodness of Fit Test

In addition to performing a verification check on the Power Law analysis method it was deemed beneficial to perform the corresponding goodness of fit method. [START-2004]. The goodness of fit method installed by the Reliasoft analysis software manufacturer (www.reliasoft.com) and quoted as the most suitable for this analysis method is the Cramer von Mises method. A similar methodology to the Power Law verification testing was carried out using all datasets

5.5.1 Cramer von Mises (CvM) Test

This analysis compared the TRAM method and the commercial software to ensure the verification of all results .The results from the verification tests are depicted in Table 5.4 This test used a worksheet in a similar format to Table 5.2 which was constructed using the Cramer von Mises method (equations 2.25 -2.27). This allowed the calculation of the parametric Cramer von Mises statistic for the entire area failure data sets. As both analysis methods used identical equations this analysis returned the expected result of correlating the Cramer von Mises test in the TRAM method with the results obtained from the commercial software model. Due to most data sets failing the test criteria an additional data set from Zhao [Zhao et al 2005] was included as an additional check. The results from both analyses were identical and are therefore verified. The goodness of fit tests indicated that most of the area data sets were not termed as statistically significant (i.e. unlikely to have occurred by chance) for the null hypothesis to be applicable to the Power Law model. This feature is discussed further in Chapter 5.7.

5.6 General Renewal Process (GRP) Testing

The Reliasoft commercial software manufacturer has presented the General Renewal Process analysis module as a new attempt at using reliability analysis for repairable systems. This manufacturer is the sole supplier of this analysis method and it is presented as an alternative to the Power Law analysis method contained in their RGA7 module.

Table 5-3 CvM Verification Test Using Year to Date 2007-2009 Data

CvM analysis of year to date 2007-2009 data sets							
	TRAM method			failures	Commercial Software		
Using Analysis model 16-2-10	CVM	Limit	Fail		CVM	Limit	Fail
A FURNACE	0.4	0.22	Fail	312	0.4	0.22	Fail
B FURNACE	0.5	0.22	Fail	355	0.5	0.22	Fail
COIL HANDLING	No Data						
COIL BOX	0.51	0.22	Fail	480	0.51	0.22	Fail
COILER 4	1.22	0.22	Fail	254	1.22	0.22	Fail
COILER 5	0.19	0.22	Pass	136	0.19	0.22	Pass
COILERS	0.26	0.22	Fail	125	0.26	0.22	Fail
CRANES	0.25	0.17	Fail	39	0.25	0.17	Fail
F5	0.22	0.22	Fail	121	0.22	0.22	Fail
F6	0.61	0.22	Fail	223	0.61	0.22	Fail
F7	0.25	0.22	Fail	103	0.25	0.22	Fail
F8	0.58	0.22	Fail	119	0.58	0.22	Fail
F9	0.23	0.22	Fail	162	0.23	0.22	Fail
F10	0.62	0.22	Fail	222	0.62	0.22	Fail
F11	0.42	0.22	Fail	199	0.42	0.22	Fail
FINISHING	0.74	0.22	Fail	314	0.74	0.22	Fail
FLUID POWER	0.23	0.22	Fail	100	0.23	0.22	Fail
FSB	1.02	0.22	Fail	82	1.02	0.22	Fail
FURNACES	1.18	0.22	Fail	268	1.18	0.22	Fail
HSB	0.13	0.17	Pass	58	0.13	0.17	Pass
HSF	0.14	0.17	Pass	56	0.14	0.17	Pass
ROTS	0.44	0.22	Fail	162	0.44	0.22	Fail
R-ROUGHER	1.26	0.22	Fail	742	1.26	0.22	Fail
SLAB YARD	0.30	0.22	Pass	125	0.30	0.22	Pass
VSB	1.13	0.22	Fail	48	1.13	0.22	Fail
Zhao - Test	0.09	0.17	Pass	56	0.09	0.17	Pass

The General Renewal Process analysis method is stated as accommodating all analysis types from the HPP through to the NHPP. At face value this analysis method appears to be more flexible than other analysis methods and warranted further investigation. This investigation would identify if this analysis method can be incorporated into the Development analysis model. The General Renewal Process analysis method is contained in the Reliasoft Weibull ++ module,

The General Renewal Process is an adaptation to the Power Law Process through the incorporation of a system “ageing” factor. The earliest applications of this method were proposed in articles by Kijima et al [Kijima et al 1986 & 1989] and expanded upon by Zhao et al [Zhao et al 2005]. The Reliasoft Corporation has developed this method into the commercial analysis software program Weibull ++.

Dr Zhao has been instrumental in facilitating this analysis methods progression into the commercial package. The General Renewal Process addresses the situation where the system falls between the two extremes (as good as new & as bad as old) of repair status by introducing the virtual age (ageing factor υ),:all equations relating to this analysis method are depicted in Equations 2.13-2.18.

The commercial analysis software uses maximum likelihood estimation (MLE) to calculate the variables $\lambda \ \beta \ \ \upsilon$. These values are run through a Monte Carlo simulation to identify the failure intensity $\lambda_i(t)$ and its reciprocal the instantaneous mean time between failures (IMTBF) through identification of the systems “virtual” operating time. As stated earlier the commercial software uses an iterative analysis method the maximum likelihood estimation method, to calculate these variables. This is facilitated by using the natural log likelihood function for the Type1 analysis (Equation 5.1).

$$\ln(L) = \Lambda = n(\ln\lambda + \ln\beta) - \lambda\left[(T - t_n + \upsilon_n)^{\beta} - \upsilon_n{}^{\beta}\right] - \lambda\sum_{i=1}^{n}[(x_i + \upsilon_{i-1})^{\beta} - \upsilon_i{}^{\beta}] + (\beta - 1)\sum_{i=1}^{n}\ln(x_i + \upsilon_{i-1})$$

Eqn. 5.1

The maximum likelihood estimation (MLE) of the three variables is obtained by deriving the partial derivatives from the log likelihood function (Equation 5.3-5.5).The author has recognised that the derivation of the log likelihood function could be carried out in the development TRAM method through the use of programs (macros), utilise the

visual basic for applications (VBA) programming language to automatically calculate the partial derivatives depicted in (Equations 5.2-5.4).
which

$$\therefore \frac{\partial \Lambda}{\partial q} = -\lambda\beta\, t_n\left(T - t_n + qt_n\right)^{\beta-1} + \lambda\beta\, t_n(qt_n)^{\beta-1} - \lambda\sum_{i=1}^{n}\ [\beta(t_i - x_i)(x_i + qt_i - qx_i)^{\beta-1} - \beta\, t_i(qt_i)^{\beta-1}]$$
$$+ (\beta - 1)\sum_{i=1}^{n}\frac{t_i - x_i}{[x_i + qt_i - qx_i]}$$

Eqn.5.2

$$\therefore \frac{\partial \Lambda}{\partial \beta} = \frac{n}{\beta} - \lambda\left(T - t_n + qt_n\right)^{\beta}\ln\left(T - t_n + qt_n\right) + \lambda\,[(qt_n)^{\beta}\ln(qt_n)]$$
$$- \lambda\sum_{i=1}^{n}\ [(x_i + qt_i - qx_i)^{\beta}\ln(x_i + qt_i - qx_i) - (qt_i)^{\beta}\ln(qt_i)\ ] + \sum_{i=1}^{n}\ \ln(x_i + qt_i - qx_i)$$

Eqn. 5.3

$$\boxed{\begin{array}{l}\text{Section 1}\\ \therefore \dfrac{\partial \Lambda}{\partial \lambda} = \dfrac{n}{\lambda} - \left(T - t_n + qt_n\right)^{\beta} + (qt_n)^{\beta}\end{array}} - \boxed{\begin{array}{l}\text{Section 2}\\ \displaystyle\sum_{i=1}^{n}\ [(x_i + qt_i - qx_i)^{\beta} - (qt_i)^{\beta}]\end{array}}$$

Eqn. 5.4

The MLE calculation of each variable is obtained through equating the partial derivatives of each variable to a maximum. However it can be visualised that Equation 5.4 can be separated into sections, where Section 1 can be perceived as a relatively “fixed” value minus Section 2, which is perceived as a (relatively) variable value. All of the partial derivates can be constructed to assume the form of equation 1 – equation 2. The method of deriving the partial derivatives of each variable and their subsequent deconstruction into two sections has led the author to believe that these equations are suitable for the “Solver” application in Excel. This is a bespoke iterative estimation tool, which is designed for the Excel package. The Solver application works by inputting estimated values into the variable’s parameters and equating the control cells to a maximum or minima (zero). The method allows the application of boundary conditions to be applied to all parameters.

The calculations for maximum likelihood estimation values for the three parameters were constructed using this application. It was identified that installing the equations into the worksheet was difficult due to the number of variables in each equation. Therefore the sections of each equation were further deconstructed into separate areas as depicted in Table 5.5, which is an example of the Solver worksheet that was constructed for the reliability analysis method. The control cell was set to attain a maximum by equating the error value to zero). Due to the possibility of negative numbers arising in these calculations the Solver control cell was set as error value squared and all equations used in the model were extracted from Zhao et al (Zhao et al 2005). As with the Power Law test regime, the test data supplied by Zhao [Zhao et al 2005] was included. It can be seen the Solver reliability analysis model depicted in Table 5.5 gave a solution for the reliability indices for the Zhao data set

Table 5-4 General Renewal Process analysis using Solver application (Zhao data set)

Shape Parameters (β) =		**0.9132**		**(hours)**	**365.2**	Total Operating Time (**T**)	
failure intensity (λ) =		**0.2159**		**(hours)**	**365.2**	Total Failure time (Tn)	
Repair effectiveness (q)		**1.0000**			56	No/failures (**N**)	
	Data			**Model**			
Order No.	**Time to**	**Partial β**		**Partial λ**		**Partial *q***	
(i)	**(h)**	**F(t) β -1**	**F(t) β -2**	**F(t) λ -1**	**F(t) λ -2**	**F(t) *q -1***	**F(t) *q* -2**
0	0.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	0.7	0.0000	-0.3567	0.7220	0.7220	-0.1424	0.0000
2	3.7	0.0000	1.3083	3.3028	3.3028	-0.5280	-0.0164
3	10.0	0.0000	2.3026	8.1884	8.1884	-1.0171	-0.0321
4	15.0	0.0000	2.7081	11.8579	11.8579	-0.7793	-0.0579
5	19.0	0.0000	2.9444	14.7149	14.7149	-0.6108	-0.0685
6	24.0	0.0000	3.1781	18.2141	18.2141	-0.7482	-0.0687
7	42.0	0.0000	3.7377	30.3635	30.3635	-2.5657	-0.0496
8	52.0	0.0000	3.9512	36.9024	36.9024	-1.3992	-0.0701
9	55.0	0.0000	4.0073	38.8418	38.8418	-0.4177	-0.0821
10	57.0	0.0000	4.0431	40.1296	40.1296	-0.2776	-0.0838
11	63.0	0.0000	4.1431	43.9701	43.9701	-0.8256	-0.0785
12	72.0	0.0000	4.2767	49.6725	49.6725	-1.2242	-0.0760
13	99.0	0.0000	4.5951	66.4376	66.4376	-3.5725	-0.0631
14	99.5	0.0000	4.6002	66.7440	66.7440	-0.0661	-0.0864
15	100.0	0.0000	4.6052	67.0502	67.0502	-0.0661	-0.0864
16	102.0	0.0000	4.6250	68.2737	68.2737	-0.2639	-0.0851
17	112.0	0.0000	4.7185	74.3611	74.3611	-1.3090	-0.0791
18	112.5	0.0000	4.7230	74.6642	74.6642	-0.0654	-0.0864
19	120.0	0.0000	4.7875	79.1969	79.1969	-0.9759	-0.0814
20	121.0	0.0000	4.7958	79.7994	79.7994	-0.1300	-0.0861
21	125.0	0.0000	4.8283	82.2050	82.2050	-0.5186	-0.0840
22	133.0	0.0000	4.8903	86.9964	86.9964	-1.0317	-0.0816
23	151.0	0.0000	5.0173	97.6881	97.6881	-2.2959	-0.0765
24	163.0	0.0000	5.0938	104.7538	104.7538	-1.5205	-0.0804
25	164.0	0.0000	5.0999	105.3405	105.3405	-0.1266	-0.0863
26	174.0	0.0000	5.1591	111.1910	111.1910	-1.2599	-0.0818
27	177.0	0.0000	5.1761	112.9404	112.9404	-0.3774	-0.0853
28	191.0	0.0000	5.2523	121.0709	121.0709	-1.7497	-0.0804
29	192.0	0.0000	5.2575	121.6496	121.6496	-0.1249	-0.0863
30	213.0	0.0000	5.3613	133.7446	133.7446	-2.5998	-0.0782
Split Eqn. Variable A		0.0000	274.6172	7009.2878	7009.2878	-50.4447	-4.3630
		61.3228	303.6186	259.3761			
Split Eqn. Part A		-242.2958	303.6186	24.1891	235.1870	-46.3700	46.3700
Sum part A Σ		61.32282		259.376		0.000000	
Sum part B Σ		274.617		0.000		46.082	**Sum of Error =**
	Error	-213.294		259.376		-46.082	**0.0**
	Error^2				**Sum of Error Squared =**		0.00

The Solver reliability analysis model was used to calculate the reliability indices for the original twenty-five data sets of failure data compiled from the year to date spreadsheet for years 2007 to 2009 in Table 5.6. All the area data sets were run through the commercial software (Weibull ++ RDA) module, and the resulting quantification of Beta (β) and Lambda (λ) and repair effectiveness factor (*q*) for each area were obtained. The result for the twenty five data sets for years 2007-2009 are displayed in Table 5.6

Table 5-5 General Renewal Process -Commercial software analysis results

Commercial software GRP analysis				Number of Failures
AREA	λ	β	*q*	
A FURNACE	0.588	0.113	4.5E-06	312
B FURNACE	0.510	0.116	7.6E-06	355
COIL BOX	0.544	0.137	2.6E-05	480
COILER 4	0.588	0.085	1.7E-05	254
COILER 5	0.614	0.048	0.0E+00	136
COILERS	0.462	0.121	7.6E-06	125
CRANES	0.788	0.006	0.0E+00	39
F5	0.567	0.062	6.4E-06	121
F6	0.464	0.158	5.0E-06	223
F7	0.698	0.024	3.0E-06	103
F8	0.644	0.037	1.0E-06	119
F9	0.551	0.084	2.0E-04	162
F10	0.572	0.085	5.8E-06	222
F11	0.558	0.085	3.5E-06	199
FINISHING	0.744	0.042	1.9E-06	314
FLUID POWER	0.504	0.080	2.6E-06	100
FSB	0.479	0.086	9.1E-07	82
FURNACES	0.450	0.190	1.4E-05	268
HSB	0.441	0.092	3.0E-06	58
HSF	0.471	0.073	1.4E-06	56
ROTS	0.538	0.086	5.6E-06	162
R-ROUGHER	0.618	0.142	7.5E-03	742
SLAB YARD	0.416	0.168	1.3E-05	125
VSB	0.255	0.379	3.9E-05	48
Zhao Data set	0.930	0.216	1.0E+00	56

In order to qualify the Solver reliability analysis model a test regime consisting of three approaches was constructed. This test regime used the selected data sets.

5.6.1 Test 1: Zhao Data Set

This test used the Zhao data set which is presented in Table 5.5. This example was chosen because this data set that has previously assessed against both the Power Law and General Renewal Process reliability analysis by third parties. The analysis was completed using the following methodology:

- Calculate the Power Law reliability indices using the TRAM method and the commercial software -Reliasoft RGA7 module.
- Calculate the General Renewal Process reliability indices using the Solver reliability analysis model and the commercial software - Reliasoft Weibull ++ RDA module.

This data set was run through the various analysis methods and the following results displayed in Table 5.7 were obtained

Table 5-6 Analysis comparison table for Zhao data set

	Commercial Software Power Law Analysis (RGA7)	TRAM method Power Law	Commercial Software General Renewal Process Analysis (RDA)	General Renewal Process Analysis Results from Zhao paper (Kijima 1)	General Renewal process Solver reliability analysis model
β	0.9298	0.9298	0.9132	0.9132	0.9136
λ	0.2156	0.2156	0.2339	0.2339	0.2432
q	1.0000	1.0000	1.0000	1.0000	1.0000

The results from the commercial software verified the Power Law values obtained from the TRAM method. As this method is classed as returning the system to as bad as old status the *q* value for both Power Law analysis methods is taken as 1 as stated in Section 2.4.4.

The General Renewal Process analyses returned calculated parameters that displayed less than 0.05% difference in the values obtained for both Lambda (λ) and the repair effectiveness factor *q*. The Beta value displayed a percentage differential of approximately 4%. The differences recorded in these figures could be attributed to

- Differences in the calculation methods used within in the programs. It is not known if there is a modified algorithms incorporated in the Zhao analysis method which could be different to the Solver analysis method.

- Quoted figures from the Zhao paper are to four decimal points, The details of the Zhao analysis method are not known however the Solver method is calculated to > 8 DP

Further analyses of the cumulative failures against failure times for this data set are depicted in Figure 5.3.

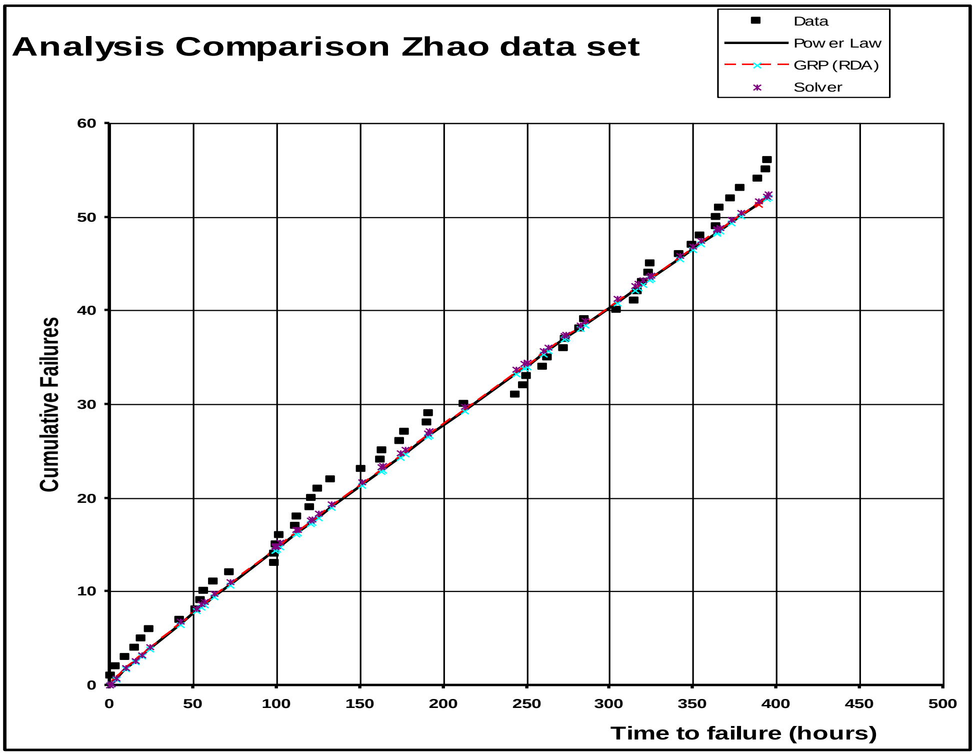


Figure 5-3 Reliability Analysis Methods Comparison for Zhao Data Set

This examination indicated that all of the analyses methods display little differences between their calculated approximations and that actual failure times for this data set. This initially indicated that the General Renewal Process analysis method may be feasible for the reliability analysis application at the Hot Strip Mill, and that the excel based, Solver reliability analysis model (Indicated by the * in Figure 5.3) may be a feasible alternative to the commercial General Renewal Process (Weibull ++ RDA) software module.

To authenticate this discovery it was decided to instigate a further testing regime with alternative data sets to identify how the Solver reliability analysis model and the commercial software would perform under different circumstances

5.6.2 Test 2 Goodness of fit Testing Using Commercial Software

The commercial package has the ability to calculate the confidence bounds of every General Renewal Process analysis. By setting the two sided confidence boundary limits at 95% for the test program and using a visual examination of the data plots it was noted that the statistical data was not a good fit on over 60% of the original data set. This was expected after the earlier goodness of fit test exercise carried out using the Cramer von Mises (CVM) test procedure (Table 5.4) for the Power Law analysis method indicated that over 80% of the failure data sets for the operating period 2007-2009. did not pass the goodness of fit test criteria.

An investigation into the Coiler 5 data set (Figure 5.4) indicates a borderline failure case with the cumulative values exceeding the confidence bounds (bottom CB line – Figure 5.4 – Area 1) at approximately 5,500 hours operating time, however the later values are well within the calculated confidence limits.

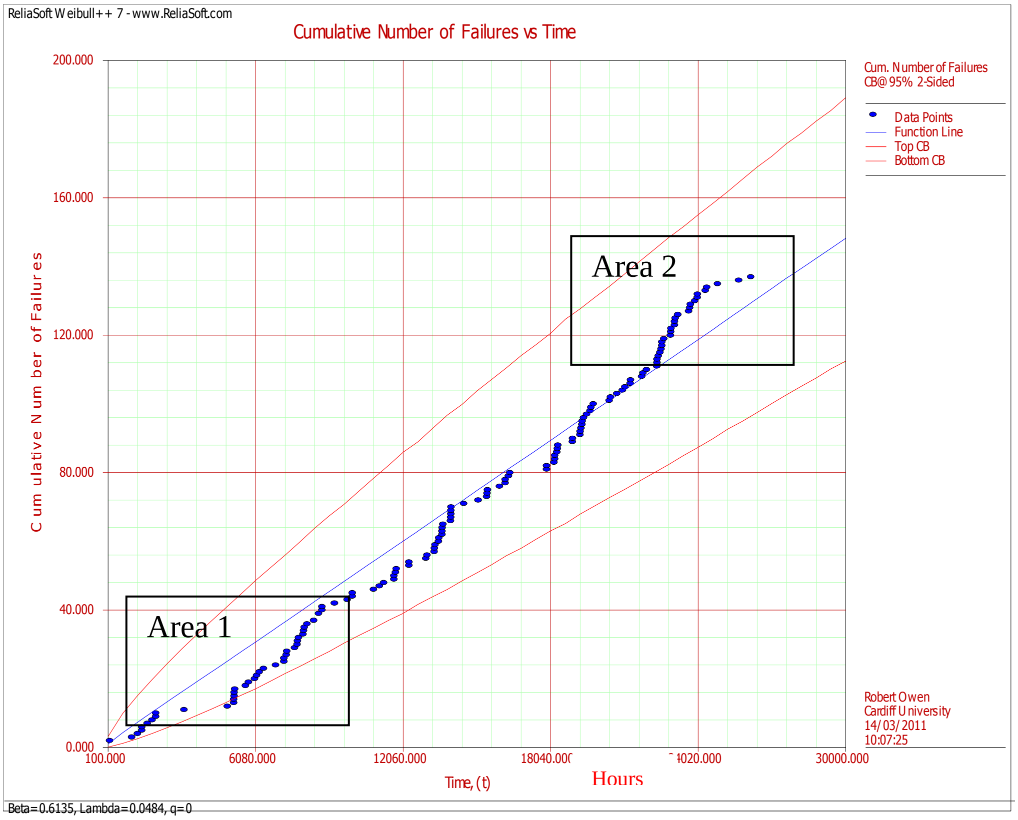


Figure 5-4 Weibull ++ RDA plot of Coiler 5 data set, Cumulative Failures versus Time (Hours)

It was noted that although this model did modify the calculated instantaneous failure intensity with respect to time (t), it was slow to react to changes in the systems condition or in the operating parameters in certain circumstances.

This can be seen by examining Figure 5.4 at Area 2, the points before and after the 24000 hours operating time period. The cumulative failures data points show a significant difference to the calculated function line. This is examined further in Table 5.8, which is a manual comparison of the number of breakdowns recorded on Coiler 5 for every four week period against the calculated IMTBF which is taken from the calculated reliability indices. It can be seen that between the 23520 and the 24192 operational hours the number of breakdowns dropped from six per four weeks to two per four weeks, however the IMTBF remains constant at 344 hours. This is confirmed by examining other four week periods. This example identifies that even though the number of breakdowns can fluctuate significantly within a four week periods, the General Renewal Process does not appear to react to these short term fluctuations and performs more as an averaging function.

Table 5-7 IMTBF Values for Coiler 5

Coiler 5 breakdown data from GRP analysis			
Operating time (Hrs)	calculated failure intensity	IMTBF	Actual Breakdowns in 4*week period
23520	0.0029	344	6
24192	0.0029	344	2
24864	0.0029	344	1
25536	0.0029	344	1
26208	0.0029	344	1

This can be confirmed from Figure 5.5 which indicates a straight line function for the General Renewal Process analysis on the Coiler 5 data set. It can be seen from Figure 5.5 that the commercial GRP RDA model does construct the best approximation for this data set when compared to the TRAM method (Power Law) and the Solver reliability analysis model (Solver GRP). However when comparing the analysis methods it can be seen none of the models accurately reflect this failure data set. The Power Law method gives a close approximation up to 10000 hours then deviates away from the cumulative failure values. The Solver GRP method initially performs a poor approximation and intersects the cumulative values at approximately 22,000 hours whilst the commercial

GRP (RDA) software does appear to give the best overall fit. As shown in Table 5.8 this method will not account for short term fluctuations in failure numbers.

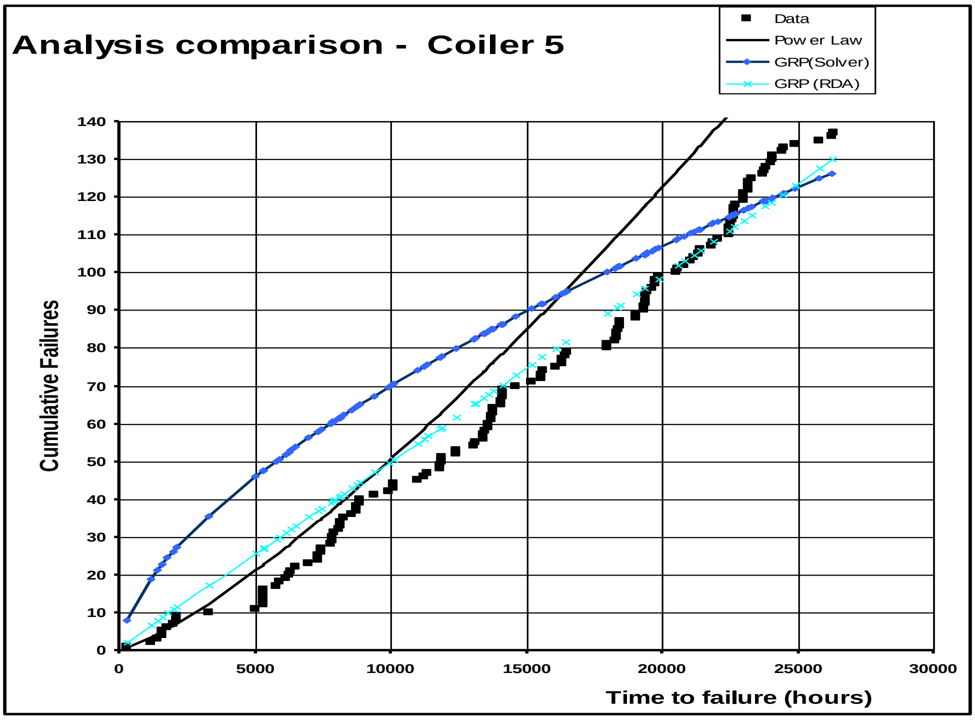


Figure 5-5 Analysis Comparison of Coiler 5 Data Set

5.6.3 Test 3 Vertical Scale Breaker (VSB) Data Set Testing

A further testing regime using the VSB data set was instigated to indentify how the General Renewal Process Model would react when analysing a highly non uniform data set. This data set fails the earlier Cramer von Mises test which was applied to check its goodness of fit to the Power Law analysis method. This data set contains a diverse breakdown pattern which records over 35 breakdowns in approximately 8000 operating hours (Area 1- Figure 5.6) dropping to 12 breakdowns in the following 8000 operating hours (Area 2 Figure 5.6).

It can be seen in Figure 5.6 that this data set is near or over the confidence limits (top confidence boundary (CB) line Figure 5.6-Area 2) from approximately 6,000 operating hours up to 18,000 operating hours, the majority of the operating period. From this it is deduced that the General Renewal Process model can not perform a good approximation of this failure data set.

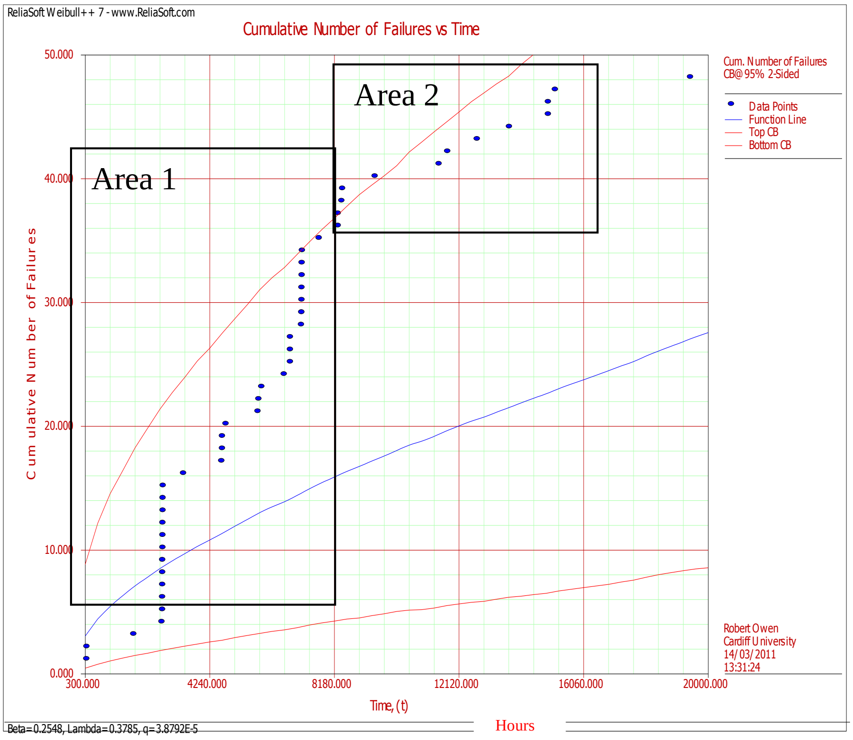


Figure 5-6 Confidence Boundaries on Vertical Scale Breaker (VSB) Analysis

The additional comparison of the commercial General Renewal Process (RDA) analysis method to the TRAM method (Power Law) and the Solver reliability analysis model (GRP Solver) is indicated in Figure 5.7.

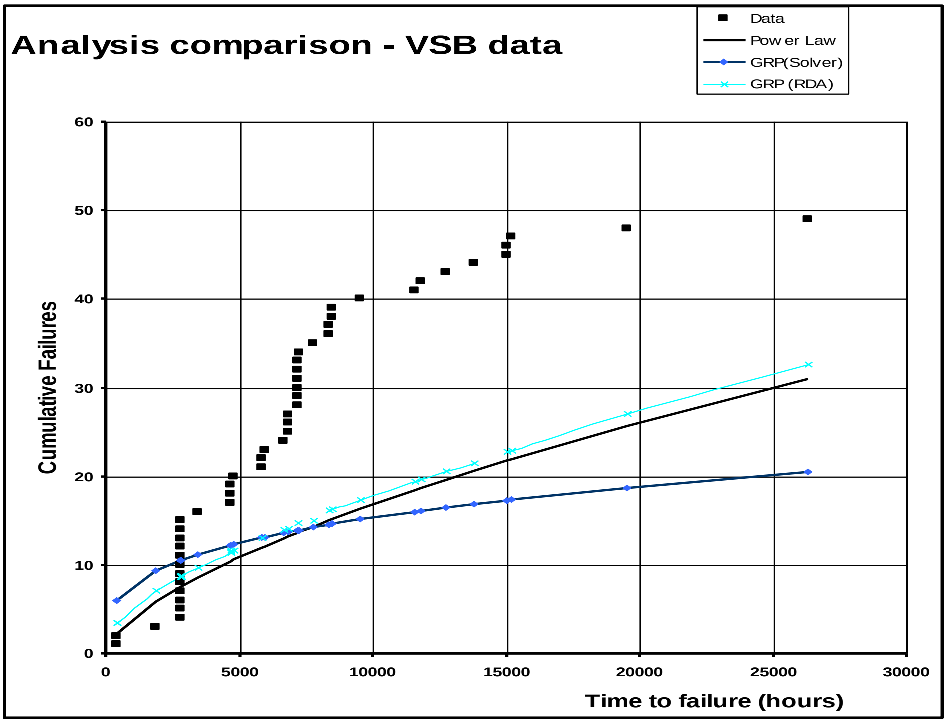


Figure 5-7 Comparison of Vertical Scale Breaker (VSB) Analysis Methods

Figure 5.7. shows that it constructs a similar approximation to the Power Law for this data set. In addition the Solver approximation performs comparatively poorly in this test regime compared to the Power Law and RDA calculated parameters.

5.6.4 Discussion

Early indications led to the belief that the incorporation of the ageing factor (υ) in the General Renewal Process model would allow it to be more flexible than the Power Law and HPP methodologies. This would allow this method to be used for all analysis requirements and could be superior to the stand alone HPP and NHPP models. The initial test regime indicated that this analysis method could be flexible enough to accommodate the ranges of failure data being compiled at this manufacturing facility.

This would allow a full system analysis to be carried out, with possible corroboration by goodness of fit tests which would give statistical confidence in the calculated results. However further examination through the additional testing regimes have indicated that this is not the case, with the Coiler 5 data set indicating that the General Renewal Process analysis method is unable to capture short term fluctuations in failure data. This is further illustrated by the applications of the analysis methods to the vertical scale breaker (VSB) data set. This data set has been chosen as an extreme example of the dysfunctional data sets which can be found within this manufacturing area. This data set is explored further in Section 5.7.3.

The Reliability Analysis method under construction will be required to accommodate data of this type automatically, continue with the analyses and inform the operator that there are significant discrepancies in the data set under examination. The closest model found to correlate this data set is the Weibull bi-modal analysis, which shows a good depiction of the change in operating methodology. It can be seen from figure 5.7 that the commercial software General Renewal Process analysis model (RDA GRP) model is not a good fit to the data and has tried to construct a best fit line which is similar to the TRAM method (Power Law). The analysis models chosen for this machine reliability monitoring regime are expected to become part of an automated program and it is concluded that the General Renewal Process does not have sufficient flexibility to accommodate all of the data types which will be presented to it. The current Solver reliability analysis model (GRP-Solver) is regarded as inferior to the TRAM method (Power Law) and the commercial software (GRP RDA) analysis methods. In conclusion, the above findings indicate that:

- The General Renewal Process analysis method does not have any substantial benefits above the Power Law analysis method in this application.
- The General Renewal Process analysis method is significantly more complicated in its operation than the Power Law Method.

It is considered that that it will be more difficult to integrate the commercial software General Renewal Process (GRP-RDA) module into the Hot Strip Mill data recording system. Therefore the General Renewal process will not be implemented as an analysis tool at the Hot Strip Mill and the consideration is made that an alternative analysis method may be more suitable for this application.

The next section reviews the statistical significance of the failure data sets under examination and considers how this feature must be accommodated in the application of reliability modelling to this manufacturing scenario. This feature will act as a control specification for the final reliability analysis model.

5.7 Statistical Testing Regimes applied to the failure datasets

It can be seen from the plant Reliability Block diagram depicted in Figure 3.2 that the steel processing plant consists of multiple systems. These are predominantly of differing construction. However there are certain sections of the process which are of similar construction working under similar but not identical operating conditions. The remainder of the process consists of bespoke systems which are considered as unique for this testing phase. This has led to the assumption by the author that all machine systems within the Hot Strip Mill can be perceived as stand alone units. As stated in the earlier examination using the Cramer von Mises test regime in Section 5.5, many of these data sets appear not to be statistically significant. Therefore additional test regimes have been utilised to confirm the earlier Cramer von Mises results. Several of these tests utilise the null hypothesis, which while indicating the probability that a result does not happen, does not infer than a result does happen.

5.7.1 Laplace Trend Test

The Laplace trend test considers the hypothesis that a trend either does, or does not exist within the dataset under examination, the test is applicable to multiple and repairable systems. All details on this test are contained in Chapter 2

It can be seen that all trend values returned by the Laplace test values confirm the failure trends identified by the Power Law process.

However when considering that the returned Laplace values are in the region of zero and the Standardised Normal value for a 95% confidence interval is + 1.96 or -1.96, it can be identified that these failure patterns do not conform to a Normal distribution pattern and are not significant to a 95% level. Therefore this test can correlate the earlier result from the Cramer von Mises testing in Section 5.5 and confirm that the Hot Strip Mill failure data sets for the years 2007-2009 are not statistically significant. The implications of this result are further explored in the following sections.

Table 5-8 Laplace Test Results for Years 2007-2009

HSM original data set 2007-2009 inclusive				
	Laplace value	Laplace Failure rate trend	Power Law failure rate trend	No of failures
A FURNACE	-0.0005	decreasing	decreasing	312
B FURNACE	-0.0003	decreasing	decreasing	355
COIL BOX	-0.001	decreasing	decreasing	480
COILER 4	0.0015	increasing	increasing	254
COILER 5	0.0013	increasing	increasing	136
COILERS	0.002	increasing	increasing	125
CRANES	0.0015	increasing	increasing	39
F5	0.0005	increasing	increasing	121
F6	0.0021	increasing	increasing	223
F7	0.0012	increasing	increasing	103
F8	-0.0011	decreasing	decreasing	119
F9	-0.0006	decreasing	decreasing	162
F10	0.0014	increasing	increasing	222
F11	0.000085	increasing	increasing	199
FINISHING	-0.002	decreasing	decreasing	314
FLUID POWER	-0.0008	decreasing	decreasing	100
FSB	0.003	increasing	increasing	82
FURNACES	-0.0018	decreasing	decreasing	268
HSB	-0.002	decreasing	decreasing	58
HSF	0.005	increasing	increasing	56
ROTS	-0.002	decreasing	decreasing	162
R-ROUGHER	-0.0006	decreasing	decreasing	742
SLAB YARD	-0.0021	decreasing	decreasing	125
VSB	0.01	increasing	increasing	48
Laplace value (criteria)	zero (0)		constant failure rate	
	negative values		decreasing failure rate	
	positive values		increasing failure rate	

5.7.2 Chi^2 testing

This test procedure, which is fully described in Chapter 2, is applicable to several distribution types. In this testing regime the test is applied to the Weibull distribution and uses the Solver application for calculating the shape factor β and the characteristic life α for the Weibull distribution.

Table 5-9 Chi^2 Table for the Vertical Scale Breaker (VSB) Data Set

Chi^2 test for VSB data set (2007-2009) - Weibull Distribution														
No.	Failure (T)	Median rank	Weibull dist	Error^2 (S.E.)					Mean	6642				
1	391.50	1.446	0.814	0.400					Std.Dev.	4242				
2	394.58	3.512	0.825	7.224	1.6380847	β	Shape factor		*N*	48				
3	1875.97	5.579	10.098	20.425	7364.2	α	Characteristic Life							
4	2764.03	7.645	18.196	111.334	1330.7	Sum.Err^2								
5	2791.00	9.711	18.459	76.533					Cum Prob	Exp. No.	Actual No.	Chi Squared		
6	2791.50	11.777	18.464	44.717			10	2796	0.185	9	9	Group1	0.0015	
7	2792.67	13.843	18.475	21.459			19	4669	0.377	9	9	Group2	0.0059	
8	2795.10	15.909	18.499	6.708			28	7010	0.602	11	9	Group3	0.2996	
9	2796.00	17.975	18.508	0.284	2796.4		37	8343	0.707	5	9	Group4	3.1801	
10	2796.80	20.041	18.516	2.327			46	14985	0.959	12	9	Group5	0.8035	D.O.F
11	2801.40	22.107	18.561	12.579					1	2	3	Group6	0.5615	=5-1-2 =
12	2801.75	24.174	18.564	31.466										
13	2805.77	26.240	18.603	58.313				Confirm	N	48	48	Sum Chi^2	4.8521	
14	2785.00	28.306	18.400	98.115							Chi Distance		**8.8386**	%
15	2787.83	30.372	18.428	142.653						Chi Distance test checks the probability that this data set fulfills the specified distribution pattern				
16	3451.68	32.438	25.100	53.851										
17	4678.72	34.504	37.853	11.214										
18	4678.83	36.570	37.854	1.648	4668.55	9	No. Groups		1.87(n-1) ^0.4					
19	4658.27	38.636	37.641	0.991			G	5.99	require	8.011	Per group			
20	4794.10	40.702	39.045	2.748				6	Round up	9	Per group			
21	5827.93	42.769	49.421	44.258										
22	5808.57	44.835	49.233	19.349			of group value = End value plus 0.5 next value - end v							
23	5924.40	46.901	50.352	11.913										
24	6635.02	48.967	56.958	63.855										
25	6826.72	51.033	58.656	58.117										
26	6829.18	53.099	58.678	31.124										
27	6829.45	55.165	58.680	12.356	7009.975	9								
28	7190.50	57.231	61.774	20.636										
29	7192.53	59.298	61.791	6.218										
30	7192.78	61.364	61.793	0.185										
31	7197.40	63.430	61.832	2.553										
32	7197.67	65.496	61.834	13.409										
33	7178.83	67.562	61.676	34.641										
34	7210.13	69.628	61.938	59.133										
35	7737.88	71.694	66.192	30.278										
36	8342.65	73.760	70.675	9.519	8343.325	9								
37	8344.00	75.826	70.685	26.438										
38	8454.55	77.893	71.458	41.400										
39	8481.52	79.959	71.645	69.121										
40	9505.80	82.025	78.111	15.322										
41	11528.58	84.091	87.554	11.995										
42	11805.22	86.157	88.540	5.680										
43	12740.73	88.223	91.410	10.157										
44	13756.17	90.289	93.815	12.434										
45	14983.00	92.355	95.928	12.767	14985.183	9								
46	14987.37	94.421	95.935	2.290										
47	15207.42	96.488	96.237	0.063										
48	19483.80	98.554	99.272	0.516		3								

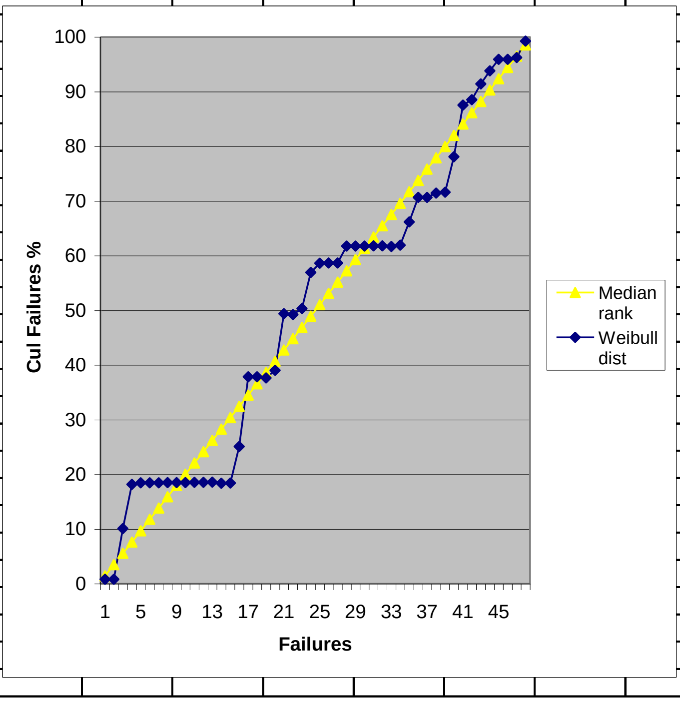


Table 5.10 illustrates an example of the Excel worksheet used to test the Weibull distribution hypothesis. This example uses the vertical scale breaker (VSB) data set for 2007 – 2009. The calculated values for the Chi Distance test shown in Table 5.10 indicates that there is approximately 8.8% probability that this data set corresponds to the Weibull Distribution. This is easily identified by examining the graph in Table 5.10 which shows poor line verification between the Median rank and the Weibull Distribution. This testing regime was implemented on all twenty five data sets relating to the operating years 2007-2009 for the Hot Strip Mill. This resulted in the formation of fifty analysis sheets for this test regime. The calculated results indicate that all the data sets for this period do not fit the Normal or Weibull distribution pattern. A summary review of all the calculated Chi Distance (Probability) values for these data sets is contained in Table 5.11.

Table 5-10 Chi^2 Test Results for 2007-2009 Data Set

HSM original data set 2007-2009 inclusive				
	Chi^2 Distance value Normal distribution	Chi^2 Distance value Weibull distribution	Maximum probability fit for failure distribution	No of failures
A FURNACE	1.25717E-31	1.02725E-44	0.00%	312
B FURNACE	3.67793E-27	1.96915E-23	0.00%	355
COIL BOX	3.33897E-43	1.90803E-34	0.00%	480
COILER 4	8.31951E-33	7.4744E-110	0.00%	254
COILER 5	0.000105373	3.372E-10	0.00%	136
COILERS	3.09782E-16	1.83049E-23	0.00%	125
CRANES	0.068328059	0.000630302	0.07%	39
F5	2.51407E-09	7.91176E-23	0.00%	121
F6	6.05161E-29	1.92861E-34	0.00%	223
F7	3.85399E-09	1.52312E-12	0.00%	103
F8	3.94443E-08	1.45028E-66	0.00%	119
F9	1.40052E-06	3.33832E-09	0.00%	162
F10	5.7004E-21	1.96912E-28	0.00%	222
F11	7.71769E-17	1.13165E-20	0.00%	199
FINISHING	1.05807E-10	0	0.00%	314
FLUID POWER	1.49564E-12	2.37142E-12	0.00%	100
FSB	9.8647E-124	4.2155E-160	0.00%	82
FURNACES	1.41633E-16	3.04632E-08	0.00%	268
HSB	0.010770199	8.92489E-05	0.01%	58
HSF	5.06332E-16	6.81506E-16	0.00%	56
ROTS	2.8359E-15	2.3555E-23	0.00%	162
R-ROUGHER	2.90555E-35	1.73729E-24	0.00%	742
SLAB YARD	2.4565E-191	2.3468E-229	0.00%	125
VSB	1.698809469	8.83860123	8.84%	48
Chi^2 distance criteria	zero (0)		No Correlation	
	100%		Perfect Fit	

5.7.3 Cramer Von Mises Test (CvM)

The equations and working methodology for the Cramer von Mises test are described in detail in Section 2. A more detailed examination of the twenty four systems failure data sets obtained from the Hot Strip Mill operating areas for the years 2007-2009 was carried out using the Cramer von Mises (CvM) goodness of fit test criteria. This goodness of fit test is proposed by the commercial software manufactures as the most suitable for the Power Law process, and is contained in their reliability analysis software. The calculated results are tabulated in Table 5.12.From this analysis on these data sets it can be deduced that:

- 21 out of 24 data sets failed the CvM pass criteria (>90%).
- 8 out of the failed 21 sets were within 20% of the CvM pass criteria.

Table 5-11 Cramer von Mises test results

HSM original data set 2007-2009 inclusive				
Using Analysis model 16-2-10	Original data set			failures
	CVM	Limit	Fail	
A FURNACE	0.350	0.22	Fail	312
B FURNACE	0.457	0.22	Fail	355
COIL BOX	0.511	0.22	Fail	480
COILER 4	1.223	0.22	Fail	254
COILER 5	0.188	0.22	Pass	136
COILERS	0.263	0.22	Fail	125
CRANES	0.246	0.22	Fail	39
F5	0.222	0.22	Fail	121
F6	0.610	0.22	Fail	223
F7	0.252	0.22	Fail	103
F8	0.583	0.22	Fail	119
F9	0.226	0.22	Fail	162
F10	0.623	0.22	Fail	222
F11	0.415	0.22	Fail	199
FINISHING	0.738	0.22	Fail	314
FLUID POWER	0.232	0.22	Fail	100
FSB	1.016	0.22	Fail	82
FURNACES	1.175	0.22	Fail	268
HSB	0.129	0.22	Pass	58
HSF	0.144	0.22	Pass	56
ROTS	0.441	0.22	Fail	162
R-ROUGHER	1.256	0.22	Fail	742
SLAB YARD	0.297	0.22	Pass	125
VSB	1.127	0.22	Fail	48

When examining Table 5.12 it could be assumed that this indicates that the Power Law analysis method is not suitable for the analysis of these systems. However it should be pointed out that these data sets incorporated three years operating practice in a dynamic working environment which has undergone a global recession in addition to the normal changes in working practises. When examining the one of the worst performing areas, the Vertical Scale Breaker (VSB), which failed the CvM test with a score of 1.27 against the CvM Criteria of 0.22 we can identify large changes in the failure data logged for this system in these three operating years. When reviewing this data set we can see that the breakdowns on this system averaged:

- 2007 – 39 breakdowns per annum.
- 2008 – 8 breakdowns per annum.
- 2009 - 1 breakdown per annum.

It can easily be identified that there has been a significant range change in the number of failures per annum for this processing system. Further investigation revealed that this unit was not operated for a significant portion of 2008 and “mothballed” for the year 2009 as it was not required for the process requirements for this period. The unit was not removed from the process; instead it has been retracted away from the process flow.

The failure recorded for 2009 is due to a loose buffer plate impinging on the processed steel slab. From this result the decision was made to analyse selected data sets against the Cramer von Mises criteria on an annual basis and compare the result with the overall CvM results depicted in Table 5.12. This would ascertain whether the Power Law process would be suitable (according to CvM criteria) for system examination on a year by year basis. It can be seen from the examination into the statistical significance of the areas data set in Table 5.13 that each area has at least one annual data set which could be termed statistically significant when judged by the CvM test criteria. This investigation has identified the possibility that the construction of the failure data sets are subject to considerable interference through changes in working practises. This factor is in addition to the identification of errors in failure data compilation through standard working practises at this manufacturing unit.

Table 5-12 Cramer von Mises Analyses of Selected Failure Data Sets

Using Final Analysis model	CvM value for 2007 - 2009 data set	2007 data-CvM Value	2008 data-CvM Value	2009 data-CvM Value
VSB	1.127	0.169	0.077	NA
FURNACES	1.175	0.65	0.67	0.145
FSB	1.016	0.35	0.22	1.2
FINISHING	0.738	0.0609	0.24	0.036
F10	0.623	0.21	0.28	0.59
F6	0.61	0.11	0.72	0.32
CRANES	0.246	0.798	0.05	0.39
FLUID POWER	0.232	0.178	0.163	0.25
F9	0.226	0.78	0.91	0.107
HSB	0.129	0.104	0.24	0.32
HSF	0.144	0.041	0.122	0.41

These factors have led to the decision that there is a considerable risk of these data sets being deemed not statistically significant for any chosen analysis method due to outside inferences. This reasoning is carried forward to include normal changes in the individual systems operating parameters which cannot be easily identified through the normal goodness of fit tests applicable to the analysis method. This research has identified a possible reliability analysis methodology which could be implemented even if the failure data set is not statistically significant. This feature is explored further in the next section

5.8 Discussion

It should be noted that the Hot Strip Mill at Port Talbot is constructed as a continuous production operation. The global financial crises over the period 2008 to the present has required multiple changes in its production requirements, particularly in the 2008-2009 operating period. This has led to many changes in working patterns which are not expected in a normal production scenario. These have included unscheduled stoppages, running below capacity and other changes in working practises, often carried out with minimal notice. These operating changes have been necessary to ensure the financial viability of the manufacturing unit.

It is recognised that the statistical significance is a major feature in identifying the analysis method suitable for a particular failure data set. This is one of the major factors in assessing the suitability of any reliability analysis method for any data set. This feature has led to a tendency to create specialised methods for the reliability analysis of repairable systems. However, it can be expected that a non-normal operating scenario will have a significant impact on the probability of a Normal or other standard distribution pattern fitting the failure data sets being exhibited by these machine systems over any time period. The 2007-2009 operating period has been influenced by special causes, namely the global financial crises. However manufacturing is an unstable discipline which is affected by seasonal and a plethora of other factors.

This initial assessment has confirmed the there is no possibility that there is a currently available reliability analysis method which will fulfil the requirements for a robust analysis on all repairable machine systems. In particular this applies to the Hot Strip Mill at Tata Steel, Port Talbot. However the data presented in Table 5.13 has identified an important function of statistical significance testing. Through dissecting a systems failure data set into annual data sets it is possible to identify if any years failure dataset has attained statistical significance. By default this identifies the corresponding datasets which are not significant and allows the program operator to explore the causes affecting the data sets statistical significance. This feature allowed the author to identify the changes in operating practises on the vertical scale breaker.

5.9 Conclusion

This has led the author to the conclusion that the application of these statistical testing tools to the Hot Strip Mill’s failure data sets has confirmed that there is no single, generic reliability analysis modelling technique currently suitable for their reliability analysis. This is due to the failure data sets observed, not to the statistical testing regimes employed.

However the method of performing statistical testing on each years failure data does allow the assessment of each year’s failure data , and whether it is statistically significant or not. This allows the investigator to delve further into the failure data for the years which have not passed the statistically significant test regime, identifying the causes behind the disjointed failure data and, if possible, inputting remedial actions to ensure that this scenario is not repeated.

On the Reliability Analysis Methods themselves,. The General Renewal Process (GRP) appears to have no appreciable benefit over the Power Law analysis for this application and as outlined in Section 5.6 it often returns a calculated “best fit” line (equation), which is similar to the calculated equation provided by the Power Law Model.

The homogeneous Poisson process (HPP) model is not intended as an analysis model for repairable systems and its requirement for statistically identical and independent (SIID) data sets mean that it cannot be applied in this case.

It is possible that an advanced methodology such an artificial Neural Network (ANN) or similar method could be constructed to monitor these systems. Such a network would have to access the twenty five areas on the first level, and would possible see significant expansion upon the introduction of failure causes etc. However this method would not be easily transferable and would require rebuilding and retraining upon transference to another operating unit. Such modelling techniques require considerable expertise and often demand high specification hardware for efficient operation

Therefore the decision has been taken to identify if there is an approach to reliability analysis at this manufacturing unit which can accommodate this feature. This is explored further in the next section.

This has led to the derivation of a reliability analysis method which, whilst still not fulfilling all statistical criteria, can fulfil this project’s remit. This method involves an overall analysis of the total failure data set and the dissection of these data sets into smaller subsections for further analysis. This methodology is explained in the next chapter. It is the authors belief that this method has not been implemented in any manufacturing environment to date.

6 Tata Reliability Analysis Model (TRAM) - Construction

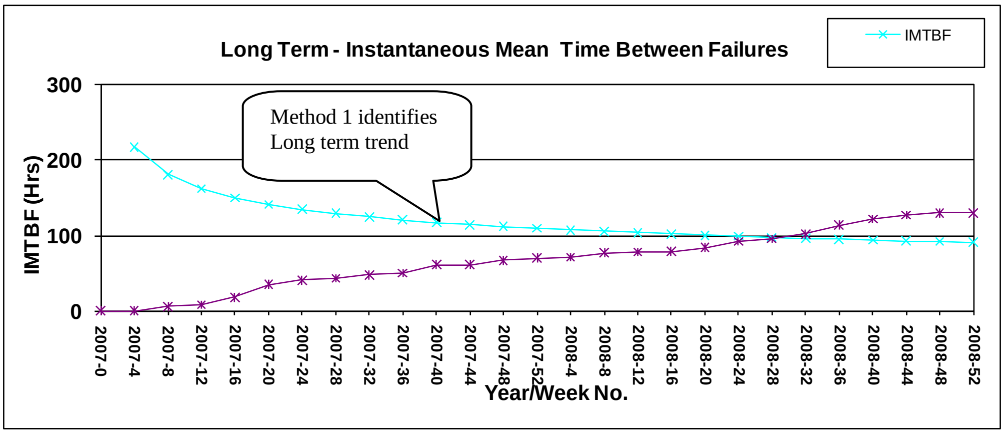
This Chapter shows the reliability analysis model's evolution into the Tata reliability analysis model (TRAM) methodology. The chapter contains details of the TRAM methods construction plus the test regime that is undertaken.

From the previous research and testing described in Chapter 5 it was shown that there is no readily available, reliability analysis method for repairable systems, suitable for accurately tracking and monitoring the machine system's reliability. In particular the fact that the data sets accrued for each system may not be statistically significant leads to the summation that care should be taken examining the results from a single analysis model when applied to all systems.

It is the author's belief that there are two further features that must be added to the model in order to fulfil the Hot Strip Mill's analysis requirements. It should be capable of calculating the time between failures of all systems at a point in time and it will be required to act as a monitoring tool for the individual and combined systems reliability development, whether positive or negative, relative to time increments. This leads to the conclusion that even if an analysis method is not deemed statistically significant, the analyses of multiple systems by a single analysis method could yield important detail on the systems status. In effect the analysis will act as a "comparative analysis" between these systems. This can lead to the identification of significant differences particularly between similar systems under the same operating regime. It can also monitor the effect of any changes to the system, for example changes that could occur following the replacement of a part, element or subsystem.

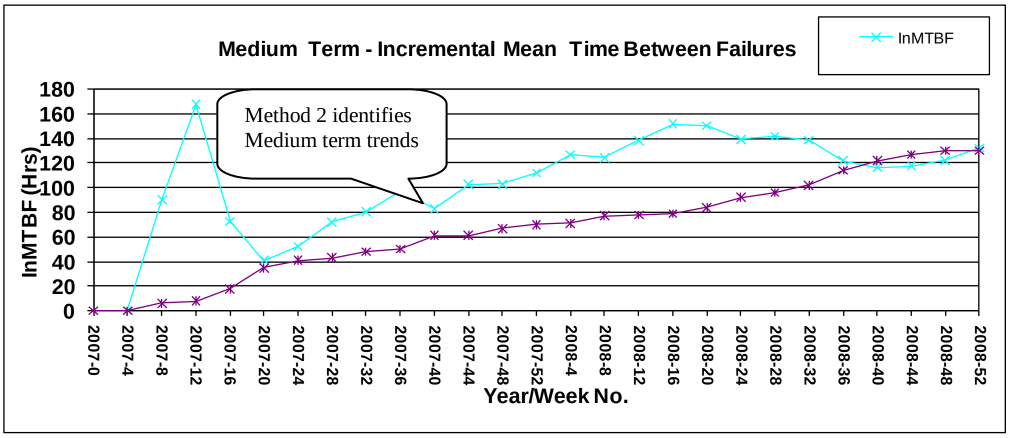
6.1 Derived TRAM Method

It was been decided by the author that a bespoke analysis method could be constructed using the Power Law analysis in combination with additional, complimentary, analysis methods. These analysis methods will be configured to act as a comparator between all of the operating systems in the Hot Strip Mill. It is envisaged that if the goodness of fit tests initially discounts the Power Law method as a suitable analysis medium, further examination of the additional analysis methods will allow the user to identify the probable root causes for the non- significance in the systems data set. Further iterations of the goodness of fit tests will allow identification of the portion of the data that could be influencing the overall goodness of fit test result. In effect this method will provide a means of allowing for the analysis of the cause of the non-significance of the data. Using analysis methods that can focus on specific time intervals within the failure data sets will facilitate this. The operating methodology is depicted in Figures 6.1-6.3:



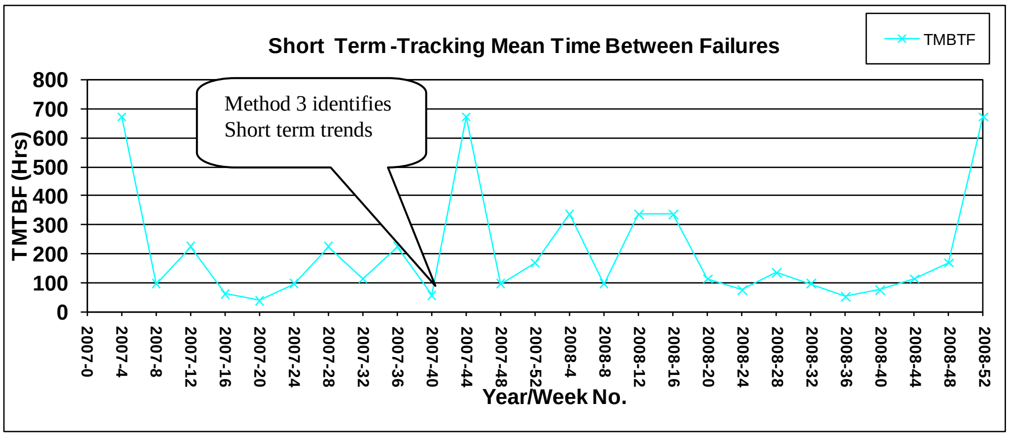
Method 1 identifies
Long term trend

Figure 6-1 Long Term - Instantaneous Mean Time between Failures



Method 2 identifies
Medium term trends

Figure 6-2 Medium Term - Incremental Mean Time Between Failures



Method 3 identifies
Short term trends

Figure 6-3 Short Term - Tracking Mean time Between Failures

The proposed bespoke analysis model combines three separate analysis methods, each of which is based on current reliability analysis techniques, with modifications where necessary:

- Method 1: Instantaneous Mean time Between Failures (IMTBF) used to characterise the long term trend in time between failures, this is the Power Law analysis method (Figure 6.1).
- Method 2: Incremental Mean Time between Failures (InMTBF) used to track the medium term time between failures and identify medium term trends in the systems' operation, based on the assessment of the variation from the application of the Power Law process at four weekly intervals (Figure 6.2).
- Method 3 Tracking Mean Time between Failures (TMTBF) Used to monitor the short term time between failures and identify short term trends in system status over a four week operating period, based on a modification to the homogeneous Poisson process (HPP). This analysis method is not intended to be statistically significant, rather more of a visual aid to identify the short term fluctuations in a systems performance (Figure 6.3).

As stated earlier the majority of operating systems in the Hot Strip Mill, or indeed the whole steel plant, are of indeterminate age and often consist of machinery ranging from almost new (< 1 year old) to several decades old (>10 years old). Most of the data sets in this facility appertaining to machine failure are logged on an annual basis. In order to devise a method which can continuously track the performance of all systems for the foreseeable future a uniform date monitoring/logging system is required. To implement this date monitoring facility it was decided to use the annual "week number" parameter which automatically adjusts for annual date fluctuations by stipulating the year as consisting of "52 weeks" with the start date of week 1 and the end date of Week 52 accounting for leap years and other calendar fluctuations.

This method will allow the engineer to access any time period from the beginning of data installation, which, for convenience, is stipulated as the beginning of 2007. All of the proposed analysis methods access the data sets starting at week 0 (zero) of 2007. All subsequent week numbers are allocated as operating hours worked since week 0. This allows all data sets to be linked by allowing the last week of the previous year (week 52) to be equal to the start week (week 0) of the following year. To ensure continuity the failure data sets for the years 2007 to 2009 are used in every analysis in this chapter.

The three chosen analysis methods are contained in one dedicated “ANALYSIS” Excel workbook, with the individual analyses assigned to separate worksheets within this workbook. The goodness of fit tests and trend testing facilities are also contained within this workbook as shown in Figure 6.4 which is the flow diagram of the Tata Reliability Analysis Modelling (TRAM) method. Each analysis method will now be considered in the following sections.

6.2 Method 1: Instantaneous Mean Time between failures

This method uses the standard Power Law analysis method, which is the most widely, used reliability analysis method applied to repairable systems. This method is incorporated in most commercially available reliability analysis software for repairable systems and is often used as a predictive mechanism for reliability growth. The operating algorithm was described in Equations 2.9-2.12. The operating parameter which is used for this analysis is the Instantaneous Mean Time between Failures (IMTBF).

The IMTBF is a standard term used in this reliability field and is normally calibrated in hours. In this application it is used as a long-term reliability monitoring method used for tracking the time between failures and identifying the overall trend in reliability performance from inception to current status. This reliability tracking method is intended to be beneficial to senior area engineers and higher level plant engineers by allowing them to visually identify the overall top-level reliability trends of the plant, area or system under consideration.

This method does not fluctuate with the relevant breakdown numbers during each four week (672 hours) period, but is intended to identify the overall system reliability trends. This indicates whether the system is undergoing overall reliability growth or deterioration.

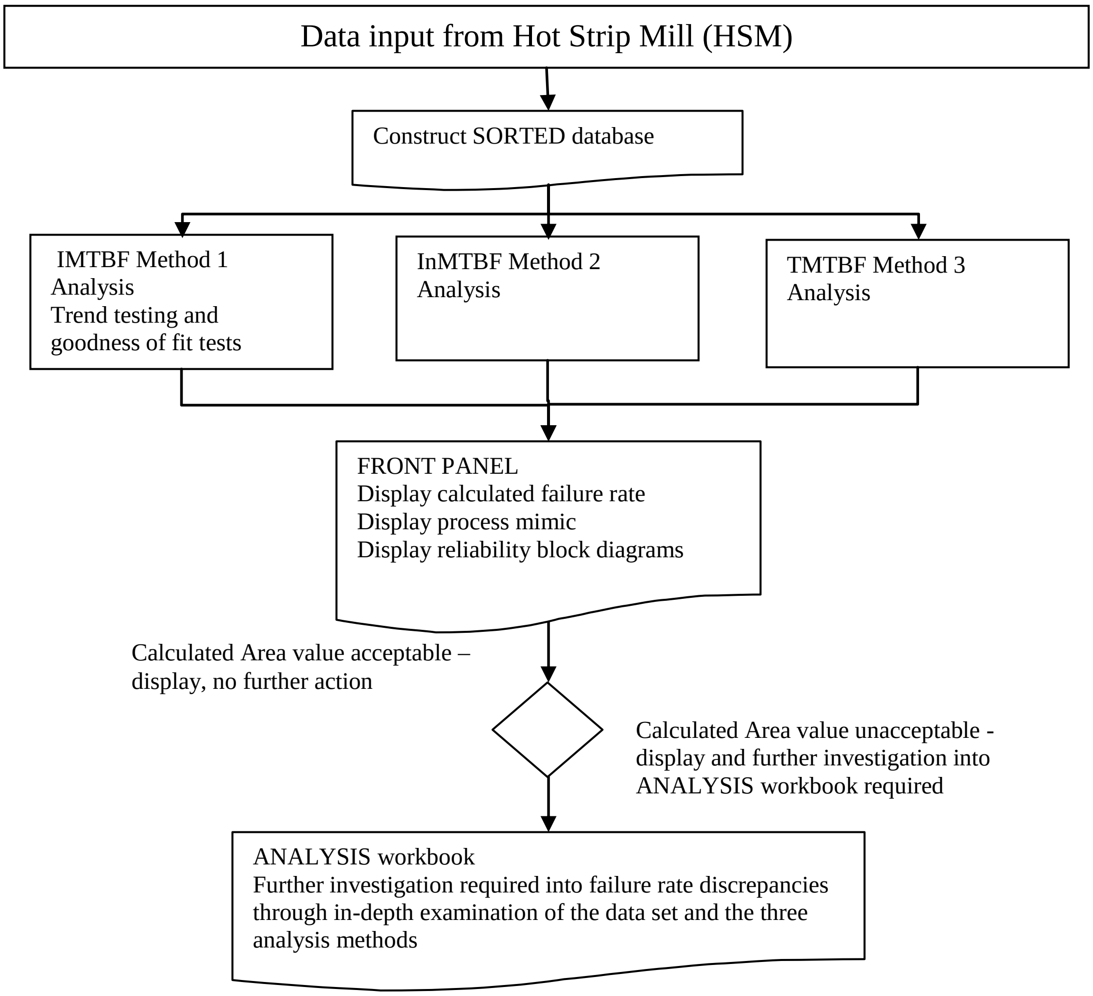


Figure 6-4 Flow Diagram of TRAM Method.

From the testing analysis methods carried out in Chapter 5 it was confirmed that most data sets accessed by this analyses method are sometimes not statistically significant. This feature casts doubt on the accuracy of this analysis when used as a stand alone tool. This is an expected risk when accessing large data sets over a significant timescale with the large range of operating parameters and outside influences seen by these operating systems. This feature is catered for in this work by the incorporation of the goodness of fit tests within the ANALYSIS workbook which allows the identification of the data sets’ statistical significance status. The ANALYSIS workbook also allows further examination into the status of the data set by allowing a goodness of fit test to be carried out over a set period e.g. annually which would:

- Identify if the system is statistically stable over this set period.
- Identify discrepancies in the data which infer non-system stability.

In effect this research introduces the feature of "statistical stability" that can be used as a method of identifying the special causes (if any) which could affect the system. Operators may then use this to instigate any repairs or modifications which can return the system to a "normal" level of statistical stability. The continuous tracking feature inbuilt within the analyses will allow further monitoring of the systems statistical stability following such actions.

In addition the standard Laplace trend testing mechanism is incorporated into the analyses model, which allows an overall identification of the examined systems reliability trend. This can act as a further check on the veracity of the IMTBF analyses and will either correlate or dispute the calculated result. An example of the discrepancies that can be found through this method of system analysis can be presented in the context of the Coilers (Figure 6.5).

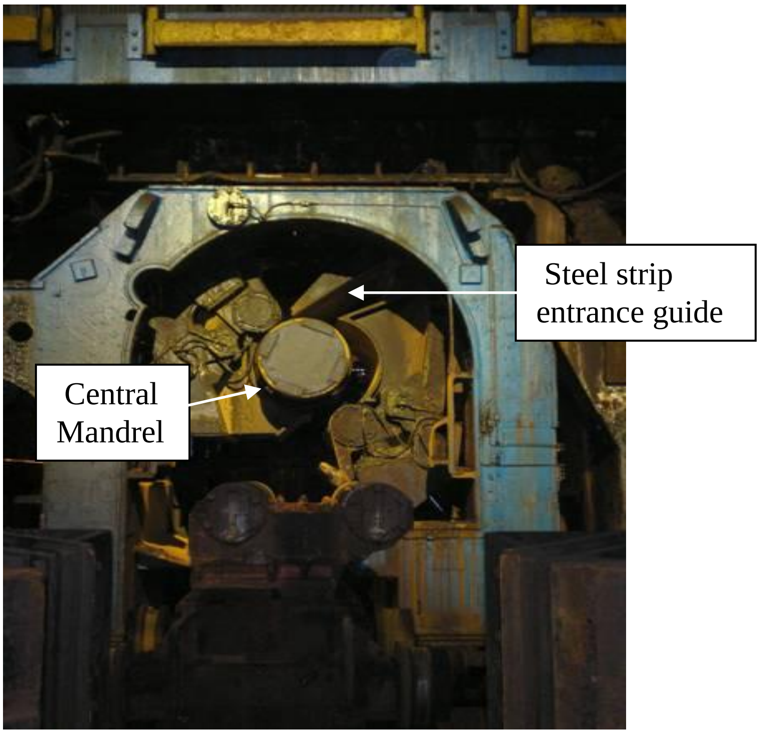


Figure 6-5 Steel Strip Coiler

There are two Coilers at the Hot Strip Mill in Port Talbot, Coiler 4 and Coiler 5. They are rotational devices which coil the finished metal strip around a central mandrel into steel coils of standard sizes ready for transference to further processing stations. From the graphical representation of the Coiler 5 IMTBF analysis depicted in Figure 6.6 it can be seen that the system is undergoing a steady deterioration in its reliability status from the start of this data logging exercise in 2007. This "negative" reliability growth situation is readily identifiable and appears to be levelling off over the operating period in year 2009.

This indicates that improvements are required to reverse this performance trend. The goodness of fit tests for this system returns that this data set is statistically significant with a CvM calculated value of 0.188 against the CvM set value of 0.22 with 136 recorded failures over the three year period.

In contrast the same Power Law analysis carried out on Coiler 4 (Figure 6.7) which is an identical operating system situated next to Coiler 5 gives a totally different IMTBF result, with Coiler 4 returning an IMTBF of 82 hrs whilst Coiler 5 returns an IMTBF figure of 152 hours for week 52 of 2009. The CvM test on Coiler 4 returns a calculated result which is highly insignificant with a value of 1.223 against the required result of 0.22. Coiler 4 returned 254 failures over the three year period.

Both of these Coiler process systems are of the same age and are constructed in a l series configuration with Coiler 5 situated directly behind Coiler 4. They are intended to operate sequentially and are designed to be fully utilised when the process line is operating at full capacity. In reality the current operating strategy is to designate Coiler 4 as a preferred coiling unit, which takes on most of prescribed steel coiling activity on this process line.

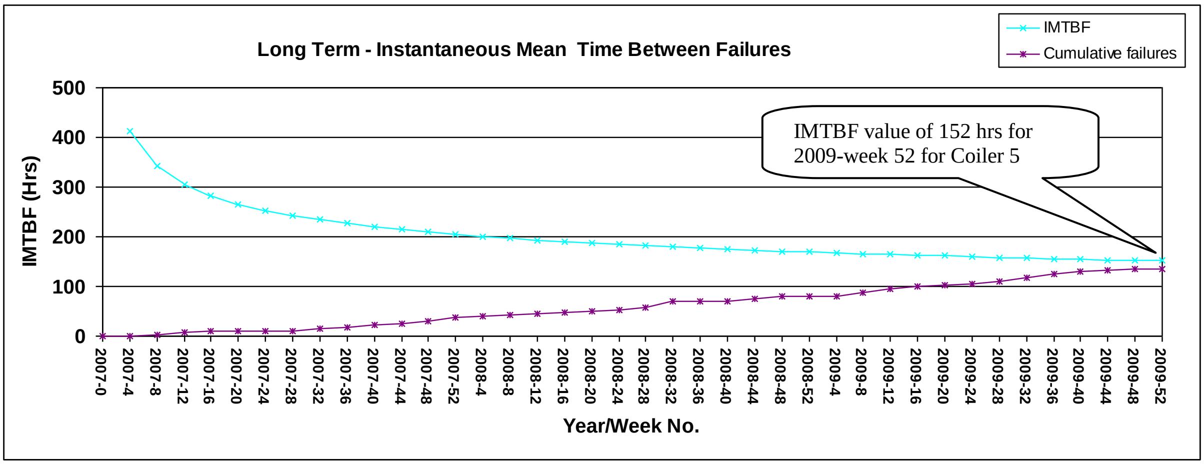


Figure 6-6 Coiler 5 Instantaneous mean time between failures

When examining the graphical representations of the failure patterns of these two identical systems it is noted that both systems indicate steady deterioration in reliability growth with their quoted IMTBF figures in a ratio of approximately 2:1 in favour of Coiler 5

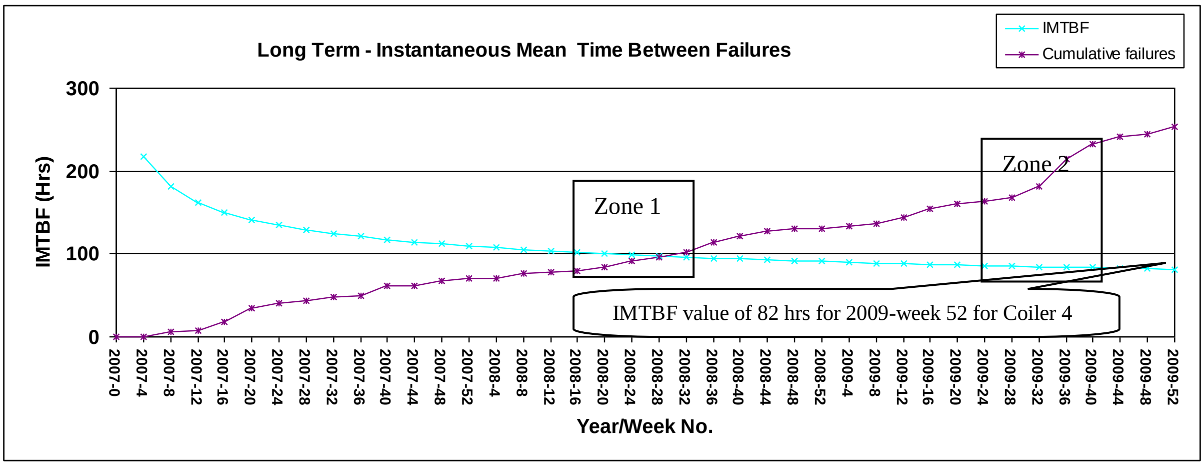


Figure 6-7 Coiler 4 Instantaneous mean time between failures

The Power Law process has described the deterioration as occurring at a uniform steady state decline in reliability growth. When examining the relative changes in cumulative failures on both systems it is relatively easy to identify the main differences in their failure growth patterns. Coiler 5 indicates an almost linear consistent rise in failures over the three year operating period. Whilst Coiler 4 shows major periods of deterioration particularly in 2007 between week 16 and week 28 (Zone 1 Figure 6.7), with a second severe deterioration in the system performance occurring between weeks 28 – 34 in 2009 (Zone 2 Figure 6.7). Further research into the operation of the mill indicates that in effect these changes in the respective failure rates are a reflection of the working pattern placed upon Coiler 4 by the operating process. As Coiler 4 is situated in front of Coiler 5 it is easier to divert all manufactured product onto this Coiler, this appears to be the strategy employed in this operating period. The deviations in failure patterns attributed to Coiler 4 are captured in its corresponding goodness of fit (CvM) test.

These systems are indicative of the widely disparate operating regimes which can be enforced on two identical systems which were originally designed to operate at identical work rates. The corresponding effects on their failure patterns is mirrored in their goodness of fit tests which can be recorded as not statistically significant and therefore the analysis is initially viewed as "not fit for purpose". This is an important point which would normally invalidate the application of Power Law based reliability assessments. It is also one of the major reasons why such techniques are normally not applied in this context. However this is not the case in this approach where this finding will trigger deeper analysis to consider if the review of the systems' cumulative failures can identify where outside "special causes" have influenced the statistical significance testing regime. The additional analysis methods proposed in this reliability model are intended to enhance the ability of the deployed analysis system to identify if any special causes are impinging on the systems operation.

6.3 Incremental Mean Time between Failures (InMTBF)

This method uses the standard Power Law analysis method, applied incrementally at four week operating periods. These periods are based on the standard "week number" parameter. The incremental mean time between failures (InMTBF) is the operating parameter that is used for this analysis. This is a parameter defined by the author and is derived from the instantaneous mean time between failures used in this reliability field. This parameter is calibrated in hours and the operating algorithms are described in Equations 2.9-2.12. This is a medium term reliability monitoring for tracking time between failures and identifying the trends in the systems reliability performance from inception (or start point of data logging) to current status. This reliability tracking method is intended to be beneficial to area engineers and section engineers in the Hot Strip Mill and will allow them to visualise and identify the reliability trends of the area under examination. This will be useful for monitoring the longer-term effects of process improvements, machine upgrades or any other changes to operating parameters. The method is expected to continually track system performance and allow the engineer to access any time period from data installation in the beginning of 2007. This analysis is applied in incremental stages based on a 672-hour cycle. This process starts at week "0" in 2007 so for example week 4 2007 is regarded as having occurred after 672 operating hours. All subsequent week numbers are allocated as operating hours worked relative to week "0". The reliability assessment/appraisal process is described below:

- The system breakdowns are recorded for 672 hour periods and the analyses performed. The resulting time between failures recorded at the 672 hourly intervals.

- The analysis process continues incrementally at 672 hourly intervals until the required week number (current date) is reached.

From the graphical representation of the Coiler 5 InMTBF analysis shown in Figure 6.8 it can be seen that the same deviations in failure numbers recorded in Figure 6.6 are captured. However the different application of this analysis method allows it to be significantly more reactive to changes in the rate of change of failure over the operating period, e.g. week 28 of 2007(zone 1 Figure 6.8) shows a considerable improvement on its predecessors (week 24 & week 26). This is not indicated in the IMTBF analysis, (Figure 6.6) which performs an averaging function over the calculated data range.

This analyses method also indicates a useful method for visualising trends in the failure data sets, as can be seen in the short term improvement in system performance which is captured within this graph. This can be further illustrated by considering Zone 1 on Figure 6.8 which shows a peak in InMTBF of 541 hours. In addition more moderate deviations in system performance can be visualised in the graph notably the performance deterioration trend changing to an improvement trend depicted between Week 44 2007 and Week 08 2008 (Zone 2 Figure 6.8) and the reliability deterioration to improvement trend depicted between Week 28 2008 and Week 44 2008 (Zone 3 Figure 6.8). The reaction rate of this analysis method is considerably faster then the pure Power Law application; this is a useful function in identifying trends in failure patterns.

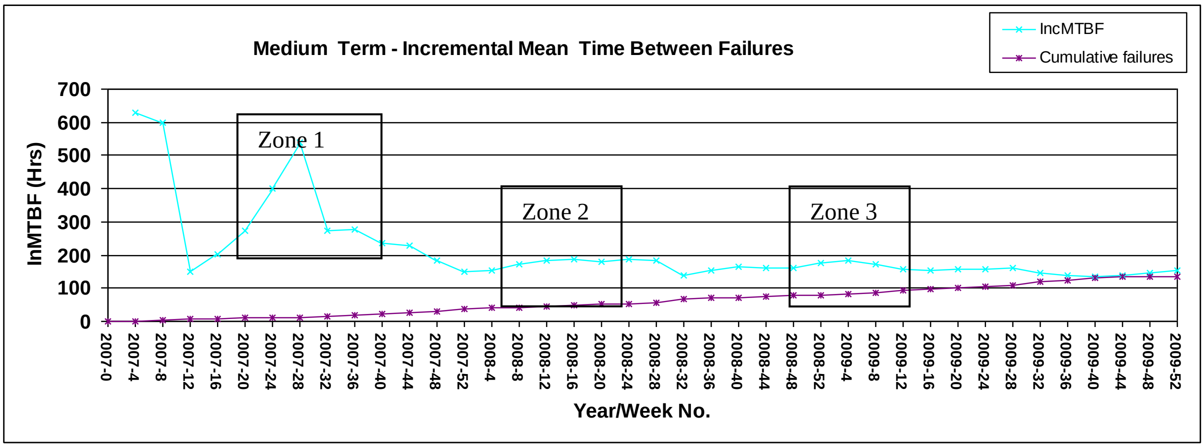


Figure 6-8 Coiler 5 - Incremental Mean Time Between failures (InMTBF)

The Cramer von Mises goodness of fit test, which has been applied to this data set, indicated that the Power Law process is a “good fit” to the Coiler 5 data set. When reviewing the overall analysis of this system it can be seen that there were major fluctuations in system performance being recorded during 2007. After this period the system performance is predominantly deteriorating albeit at a slower more uniform decline rate. This supports the CvM analysis that the data set is statistically significant over this data period. The benefits of this method indicated in the previous paragraph are supported by an additional analysis of its sister operating unit Coiler 4 shown in

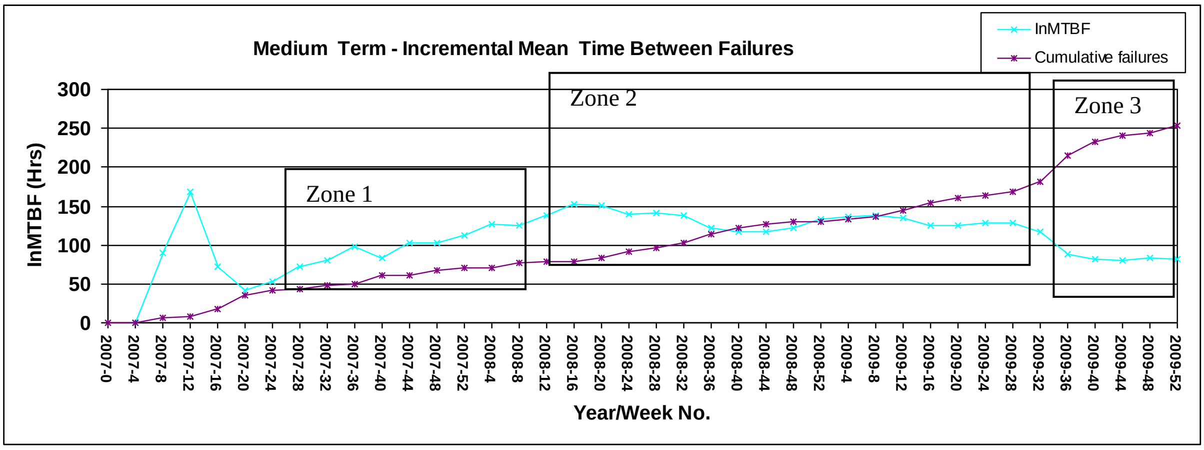


Figure 6-9 Coiler 4 - Incremental Mean Time Between failures (InMTBF)

Figure 6.9.From the Coiler 4 analysis it can be instantly recognised that this a more volatile system showing several different data trends including:

- A Predominately improving trend from Week 40 2007 to Week 16 2008 (Zone 1 Figure 6.9).
- Predominately deteriorating trend from Week 20 2008 until Week 28 2009 (Zone 2 Figure 6.9).
- Severe deterioration trend from Week 32 2009 until Week 44 2009 (Zone 3 Figure 6.9).

It can be recognised that the major discernable pattern in the failure trends in this system indicates deterioration in operational performance. This can be visualised when comparing the decrease in InMTBF which mirrors the increase in cumulative failures in Zone 3. The cumulative failures show large fluctuations on a year-by-year basis, this supports the previously attained CvM result which showed that this data set is not statistically significant. The assumption can be made that there are special causes in this operating system, which may be linked to the overall operating strategy of this system. This analysis method fluctuates with the relevant incremental breakdown numbers recorded during each 672 hour period, which allows it to be useful in identifying performance trends in operating systems, this feature will be useful when constructing:

- Business case for improvements, such as machine upgrades.
- Changes in maintenance strategy, allowing engineers to focus on the worst performing systems in the manufacturing facility.

As stated earlier this analysis method has a slower tracking rate than the following analysis method (method 3) and is designed to allow the plant engineer to identify performance trends and plan strategic developments. After reviewing these analyses the Coiler area engineers are discussing the operational performance implications and are reviewing the work allocation strategy which is in place for Coiler 4 and Coiler 5. The final analysis method developed by the author is depicted in method 3, this method is designed for the shop floor area engineer to identify the short term performance of their local systems

6.4 Tracking Mean Time Between Failures TMTBF

It was identified from the previous InMTBF analysis method that fluctuations in the systems reliability indices (times between failures) can be used as an indicator of the systems reliability performance through identifying the trends in operational performance. It was recognised by the author that an additional reliability measure is required to supplement the previous reliability analysis method. Whereas the previous InMTBF analysis can indicate the performance trend, a more focussed analysis method is required to identify the short-term deviations in a systems reliability performance causing this trend. It is believed that this short-term reliability analysis method will be of particular use to the area engineers in the Hot Strip Mill. Each “Area” engineer in the Hot Strip Mill is responsible for a specific portion of the manufacturing process, e.g. the roughing mill area engineer is responsible for the roughing mill plus additional equipment situated before and after the mill stand. This process is repeated for each area engineer in the Hot Strip Mill.

These area engineers are responsible for all day to day operations and for the implementation of the maintenance strategies and remedial actions required to counteract machine failures. They require immediate access to the specific data sets relevant to their section of the manufacturing process. Therefore it is beneficial for these engineers to have the ability to easily access the individual reliability data sets or the whole of the "Area" data set. It has been identified that a short-term reliability tracking method would be beneficial to the area engineers in the Hot Strip Mill by allowing them to visualise and quickly identify the current status of the area under examination. This reliability tracking method would be expected to continually track the performance and allow the engineer to access any time period from data installation.

The derived analysis method is based on the standard homogeneous Poisson process (HPP) reliability analysis method. In this application the reliability tracking method requires access to uniform time increments to allow continuous monitoring to be an effective comparison method. For this reason it was decided that a four-week operating period based on week number increments was the most feasible analysis segment. Basing these periods on the standard "week number" parameter will ensure continuity with analysis methods 1 and 2. This analysis method is intended as a short term reliability monitoring method for tracking the time between machine failures and identifying the current trends in the systems reliability performance from inception (or start point of data logging) to current date.

It is recognised that the data sets are required to be statistically identical and independently distributed for this analyses method to be robust, a proviso that cannot normally be met with repairable machine systems due to their interdependency. However as this analysis is intended more as a comparative method between systems and is not expected to be statistically robust, the assumption can be made that the breakdowns are statistically independent and identically distributed (SIID). The short term reliability analysis model developed from the homogeneous Poisson process (HPP) will be required to accommodate the following features:

- The requirement for the incremental application of the model at four weekly operating periods has resulted in a maximum total operating time over this period of 672 hours. This is deemed as the maximum mean time between failures that can be attained.
- If one uses a straightforward HPP application it can be realised that at the limits of this assumption the calculated MTBF value tends towards infinity.

This can be easily identified through the following HPP equations:

$$\lambda = \frac{N(Breakdowns)}{T(Time)} \quad \text{Eqn. 6.1}$$

Where

$$MTBF = \frac{1}{\lambda} \quad \text{Eqn. 6.1}$$

Where λ is the failure rate, as N tends towards zero, the MTBF value tends to infinity. The use of the HPP model in the analysis of repairable systems will be considered in this research through the initial reliability analysis of the descaling system (Chapter 8). That analysis produced calculated reliability indices for the descaling system but the author considers that more detail is required in order to carry out a robust analysis for this application.

The HPP model has been previously applied, with care, by Tan (Tan 2008). Who puts forward the argument that when a system contains multiple subsystems and their differences are so great that they bear no relationship to their sister systems. They can be assumed to statistically identical and independently distributed thereby fitting the requirements for the application of a HPP analysis. There appears to be little other reported evidence for using the HPP model for the analysis of repairable systems.

The derived analysis method uses an operating parameter derived by the author; the manufactured variable is depicted as Tracking Mean Time Between Failures (TMTBF). This function is derived from the standard mean time between failures (MTBF) parameter used in this reliability field for non repairable systems. The TMTBF parameter is calibrated in hours and the operating algorithms are described in Equations 6.3 – 6.4

The HPP equations have now been modified so that:

$$\lambda_{MOD} = \frac{N+1}{T(Time)} \quad \text{Eqn. 6.3}$$

And

$$TMTBF = \frac{1}{\lambda_{MOD}} \quad \text{Eqn. 6.2}$$

This modification allowing the calculation of the individual four week operating segment TMTBF to reach a maximum of 672 hrs when the breakdown level equates to zero. The main purpose of this analysis is to focus attention on the four week operating periods which indicate poor reliability indices, through the low hourly TMTBF value. This can be used to indicate to the area engineer the section of the process which requires prompt attention. It can be seen from Figure 6.10 that this analysis method is quick to react to any changes in a system's condition and allows a comparison of the short term operating trends displayed by this system.

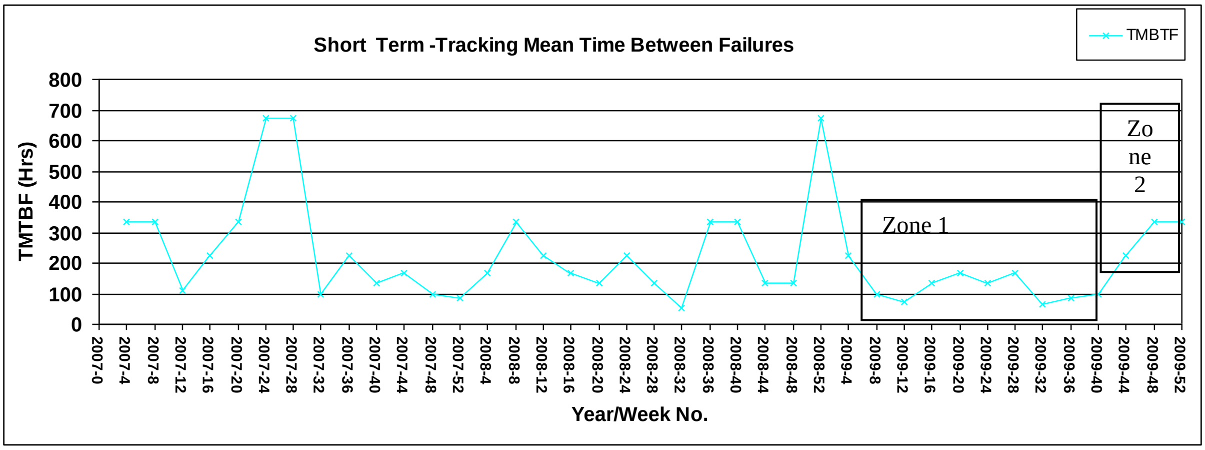


Figure 6-10 Coiler 5 Tracking Mean Time between failures

This is illustrated in the TMTBF graph shown in Figure 6.7. It can easily be identified that Coiler 5 underwent a significant number of breakdowns during the period Weeks 8 to 40 in 2009 (Zone 1 Figure 6.10) with a major improvement in weeks 44 to 52 of 2009 (Zone 2 Figure 6.10). The usefulness of this analysis of Coiler 5 is supported by the additional analysis of Coiler 4 illustrated in the TMTBF graph shown in Figure 6.11.

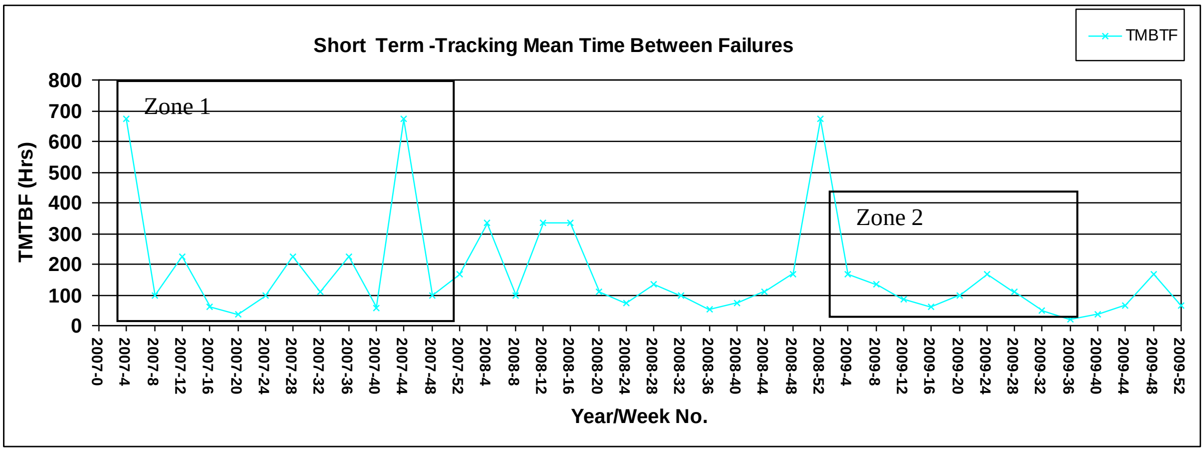


Figure 6-11 Coiler 4 Tracking Mean Time between Failures

From the Coiler 4 analysis it can still be recognised that this is a more volatile system indicating several different data trends. The trends detail is not as readily identifiable as in the InMTBF analysis, therefore the identification of the subtler improving or deterioration trends is not readily available. Some of the features that can be identified from this graph are: Major variations in the recorded TMTBF during 2007 (Zone 1 Figure 6.11) and very poor reliability performance prior to Week 36 2009 (Zone 2 Figure 6.11). The analysis of Coiler 4 in figure 6.11 confirms that this analysis method is quick to react to any changes in a systems condition. Interestingly the operating stoppage periods such as week 52 in 2008 can be easily identifiable from the graph which allows an informed opinion to be drawn regarding the operational status of the system.

6.5 Additional Example - A Furnace

Coilers 4 and Coiler 5 were chosen as the prime example in this Thesis due to the disparity that can be displayed between two identical models. However the TRAM method can also detect less obvious changes in more stable systems as indicated by the analysis of the A Furnace for the operating period 2007-2009. It can be seen from Figure 6.12 that this is a system which is exhibiting a uniform reliability trend which has displayed little fluctuation over this period.

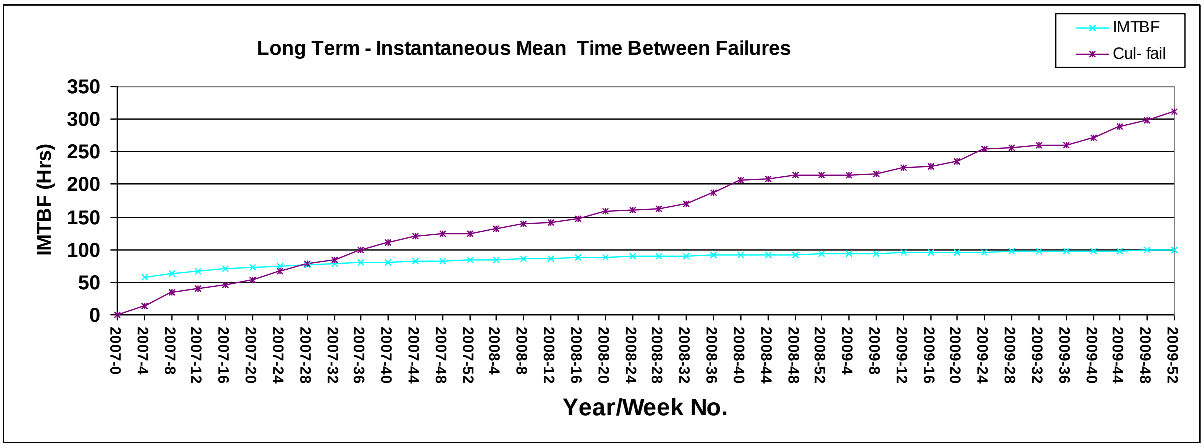


Figure 6-12 A Furnace Instantaneous Mean Time between Failures

The IMTBF graph in Figure 6.12 indicates a slow uniform reliability growth rate over the operating period 2008 to 2009 with an improvement in reliability indices during 2009 from 93 hours to 99 hours. Further examination of the InMTBF graph in Figure 6.13 confirms this with an almost uniform rate of failures from the beginning of

2008 to the end of 2009. It can be seen that from further examination that there was a slight decrease in reliability in Zone 1, however there was a slight increase in reliability in Zone 2

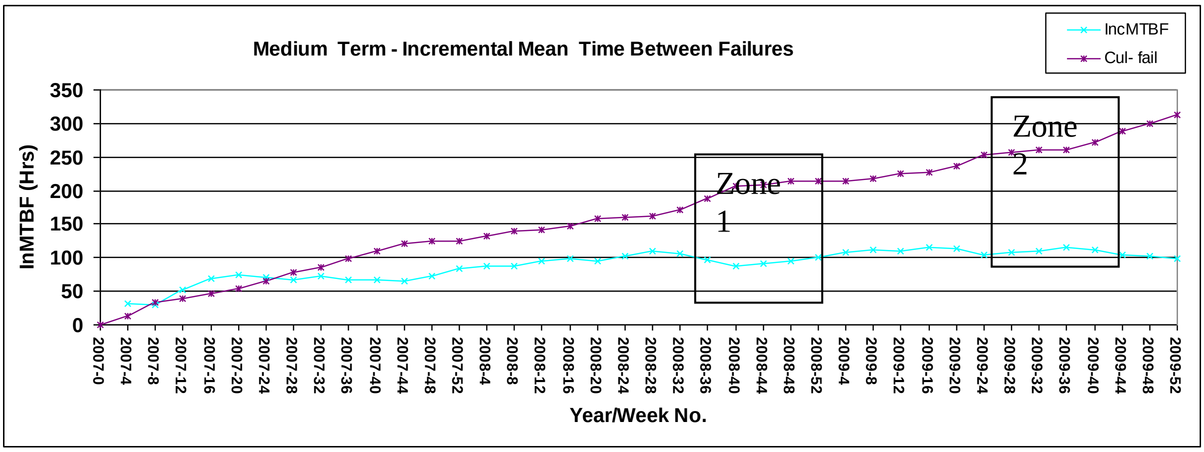


Figure 6-13 Furnace Incremental Mean Time between Failures

The short term analyses method displayed in Figure 6.14 illustrates that there a significant amount of failures recorded by the A Furnace over this operating period. However the failures appear to be fluctuating around the 100 hours median line. If we examine Zone 1 in Figure 6.14 we can see that it returns a TMTBF figures of between 67 and 224 hours indicating that this system is failing between three to ten times every four week period.

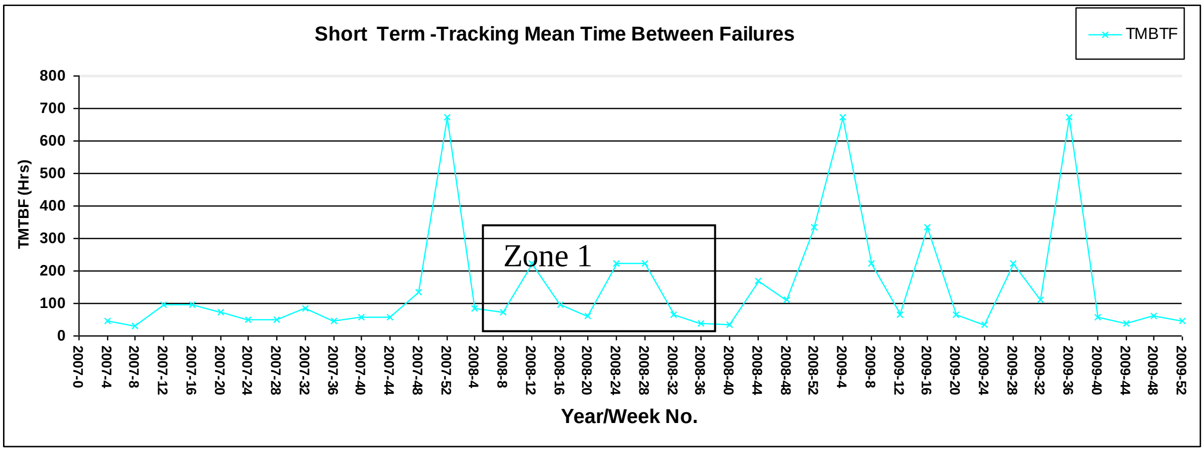


Figure 6-14 A Furnace Tracking Mean Time between Failures

When examining the graph further it appears that the A furnace performed very poorly in 2007 with a TMTBF consistently under 100 hours. It appears that remedial action took place in week 8 2008 which improved the furnaces performance over the next four week period. However this remedial action was not effective as the failure performance deteriorated up to week 20 of 2008. This pattern is repeated until week 40 of 2009 whereupon the failure performance of this system has deteriorated to pre 2008 levels.

6.6 Additional Example F7 Mill Stand

This example is included to further illustrate the differences in the reliability indices of the operating systems within the Hot Strip Mill.

This example is a similar to the analysis in section 6.5; however the reliability indices are significantly higher. The IMTBF analysis (Figure 5.15) returned calculated values for week 52 of 2009 at 99 hours for the A Furnace and at 225 hours for the F7mill stand.

Further examination of the Incremental Mean Time between Failures graph in Figure 6.16 indicates that this system maintained a uniform failure rate during the whole of 2008, and indicated reliability growth during the first half of 2009 followed by a decrease in reliability performance during the latter half of 2009.

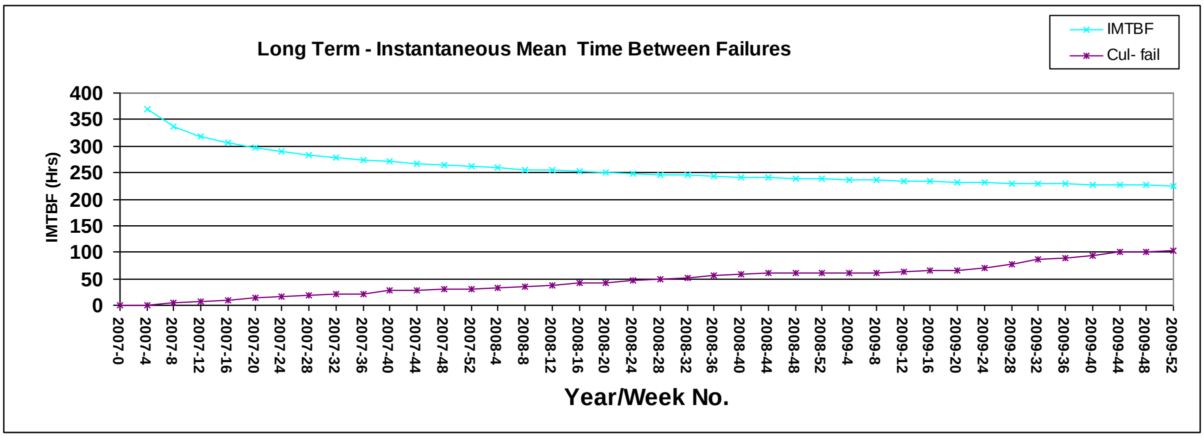


Figure 6-15 F7 Mill Stand Instantaneous Mean Time between Failures

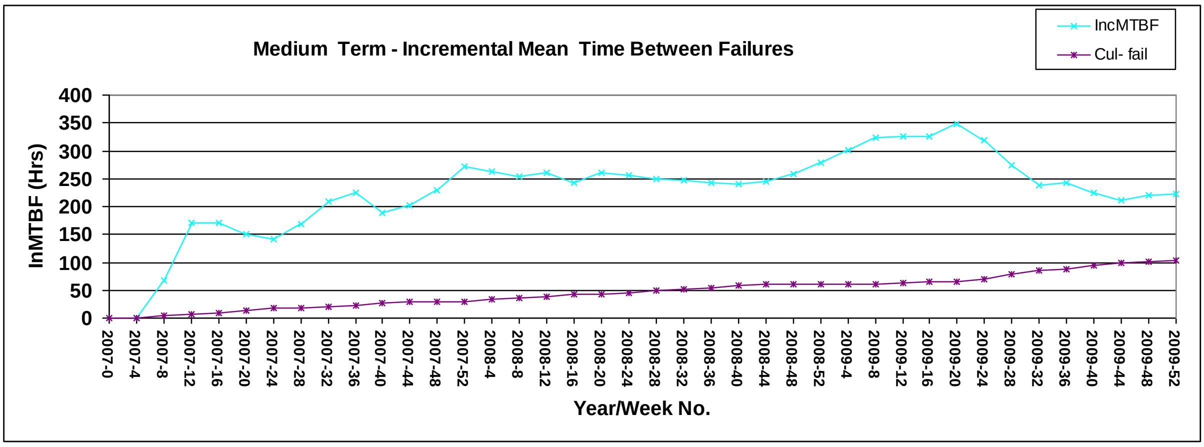


Figure 6-16 F7 Mill Stand Incremental Mean Time between Failures

Examining the short term TMTBF graph in Figure 6.17 confirms that the system did return a relatively stable failure rate in 2008

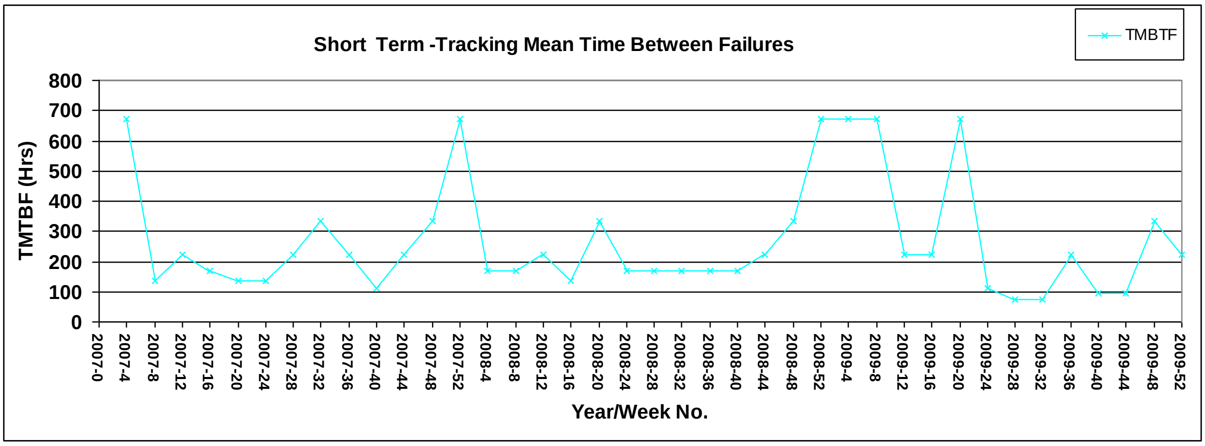


Figure 6-17 F7 Mill Stand Tracking Mean Time between Failures

This was followed by an improvement in reliability performance at the start of 2009 which was followed by a decrease in reliability performance in the latter half of 2009. The TRAM model allows for quick analysis of all the operating systems within the Hot Strip Mill, The two additional examples portrayed here took less than a minute to format. However it is expected that the analysis operator will require engineering skills to interpret the graphs and apply the correct remedial actions.

6.7 Model Application and Further Development

As stated earlier these three reliability analysis methods operate simultaneously in the developed analyses model. They are expected to be used in conjunction with each other and it is only through the simultaneous use of the three methods that an overall picture of the systems reliability status be constructed. The combination and application of these three reliability analysis methods in this research provides an innovative solution. The nature of the analysis and monitoring achieved is synergistic; with the end result being more significant than just the combination of the three methods. The author considers that this is an important advancement in the research.

It is realised that the issue of statistical significance cannot be ignored particularly as from initial investigations the majority of data sets under review are not statistically significant with respect to the reliability analysis model. Through the use of the installed goodness of fit tests one can easily identify the non- significant data sets which can instigate a cross comparison between the analysis methods to formulate a reason for the non-significance of the data set. This allows the operator to analyse the reasons for non-significance and identify if these reasons are data, process or system driven. This can lead to the installation of a countermeasure such as an upgraded machine or revised failure recording method. Further system analysis such as a reliability centred maintenance (RCM) activity may be required if there is no obvious reason for the non significance of the data set. It is intended that successful implementation of these countermeasures could return the data set to statistical significance

The use of a uniform analysis method is additionally helpful in allowing the calculated reliability analysis figures to perform a comparative analysis. This can highlight, as in the cases of Coiler 4 and Coiler 5 the differences in working patterns and their corresponding effects on system reliability. It is recognised that there are alternative analyses methods that may be more suitable for the reliability monitoring of certain process areas. However the inclusion of additional analysis methods impinges on the ability to perform cross comparisons between separate systems. This leads to the authors' opinion that the chosen reliability analysis methods are the most suitable for this application whilst operating within the stated limitation of software choice and operator ability.

However for this reliability modelling method to be truly effective there remains the considerable requirement of manipulating the analyses methods to ensure:

- Simplicity of operation.
- Readily identifiable analysis results.

- The ability to perform a deeper investigation into the analyses to withdraw root causes etc.

This is facilitated through the construction of a semi- automated analysis model which is described in Chapter 7.

7 Model Automation and Construction

This Chapter explains how the TRAM operating methodology described on Chapter 6 progresses into an automated model. This is facilitated by describing the individual workbooks contained within the model and the programming constructed to make the reliability analysis model work as an integrated unit. The main goal of this research is to identify and construct a reliability analysis model which can be utilised at the Tata Steel plant. The derived TRAM method is constructed in the Excel software package and the terminology used in this chapter will reflect that used in this package. In this respect the following terms are relevant:

Workbook will reflect the individual file; workbook names will be in block capitals (e.g. FRONT PANEL),

Worksheet reflects the individual spreadsheet within the “workbook” file. Worksheet titles will be in normal text with parenthesis to indicate the application, (e.g. “Info Sheet”), and Macro is the current Visual basic for applications (VBA) terminology for the operating program.

During the experimentation stages it was realised that the construction of separate workbooks for each operating section of the model would facilitate the most practical operating methodology. In this context it was decided to utilise three separate template workbooks:

1. FRONT PANEL Workbook: This is the main control workbook and contains the main operating programs; its operation is described in Section 7.1.
2. SORTED workbook: This performs as the main data formation tool which prepares the failure data sets prior to analysis, the workbooks construction is described in Section 7.2, whilst the workbook’s operation is controlled from the FRONT PANEL workbook its operation is described in Section 7.1.
3. ANALYSIS Workbook: This workbook analyses the failure data sets installed from the SORTED workbook and uses the specified analyses values to populate the FRONT Panel Workbook, described in Section 7.3.

These workbooks are saved in a dedicated folder and read/write protected.

After activation the main operating program saves each workbook under an abbreviated name dedicated to the manufacturing area e.g. FRONT PANEL HSM, SORTED HSM.

The standard ANALYSIS workbook is not saved. The operator can request an additional analysis from the front panel macro, which will save the requested analysis with its area name e.g. ANALYSIS F5. Saving the main workbooks as the model templates will accommodate for the models future application to all other business areas. In addition this will facilitate the further development of the TRAM method when required through the following actions:

- Modifications to the SORTED database will allow the model to be applicable to the alternative data sets which are used in the different business areas at the Tata Port Talbot plant.
- Further development of the ANALYSIS model to incorporate any required changes in analysis methods as new areas are added
- Modifications to the FRONT PANEL will aid model portability and allow future reliability engineers to construct bespoke diagrams for the plant layout, process mimics and reliability block diagrams which are relevant to the specific business area.

7.1 FRONT PANEL Workbook

This workbook contains all of the operating macros (programs) required for the effective implementation of the reliability analysis model. It is constructed to aid its transferability to alternative manufacturing units. The original FRONT PANEL workbook is retained as a template after every application. After initialising the template the modified workbook is saved as FRONT PANEL (named area) which becomes the working copy for all future updates. This workbook is the control source of the analyses and the operating methodology is described in the Figure 7.1.

The programs operating methodology is as follows: After the Initialise macro is activated the program automatically constructs the two new workbooks. The SORTED (name) workbook and the FRONT PANEL (name) workbook, these are saved under their respective names, and the original templates closed.

By initialising the Sort Database macro The SORTED (name) workbook interrogates the main database and is populated with the relevant failure data sets. The next step is for each individual failure data set to be transferred to the ANALYSIS workbook for calculation of the reliability values.

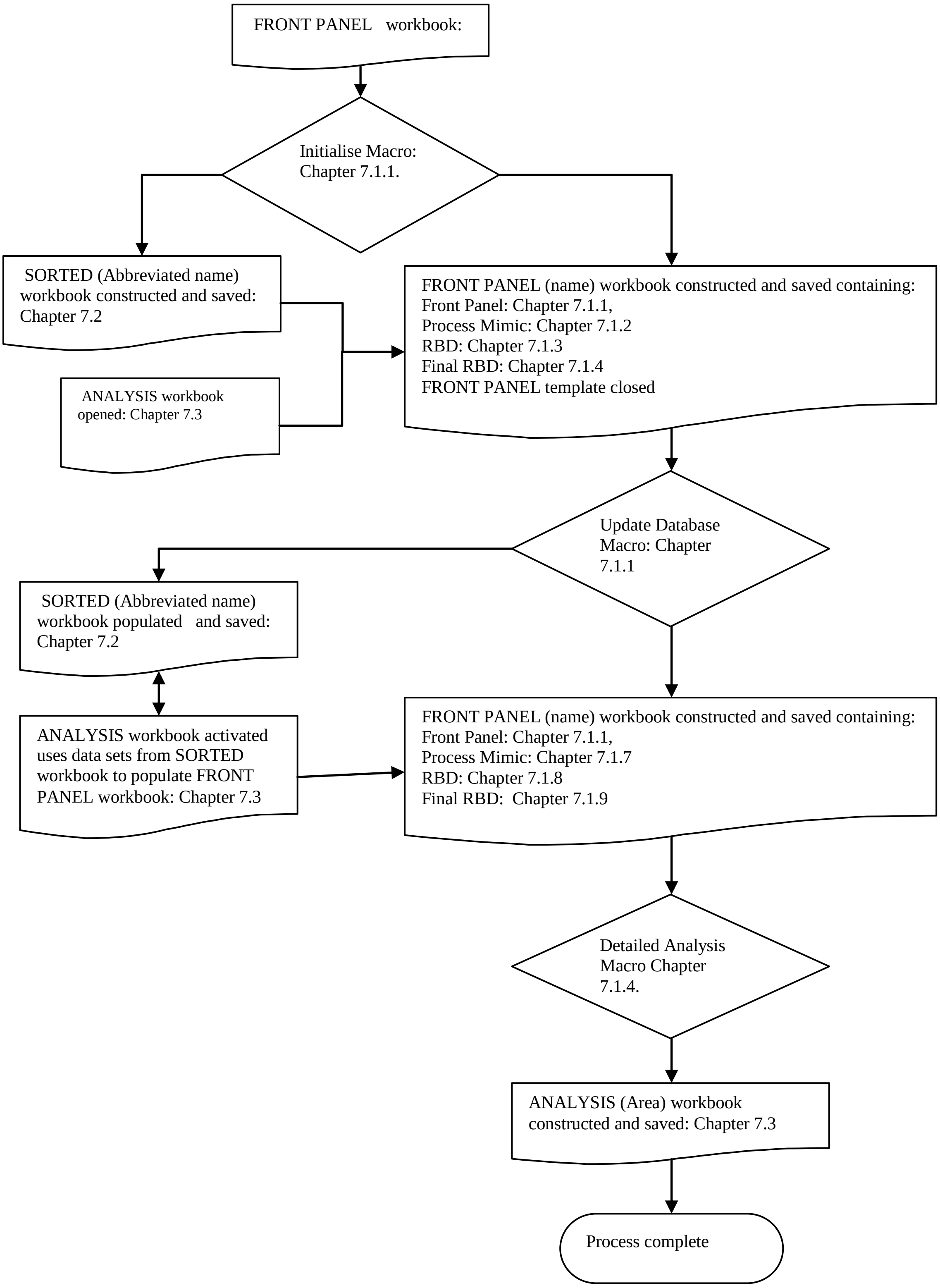


Figure 7-1 Flow Diagram of FRONT PANEL Macros

Each calculated value is transferred to populate the FRONT PANEL (name) workbook. This process continues until all data sets have been analysed and the FRONT

PANEL (name) workbook is fully populated with all of the required reliability values. The program automatically populates the “Process Mimic”, “RBD” and “Final RBD” worksheets from the data contained in the “Front Panel” worksheet.

Additional detail can be obtained through operating the Detailed Analysis macro. This runs the required failure data set which is indicated in the drop down menu through the ANALYSIS model. This is saved as ANALYSIS (data set name) this workbook contains multiple graphical representations of the systems failure performance in addition to several goodness of fit tests to indicate if the selected failure data set is statistically significant.

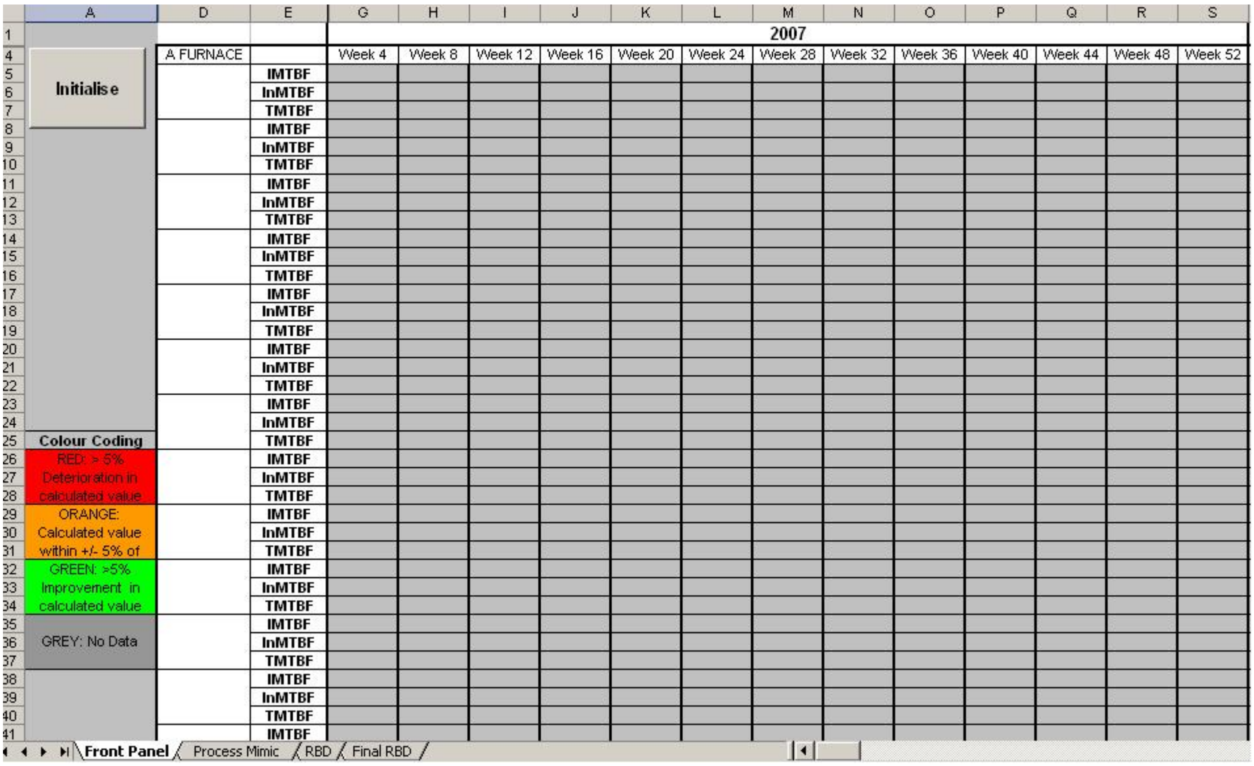
The model contains four worksheets which are:

“Front Panel”: Section 7.1.1.
“Process Mimic”: Section 7.1.2.
“RBD” (Reliability Block Diagram): Section 7.1.3.
“Final RBD” (Reliability Block Diagram: Section 7.1.4.

7.1.1 The Front Panel Worksheet:

This is the controlling worksheet and its format has previously been introduced in Chapter 6. The calculated results for the IMTBF, InMTBF and TMTBF analysis methods are sequenced in three rows which are relevant to each operating area. The results for these three analysis methods are presented in columns which are constructed relevant to the four-week operating period. The current worksheet is designed to contain ten years data analysis results covering the period from Week 0 of 2007 up to Week 52 of 2016. This worksheet can be modified to continue after this date if required. Figure 7.2 shows the worksheet in its original condition before activation.

This worksheet is designed to allow the worksheet examiner to easily identify any major deviations in the systems operational reliability status. The cell formatting is based on the “Traffic Light” system currently installed at Tata steel. The control parameter is set at +/- 5% and the intention is to review this parameter after the model’s testing period is completed. The detail relating to the named operating areas is accessed from the SORTED workbook “Info Sheet” which automatically populates the area column in the “Front Panel” worksheet.



	A	D	E	G	H	I	J	K	L	M	N	O	P	Q	R	S
1				2007												
4	Initialise	A FURNACE		Week 4	Week 8	Week 12	Week 16	Week 20	Week 24	Week 28	Week 32	Week 36	Week 40	Week 44	Week 48	Week 52
5			IMTBF													
6			InMTBF													
7			TMTBF													
8			IMTBF													
9			InMTBF													
10			TMTBF													
11			IMTBF													
12			InMTBF													
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20			IMTBF													
21			InMTBF													
22			TMTBF													
23			IMTBF													
24			InMTBF													
25	**Colour Coding**		TMTBF													
26	RED: > 5% Deterioration in calculated value		IMTBF													
27			InMTBF													
28			TMTBF													
29	ORANGE: Calculated value within +/- 5% of		IMTBF													
30			InMTBF													
31			TMTBF													
32	GREEN: >5% Improvement in calculated value		IMTBF													
33			InMTBF													
34			TMTBF													
35	GREY: No Data		IMTBF													
36			InMTBF													
37			TMTBF													
38			IMTBF													
39			InMTBF													
40			TMTBF													
41			IMTBF													

Figure 7-2 Initial Front Panel Worksheet

All of the data table (cells) in this worksheet are conditionally formatted in the following fashion:

Orange: calculated result is within +/-5% of the previous calculated value

Green: calculated result has improved > 5% of the previous calculated value

Red: calculated result has deteriorated > 5% of the previous calculated value

Grey: No data present.

The “Front Panel” worksheet is illustrated as stated in Figure 7.2 in its pre-activation state, after application of the macros illustrated in Figures 7.3 – 7.5 this worksheet is updated as in Figure 7.6. The “Front Panel” worksheet controls all program operations through the embedded buttons or drop down tables, which initiate the relevant macros when operated. The operating methodology for these macros is illustrated in their respective flow diagrams.

7.1.2 The Initialise Macro:

The Initialise Button is the first step in applying the analysis model. This operation uses a sub routine to operate the “Initialise analysis” macro. This programs operation is illustrated in Figure 7.3

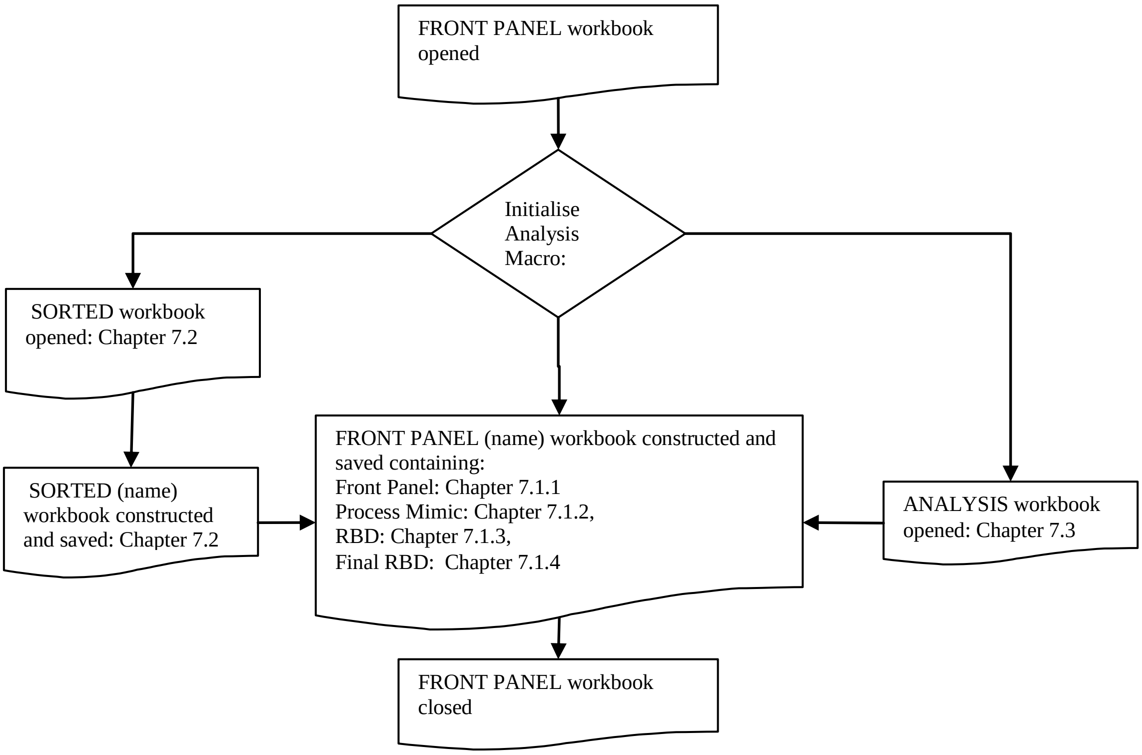


Figure 7-3 Initialise Macro

The operational status after the “Initialise” macro has been applied is:

The FRONT PANEL and SORTED workbook templates are automatically closed without modification. The macro saves the FRONT PANEL (name) template and the SORTED (name) template under the plant areas abbreviated name. The ANALYSIS workbook is opened in preparation. The saved workbooks are stored in the current directory and they become the operating medium for further applications, the initialise button is removed from view.

7.1.3 The Sort Database Macro

The Update Database button uses a sub routine to initiate the “Sort Database” macro. The operating sequence of the macro is illustrated in Figure 7.4:

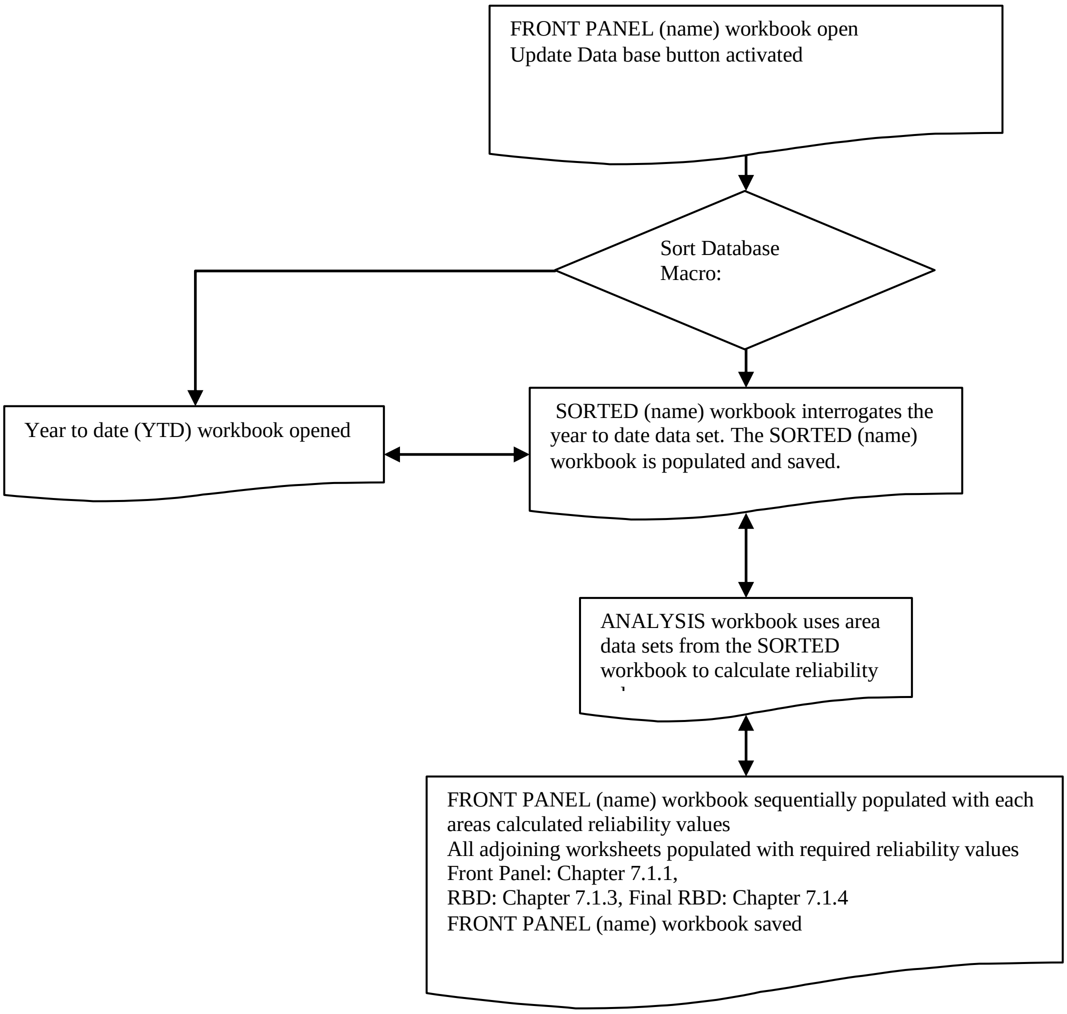


Figure 7-4 Update Database Macro

The SORTED (name) workbook is accessed and the program requests the directory address for the failure data set (year to date YTD) to be sorted. After interrogating the year to date data set the SORTED (name) workbook is populated with the relevant data sets which have been identified in the “Info Sheet”. The data in the “Areas” and “Class” columns in this worksheet are the main drivers for the data selection. All additional columns relating to stoppage description, etc are transferred to the populated SORTED (name) workbook for completion.

After the SORTED (name) workbook is populated the first area data set is passed to the ANALYSIS workbook. This macro operates the ANALYSIS workbook and transfers all the calculated results to the “Front Panel” worksheet. The ANALYSIS workbook is closed without saving. The ANALYSIS workbook is reopened and the second area data set is transferred to it, the process repeats, and the results populate the relevant section of the "Front Panel" worksheet. This process continues until all area data sets within the SORTED (name) workbook have been used and the "Front Panel" worksheet is fully populated as illustrated in Figure 7.6

7.1.4 The Detailed Analysis Macro:

The Detailed Analysis macro is the operating procedure for obtaining a detailed analysis of a specific operating area; the macro is illustrated in Figure 7.5

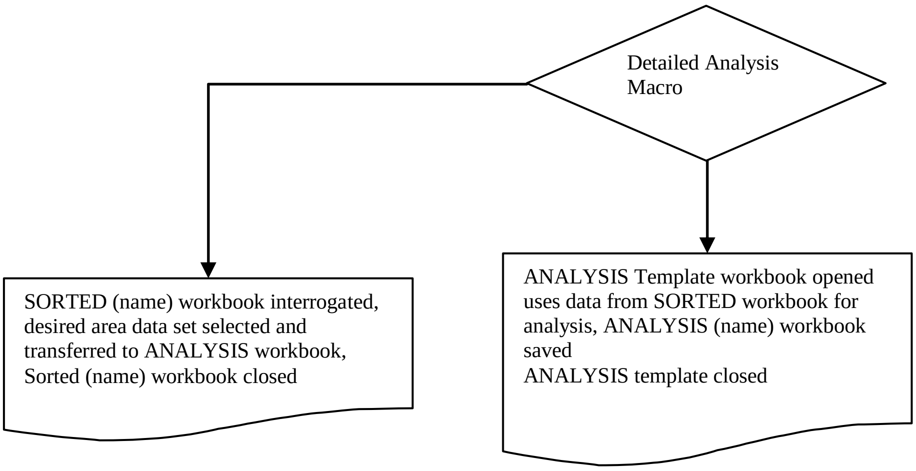
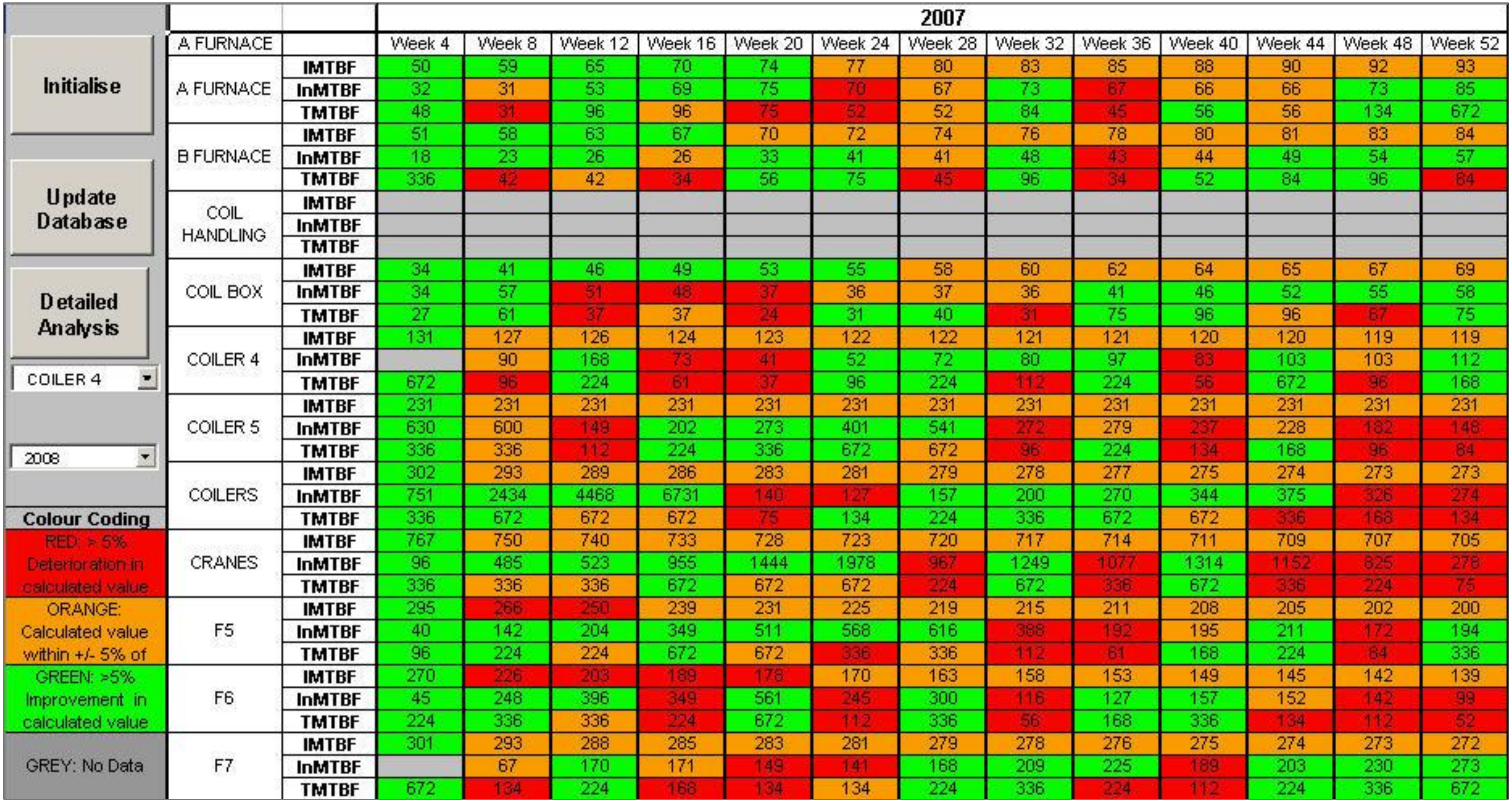


Figure 7-5 Detailed Analysis Macro

The Detailed Analysis Macro works in verification with the "Area" drop down table situated directly below it. The macro uses the area highlighted in the drop down table to reference the corresponding area data set in the SORTED (name) workbook. This data set is applied to the ANALYSIS workbook and all results are calculated. The ANALYSIS workbook is now saved as ANALYSIS (area name) in the file directory ready for further investigation by the program operator. In the case of the specific analyses being rerun, the saved file is overwritten and saved.

7.1.5 The Area drop down table

This table containing the list of all the manufacturing areas (systems) which have been analysed, this table is populated from the SORTED workbook "Info sheet".



		2007												
A FURNACE		Week 4	Week 8	Week 12	Week 16	Week 20	Week 24	Week 28	Week 32	Week 36	Week 40	Week 44	Week 48	Week 52
A FURNACE	IMTBF	50	59	65	70	74	77	80	83	85	88	90	92	93
	InMTBF	32	31	53	69	75	70	67	73	67	66	66	73	85
	TMTBF	48	31	96	96	75	52	52	84	45	56	56	134	672
B FURNACE	IMTBF	51	58	63	67	70	72	74	76	78	80	81	83	84
	InMTBF	18	23	26	26	33	41	41	48	43	44	49	54	57
	TMTBF	336	42	42	34	56	75	45	96	34	52	84	96	84
COIL HANDLING	IMTBF													
	InMTBF													
	TMTBF													
COIL BOX	IMTBF	34	41	46	49	53	55	58	60	62	64	65	67	69
	InMTBF	34	57	51	48	37	36	37	36	41	46	52	55	58
	TMTBF	27	61	37	37	24	31	40	31	75	96	96	67	75
COILER 4	IMTBF	131	127	126	124	123	122	122	121	121	120	120	119	119
	InMTBF		90	168	73	41	52	72	80	97	83	103	103	112
	TMTBF	672	96	224	61	37	96	224	112	224	56	672	96	168
COILER 5	IMTBF	231	231	231	231	231	231	231	231	231	231	231	231	231
	InMTBF	630	600	149	202	273	401	541	272	279	237	228	182	148
	TMTBF	336	336	112	224	336	672	672	96	224	134	168	96	84
COILERS	IMTBF	302	293	289	286	283	281	279	278	277	275	274	273	273
	InMTBF	751	2434	4468	6731	140	127	157	200	270	344	375	326	274
	TMTBF	336	672	672	672	75	134	224	336	672	672	336	168	134
CRANES	IMTBF	767	750	740	733	728	723	720	717	714	711	709	707	705
	InMTBF	96	485	523	955	1444	1978	967	1249	1077	1314	1152	825	278
	TMTBF	336	336	336	672	672	672	224	672	336	672	336	224	75
F5	IMTBF	295	266	250	239	231	225	219	215	211	208	205	202	200
	InMTBF	40	142	204	349	511	568	616	388	192	195	211	172	194
	TMTBF	96	224	224	672	672	336	336	112	61	168	224	84	336
F6	IMTBF	270	226	203	189	176	170	163	158	153	149	145	142	139
	InMTBF	45	248	396	349	561	245	300	116	127	157	152	142	99
	TMTBF	224	336	336	224	672	112	336	56	168	336	134	112	52
F7	IMTBF	301	293	288	285	283	281	279	278	276	275	274	273	272
	InMTBF		67	170	171	149	141	168	209	225	189	203	230	273
	TMTBF	672	134	224	168	134	134	224	336	224	112	224	336	672

Colour Coding

RED: > 5% Deterioration in calculated value

ORANGE: Calculated value within +/- 5% of

GREEN: >5% Improvement in calculated value

GREY: No Data

Figure 7-6 Populated Front Panel Worksheet – Output after Analysis is Completed

7.1.6 The Year drop down table

This table incorporates the list of all operating years contained within the analysis; this list is manually inputted into the operational macro and is currently set at ten operating years starting on 1/1/2007. Using the window activates the subroutine Year Select (see Appendix 2). The selection of a specific year moves that year into the main window. The default year for the main view window is specified as the current year, 2011 at present. The “Front Panel” worksheet is representative of the Hot Strip Mill operating process at Port Talbot. Upon transference to another manufacturing area this sheet will require updating with the relevant “Areas and Classes” which are relevant to that area.

7.1.7 Process Mimic worksheet

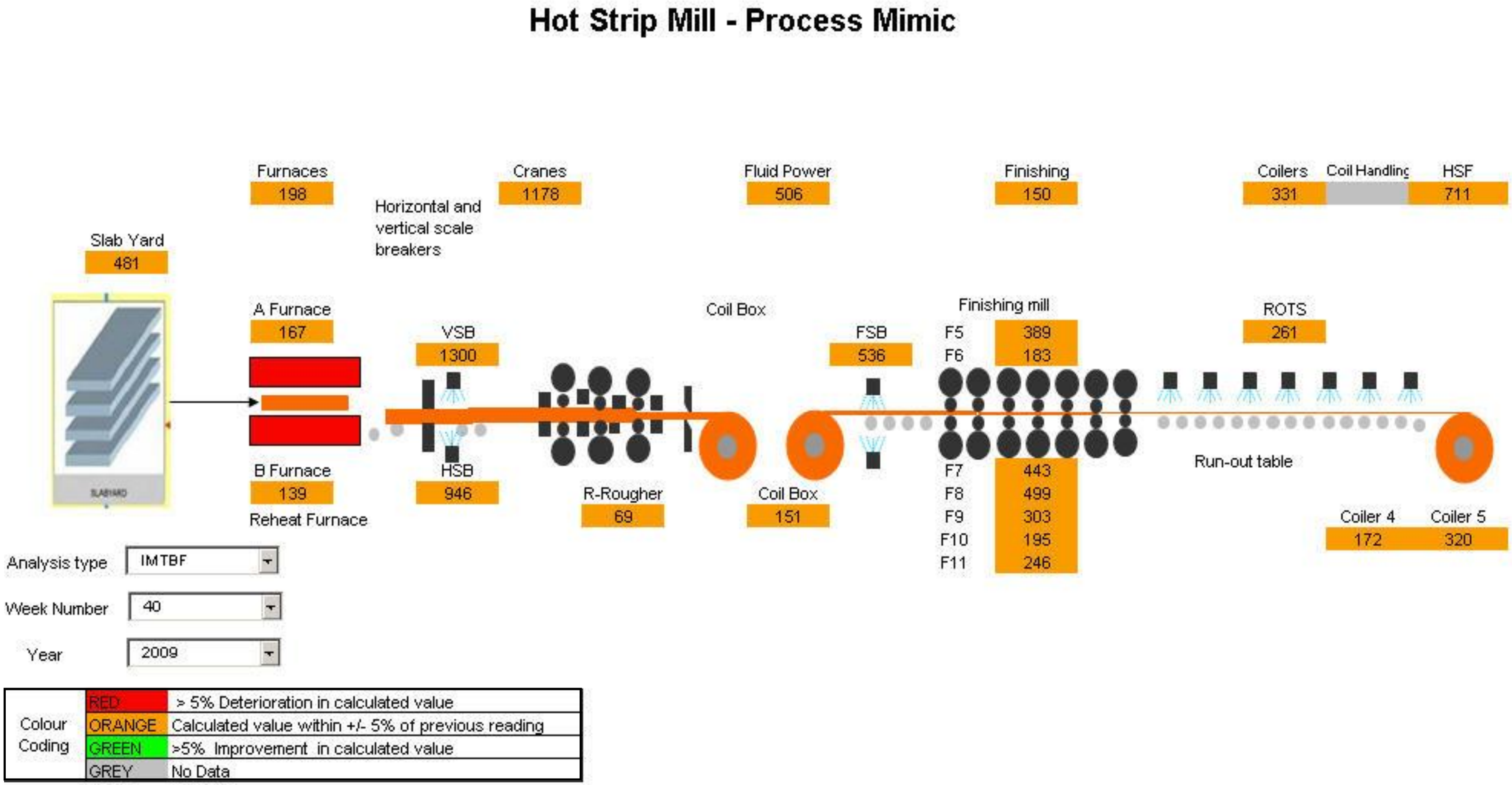
This worksheet is closely related to the Process Mimic used within the Hot Strip Mill monitoring system (see Figure 7.7) and was constructed so that the operating staff at Port Talbot could easily recognise their operating areas. The Process Mimic offers a one page schematic view of the operating process at the Hot Strip Mill. This schematic includes all of the operating areas within this manufacturing unit; these are predominantly presented in a series arrangement. The support services are depicted as running parallel to the main manufacturing process.

Situated underneath the cartoon depiction of each area is located a reference box which displays the relevant time between failures for that area when the sheet is activated.

This worksheet contains three drop down tables which allow the process mimic to be updated when required, all time between values in the Process Mimic adhere to the same colour code arrangement installed in the “Front Panel” worksheet.

Analysis type: This table accesses the respective results from the “Front Panel” worksheet. These values are inserted in the cells next to their respective areas the table allows the operator to display the IMTBF, InMTBF or the TMTBF values in the process mimic.

Week number: This table selects the calculated results from the “Front Panel” worksheet within the specified week number. This updates the values in the relevant cells.



Analysis type: IMTBF

Week Number: 40

Year: 2009

Colour Coding		
	RED	> 5% Deterioration in calculated value
	ORANGE	Calculated value within +/- 5% of previous reading
	GREEN	>5% Improvement in calculated value
	GREY	No Data

Figure 7-7 Process Mimic – Output from IMTBF Analysis for Week 40 – 2009 (all figures in hours)

Year: This table accesses the calculated results from the “Front Panel” these are inserted in the cells next to their relevant areas.

In addition the page runs a separate subroutine which updates the relevant cells to the parameters specified in the drop down tables when the worksheet is activated. This feature ensures that the Process Mimic acts as a visual aid by presenting the relevant data in an easily recognisable manner. This Process Mimic can be instantly updated using the drop down tables. The visual reference to the worst performing areas can be used to identify changes in reliability status and drive future maintenance activities. This sheet is solely representative of the Hot Strip Mill operating process. Upon transference to another manufacturing area this sheet will require updating with the relevant Process Mimic for that area. In addition the reference cells will require updating relevant to the replacement process mimic.

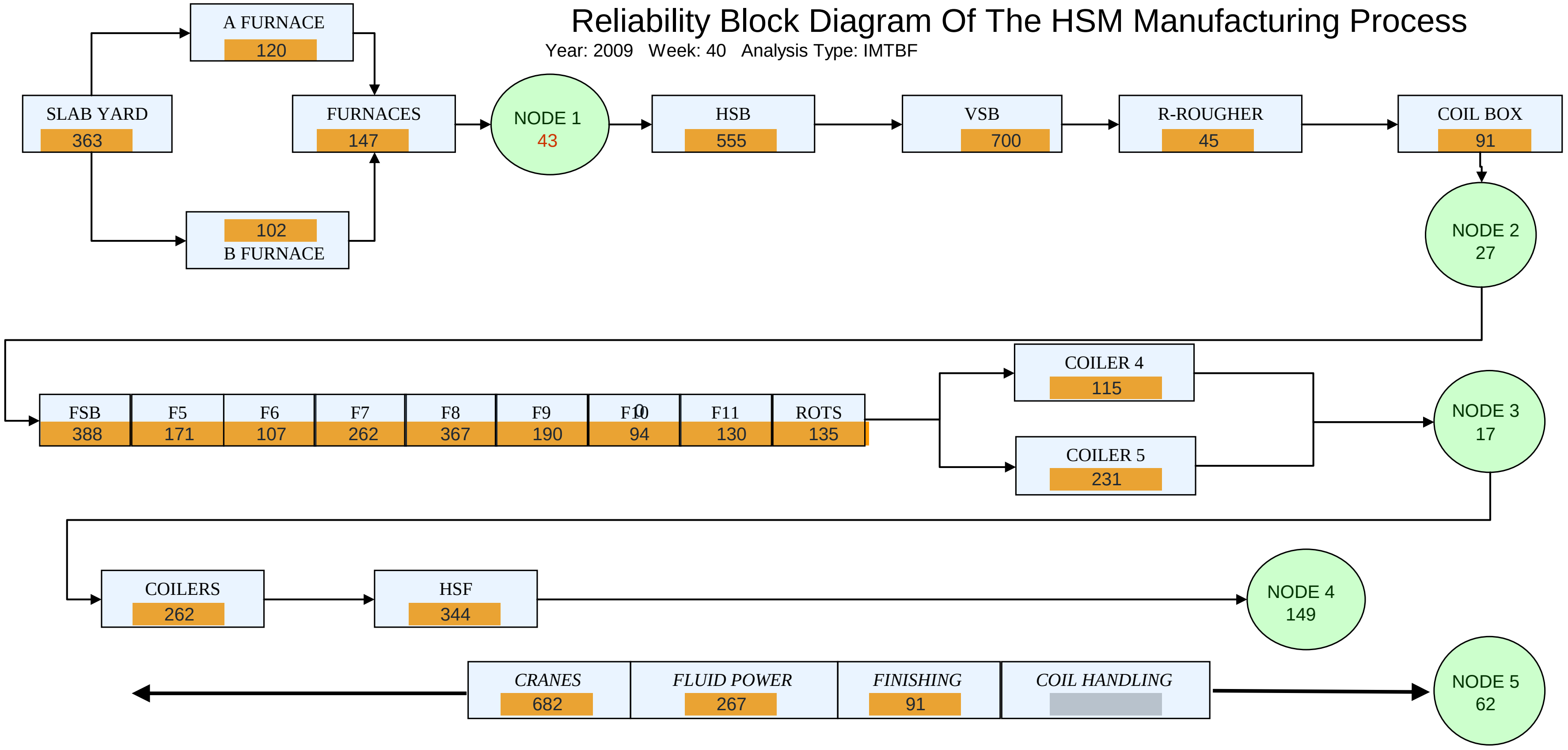
7.1.8 RBD (Reliability Block diagram) Worksheet

This worksheet is directly linked to the “Process Mimic” worksheet and was constructed so that the engineering and maintenance staff could analyse and attain the overall reliability calculations for their operating group or area.

The “RBD” worksheet (Figure 7.8) is a one-page reliability block diagram of the operating process at the Hot Strip Mill. This schematic includes all of the operating areas within the mill; these are presented in a series or parallel arrangement dependant on their construction or operating parameters. Currently the support services are depicted as running parallel to the main manufacturing process, this will be reviewed at a later date and needs to be addressed in any data reformatting exercise. Situated within the reliability “block” for each area is a reference box which displays the relevant time between failures for that area. These reference boxes draw the calculated data directly from the “Process Mimic” worksheet when the sheet is activated. The “RBD” Worksheet sheet has no active macros and is controlled and updated through the “Process Mimic” worksheet utilising the Update Mimic macro.

At the top of the diagram the following detail is indicated

- Year
- Week Number
- Analysis type



Colour Coding	RED	> 5% Deterioration in calculated value
	ORANGE	Calculated value within +/- 5% of previous reading
	GREEN	>5% Improvement in calculated value
	GREY	No Data

Figure 7-8 RBD diagram Output from MTBF analysis Week 40-2009 (all figures in hours)

This detail reflects the current analysis being used on the “Process Mimic” worksheet.

Due to the complexity of this process with its multiple arrangements of systems in series and/or parallel configuration it has been necessary to deconstruct the process into several grouped areas. The reliability calculations for these grouped areas are constructed at several “Nodes”.

These are shown as Node 1-5 in Figure 7.8. These have been defined by the author as the nodal groupings are indicative of, but not direct copies of, the area groups used to manage the Hot Strip Mill operating process. The calculated value in each Node is based on the standard reliability block diagrams for series and parallel configurations depicted in Equations 7.1 & 7.2

Average time between failures (TBF) for an active series system is

$$(TBF)_s = \frac{1}{\lambda_1 + \lambda_2 .....\lambda_n} \quad \text{Eqn. 8.1}$$

Where $\lambda_1 ....\lambda_n$ are the relevant system failure rates.

Whist the average time between failures (TBF) for an active two unit parallel system is

$$(TBF)_s = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1 + \lambda_2} \quad \text{Eqn. 7.2}$$

This sheet is solely representative of the Hot Strip Mill operating process. Upon transference to another manufacturing area this sheet will require updating with the relevant reliability block diagram for that area. In addition the reference cells will require updating relevant to the replacement process mimic.

7.1.9 Final Reliability Block Diagram (RBD) worksheet

This worksheet is directly linked to the “RBD” worksheet and was constructed so that the senior engineering and maintenance staff at Port Talbot could analyse and attain the overall reliability calculations for their manufacturing process. This diagram is intended to be used as a comparator to the Final RBD diagram of other manufacturing areas.

This is an evolutionary development in the use of calculated system reliability values. This diagram will allow high level engineering staff to compare the overall reliability figures of one manufacturing area against a competing process or even competing manufacturing plants. This could assist senior management in identifying a maintenance strategy which will be cost effective and could improve overall process efficiency. The diagram is indicated in Figure 7.9 and all calculations are based on Equations 7.1 - 7.2.

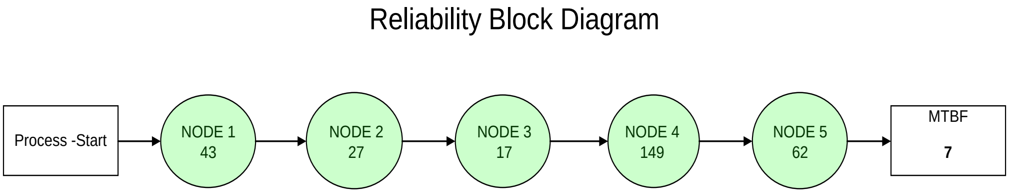


Figure 7-9 Final RBD Diagram (all figures in hours)

Again, this sheet is solely representative of the Hot Strip Mill operating process. Upon transference to another manufacturing area this sheet will require updating with the relevant reliability block diagram for that area.

7.2 SORTED Workbook

The SORTED workbook is the main data-collating workbook and becomes the data source for all of the performed analysis. This workbook is based on the Year to Date (YTD) worksheet used in the Hot Strip Mill and is formatted in a similar fashion.

This workbook contains one main worksheet the “Info” worksheet which is constructed using four main operating columns

Column 1: Search; automatically populated, denotes end of searched data set.

Column 2: Class; denotes the reason for the stoppage, this column is manually populated.

Column 3: Area; denotes the area to be investigated, this column is manually populated.

Column 4: Plant; denotes the manufacturing unit, this takes the form ABBRV which denotes the plant’s abbreviated title, this is used in the file’s saved name.

This workbook is activated by the Sort Database macro contained in the front panel workbook which constructs a new worksheet for each designated area. The macro sequentially inserts data from the separate areas in the YTD workbook into the (area named) worksheets. After all the area data sets have been compiled the SORTED workbook is saved as SORTED (name) e.g. SORTED HSM and closed.

7.3 ANALYSIS Workbook

The ANALYSIS workbook is the main calculations workbook and it performs the calculations for all subsequent analysis. This workbook contains seven worksheets each of which is considered in the following sections.

7.3.1 The “Front” Worksheet:

This worksheet contains all of the data collated from the separate analysis in readiness for exporting to populate the front panel. The data is formed into separate columns which contain:

Column 1: Operating hours: the fixed data set from Hour 0(zero) of 2007.
Column 2: IMTBF; imported from IMTBF worksheet.
Column 3: InMTBF; imported from InMTBF worksheet.
Column 4: TMTBF; imported from TMTBF worksheet.
Column 5: CvM test; imported from Goodness of fit worksheet.
Column 6: Chi^2 test; imported from Goodness of fit worksheet.
Column 7: Laplace test; imported from Goodness of fit worksheet.

Columns 2 through to 5 are exported directly to the “Front Panel” worksheet, the remaining columns are intended to be examined during the detailed analysis of the individual operating area.

7.3.2 The “Input Data” Worksheet:

This sheet is predominantly populated by data imported from the SORTED workbook. This worksheet contains four columns

Column 1: Date: imported from SORTED workbook, gives failure date.
Column 2: Time: denotes recorded start time of failure.
Column 3: Hours: calculated time of operation using the dates and times taken relative to week 0 2007.
Column 4: Start date – manually inputted as 1/1/2007, Finish date automatically inputted as today’s date.

7.3.3 The “MTBF Graphs” Worksheet:

This worksheet contains three graphical representations of the areas performance over the allotted period. This has been previously presented for Coiler 5 in Figures

6.3/6.5/6.7. All the required data for the construction of these graphs is contained within this worksheet in separate columns.

Column 1: Year/Week number: designated as 2007-0 up to 2009-52 in this example.
Column 2: Weeks: 4 week incremental rise from week 0 of 2007.
Column 3: Hours; Time of failure from INPUT DATA worksheet.
Column 4: Cum.Fail: cumulative failures taken from INMTBF worksheet.
Column 5: IMTBF; calculated analysis results from IMTBF worksheet.
Column 6: InMTBF; calculated analysis results from InMTBF worksheet.
Column 7: TMTBF; calculated analysis results from TMTBF worksheet.

7.3.4 The "IMTBF" Worksheet:

This is a version of the worksheet outlined in the development model and contains the analysis calculations for the IMTBF method using the equations depicted in Equations 4.2 – 4.6. Data from the "Input Data" worksheet is imported into column 1 and the stated equations are used to calculate the required parameters which are exported to the "Front" and "MTBF Graphs" worksheets.

7.3.5 The "InMTBF" Worksheet:

This is again a direct derivative from the IMTBF method contained in the development model. The analysis using the equations depicted in Equations 4.2 – 4.6 applied sequentially through the addition of the cumulative failures recorded in each 4 week (672) hourly period. Data from the "Input Data" worksheet is imported into column 1 and the stated equations are used to calculate the required parameters which are exported to the "Front" and "MTBF Graphs" worksheets.

7.3.6 The "TMTBF" Worksheet:

This is a direct derivative from the HPP method contained in the prototype model. The analysis uses the equations depicted in Equations 6.2/6.3 which is applied sequentially through the addition of the cumulative failures recorded in each 4 week (672) hourly period. The data from the "Input Data" worksheet is imported into column 1 and the stated equations are used to calculate the required parameters which are exported to the "Front" and "MTBF Graphs" worksheets.

7.3.7 The “Goodness of Fit Worksheet”:

This is a derived from the goodness of fit methods contained in the development model, three test methods are used:

Data from the “Input Data” worksheet is imported directly into column 1 and the stated equations are used to calculate the required parameters which are exported to the “Front” and “MTBF Graphs” worksheets.

In standard operation the workbook is activated by the macro contained in the front panel workbook which sequentially inserts data from the separate areas in the SORTED workbook into the “Input Data” worksheets, after the area analysis is complete, the analysis workbook is closed and the sequence repeats until all areas have been analysed. After the completion of the analysis sequence the FRONT PANEL workbook is populated and no additional analysis workbooks are retained. During the detailed analysis procedure the requested area examination takes place and the designated area analyses workbook is saved as ANALYSIS (name) e.g. ANALYSIS F5.

7.4 Final Analysis Model Testing and Verification

After the construction and automation of the final model had been completed a testing regime was instigated to ensure that all calculated values are within acceptable limits. All previous test regimes had used the data set obtained from the Hot Strip Mill for the period 2007-2009 inclusive. It was decided to use this data set for the verification check of the commercial software results against the final analysis model. The original data set used in the development of this model from Zhao [Zhao et al 2005] was included for continuity. The testing regime was applied directly to the ANALYSIS model. All of the IMTBF Power Law analyses in this verification test started at time 0 (zero) set at 1/1/2007 and the total test run time was taken as 26328 hours. From Table 7.1 it can be seen that there is an almost perfect match between the calculated results for β, λ and the IMTBF value in all areas.

The InMTBF calculation is a bespoke application. However this calculation applies the Power Law in an incremental manner. Therefore due to the use of identical Power Law equations it is concluded that the calculated InMTBF value for an identical analysis run time should give a value close to the corresponding IMTBF value.

Due to the construction of the latest ANALYSIS workbook, which are relative to week numbers per year, the nearest calculated test end time was a run time of 26208 hours. This gives a maximum discrepancy of approximately 4% in the calculated InMTBF and IMTBF values which are displayed in Table 7.1.

Table 7-1 Power Law Analysis Comparison

Power Law Analysis - Original Data Set (2009 Week 52)										
	Commercial Software (Power Law) Finish Time 26328hrs			**Final Analysis Model (Power Law IMTBF) Finish Time 26328hrs**			**Final Analysis Model (InMTBF) Finish Time 26208hrs**			No of Failures
AREA	Lambda	Beta	IMTBF	Lambda	Beta	IMTBF	Lambda	Beta	InMTBF	
A FURNACE	0.0516	0.8854	99	0.0516	0.8554	99	0.0501	0.8588	98	312
B FURNACE	0.0216	0.9538	78	0.0216	0.9538	78	0.0247	0.9391	80	355
COIL Handling	No Data									
COIL BOX	0.2492	0.7204	96	0.2492	0.7204	96	0.2441	0.7228	95	381
COILER 4	0.0006	1.2694	82	0.0006	1.2694	82	0.0006	1.2717	81	254
COILER 5	0.0003	1.12742	152	0.0003	1.2742	152	0.0003	1.2722	153	136
COILERS	4.0369E-05	1.4684	144	4.0369E-05	1.4684	144	0.0000	1.4783	142	125
CRANES	0.0004	1.1181	604	0.0004	1.1181	604	0.0006	1.0949	613	39
F5	0.0025	1.0595	205	0.0025	1.0595	205	0.0028	1.0470	210	121
F6	3.7113E-05	1.5325	77	3.7113E-05	1.5335	77	0.0000	1.5443	76	223
F7	0.0010	1.1380	225	0.0010	1.1380	225	0.0009	1.1439	222	103
F8	0.1105	0.6860	322	0.1105	0.6860	322	0.1084	0.6881	320	119
F9	0.0089	0.9640	169	0.0089	0.9640	169	0.0090	0.9623	169	162
F10	0.0004	1.2975	92	0.0004	1.2975	92	0.0004	1.2993	91	222
F11	0.0099	0.9734	136	0.0099	0.9734	136	0.0095	0.9778	135	199
FINISHING	0.0066	1.0576	79	0.0066	1.0576	79	0.0063	1.0627	79	314
FLUID POWER	0.0098	0.9068	290	0.0098	0.9068	290	0.0095	0.9106	288	100
FSB	0.0003	1.2429	259	0.0003	1.2429	259	0.0002	1.2500	256	82
FURNACES	0.0595	0.8266	119	0.0595	0.8266	119	0.0594	0.8266	119	268
HSB	0.0208	0.7794	582	0.0208	0.7794	582	0.0203	0.7822	578	58
HSF	3.0458E-06	1.6434	287	0.0000	1.6434	287	0.0000	1.6558	283	56
ROTS	0.0001	1.3796	118	0.0001	1.3796	118	0.0001	1.3884	117	162
R-ROUGHER	0.0840	0.8927	40	0.0840	0.8927	40	0.0822	0.8951	40	742
SLAB YARD	0.1458	0.6635	317	0.1458	0.6635	317	0.1433	0.6655	315	125
VSB	0.0868	0.6204	883	0.0868	0.6204	883	0.0855	0.6222	878	48
ZHAO data set	0.2156	0.9298	NA	0.2156	0.9298	NA				

Through manually manipulating the worksheet it is possible run both analysis methods with a run time of 26328 hours. To demonstrate this feature the three largest percentage error values (highlighted) from Table 7.1 were used to perform this additional test, the results are displayed in Table 7.2. It can be seen that the manual modification to the test run time proves that the IMTBF and the InMTBF calculated values are verified.

Table 7-2 Analysis Comparison IMBTF – InMTBF

Comparison Analysis - 26328 hours run time							
	Final Analysis Model (Power Law) Finish Time 26328hrs			**Final Analysis Model (InMTBF) Finish Time 26208hrs**			Number of Failures
AREA	Lambda	Beta	IMTBF	Lambda	Beta	InMTBF	
B FURNACE	0.0216	0.9538	78	0.0216	0.9538	78	355
CRANES	0.0004	1.1181	604	0.0004	1.1181	604	39
F5	0.0025	1.0595	205	0.0025	1.0595	205	121

From the above testing regime it is concluded that the calculations obtained from the latest TRAM method are verified to the earlier results obtained from the commercial software reliability analysis package. It can also be deduced from the earlier testing regime between the development model and commercial software that all constructed analysis models are verified to each other. The final analysis model will be used for application of the reliability analysis methodology throughout this manufacturing facility. The construction of these worksheets leads onto the intended operating methodology for the reliability analysis model from inception to monitoring the current system status.

This is illustrated in the following chapter which applies this approach to a case file of an earlier reliability investigation into the descaling system at the Hot Strip Mill. This case file indicates how the reliability analysis method constructed in this Thesis can be used to investigate and construct the reliability parameters of an operating system at this plant. This analysis demonstration in Chapter 8 presents the influences of machine reliability in respect to the descaling system in the Hot Strip Mill and the possibility of wider use of the reliability analysis techniques researched in this Thesis.

8 Case File - Reliability Analysis of the Descaling system at the Hot Strip Mill

The potential benefits of the reliability assessment made possible in this research can be demonstrated in respect of a project undertaken within the descaling system. The descaling system at this manufacturing facility is a large scale water pumping and supply system that is expected to provide up to 21,000 litres per minute at up to 180 Bar pressure. The system is expected to operate on a 24 hour 7 days per week pattern with maintenance predominantly scheduled for the plants two week shutdown period. This system has been in continuous operation since 1984 and some sections of the system are nearing the end of their design life. The project originated in January 2008 and involved capital expenditure projected at up to £2 million. During the construction of the business case for the system upgrade it became part of the project remit to identify the current reliability status of the descaling system with a view to possible improvement to the system through the replacement of strategic operational sections of the system.

The descaling system is responsible for removing the oxides that form at elevated temperatures on the processed metals surface (upon contact with the surrounding atmosphere). These oxides are known as scale and form at different rates depending on the metals processing conditions. This is a high pressure water system which forces water through directional nozzles onto the steel strips surface. The system upgrade was needed to improve several aspects of the system notably its reliability and efficiency whilst decreasing the energy usage and operating costs. This system is quality critical for the manufactured product; any scale remaining on the product can result in the product being downgraded or scrapped.

The existing descaling system generates the high pressure water supply from three pumping stations. Each of these consists of a 2.1 mega watt electric motor supplying power through a gearbox to a large centrifugal pump, as shown in Figure 8.1. The pressurised water is supplied to an internal reservoir known as the accumulator shown in Figure 8.2, which stores approximately 7000 litres of pressurised water to balance the discrepancies between water supply and demand. From here the pressurised water is supplied through several hundred meters of pipe work to series configurations of Seco control valves and their headers, which are located within the mill process (Figure 8.3).

Each header contains approximately forty nozzles and is the point of application for the pressurised water onto the processed metal.

Figure 8-1 Pumping station

Figure 8-2 Accumulator

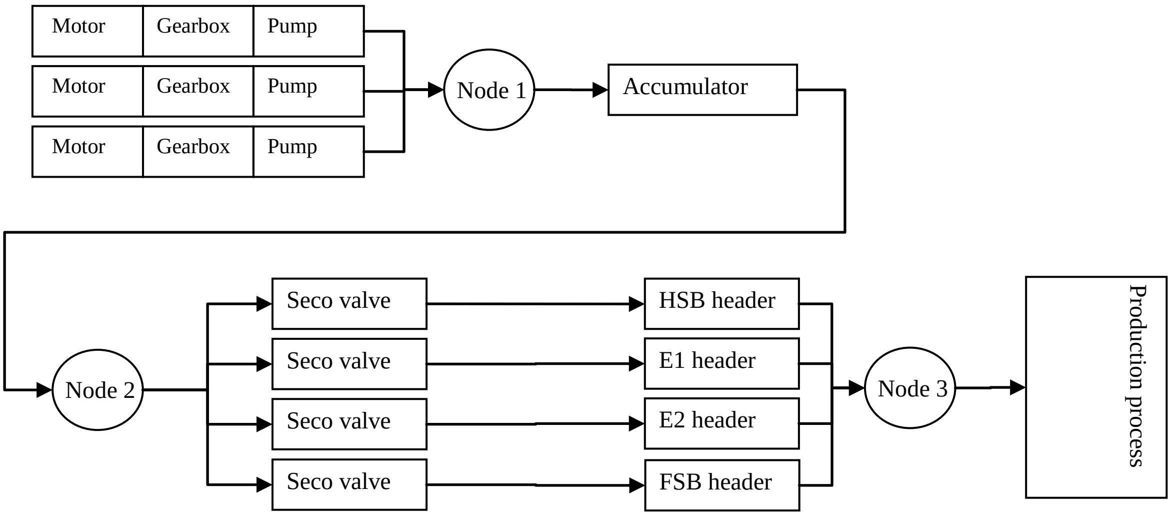


Figure 8-3 Reliability Block Diagram – Descaling system

8.1 Failure Data Sources and Their Input to the Investigation

The investigation into the original descaling system identified three main sources of data relating to its operating history. The operating data relevant to this system referenced a previous operational software system, which had been installed at Corus. This software control system had been declared obsolete and was superseded by the latest software operating system in 2005. During the transference of the data it was found that the historical data required significant amount of the new operational software's memory capacity. This memory requirement dictated that truncated versions of all historical operating data were compiled and saved. This data is the only available record of the descaling systems performance prior to 2005 and this failure data source was used as the base for the reliability centred maintenance (RCM) activity performed on the descaling system in 2005. This situation is typical of the difficulties faced in the conduct of this research with respect to the nature of reliability information and the diverse formats on which it is stored. The manual effort required to gather and analyse this information is one of the major reasons for the enactment of this research. Each of these three sources of data will now be considered.

8.1.1 Reliability Centred Maintenance Data (RCM) (Data Source1)

There had been a major RCM exercise on the descaling system in 2005; a cross functional team of engineers and operators carried out the exercise covering the period 1984 – 2005. The data was compiled from historical plant data, which was recovered from the obsolete operational software system by Tata Engineers, table 8-1 is indicative of these data collations Where no data was available estimates based on operational knowledge have been made by the team as to the reliability of the system. The review of the accumulator is shown in Table 8.1 as an example of this exercise. As can be seen in Table 8.1 the only detail on the failure frequencies is the failure frequency per annum e.g. “Frequency = 6”. Therefore the assumption was made that all of these failures were uniformly distributed over the operating period. There is no evidence available to support or disprove this assumption; therefore the validity of the assumption is questionable. However the use of this assumption allows the use of the homogeneous Poisson process (HPP). This analysis method is the only one that can be applied to this data se on these circumstances. The further assumption is made that each breakdown is statistically identical and independently distributed (SIID) as required for the application of the HPP analysis method.

Table 8-1 Reliability Centred Maintenance (RCM) sheet for accumulator

RCM II INFORMATION WORKSHEET		**System** *Descaling*		**System** *Descaling*		**Compiled by: Mick Power** **Date: 14-apr-08**
		Sub System *Accumulator*		**Ref** *Hot Mill Descaling*		**Reviewed By:** **Date: Sheet: 1 of 8**
FUNCTION		**FUNCTIONAL FAILURE**		**FAILURE MODE (Cause of failure)**		**FAILURE EFFECT (What happens when it fails**
1	To absorb fluctuations in pressure due to changes in demand.	A	Fails to absorb fluctuations in pressure due to changes in demand.	1	Excessive demand for flow caused by nozzle failure	Descaling pumps trip on low pressure, electric isolation valve closes, no water supplied to mill. Loss of descaling capability. Freq = 0
		A		2	Excessive demand for flow caused by pipe failure	Descaling pumps trip on low pressure, electric isolation valve closes, no water supplied to mill. Loss of descaling capability. Freq = 0
		A		3	Insufficient air due to non detection/replacement of lost air by pumps man	High level trip puts descaling pumps into low speed and will not allow return to high speed, even if pressure is less than 179bar. Descaling continues at a lower pressure, would eventually lead to a reduction in descaling capability. If plant is on stop and tank water level high before valve closed, cannot engage high speed on restart to create pressure on discharge side of electrical valve to balance pressure. **Freq = 6 every year**

The MTBF calculation is the measurement parameter which is applicable to this failure data set using the HPP analysis method. All MTBF calculations based on the data from the RCM exercise (Table 8.1) were manually collated and formatted on to an analysis sheet (Table 8.2) by the author. The manual formation of a calculation sheet for each unit of the descaling system allowed the reliability block diagram (RBD) of the descaling system to be constructed. A truncated version of the original RBD diagram is illustrated (Figure 8.4) which contains a breakdown of the calculated MTBF values for the descaling system at strategic points.

Table 8-2 MTBF Analysis Worksheet of Accumulator from RCM Activity in 2005,

Accumulator data taken from RCM report compiled by Mick Power in 2005			Years	Number of Hours to Breakdown	Failure Rate per 1000 Hour	MTTR Hours per Item	MTTR Total Hours
	Component- failure mode	Quantity of Breakdowns					
1	Insufficient air - on detection by pumps man	6	1	1460	0.68	18	12.33
2	Drain valve failure	1	20	175200	0.01	24	0.14
3	Pipe work/joint failure	2	20	87600	0.01	24	0.27
4	Incorrect calibration	1	2	17520	0.06	24	1.37
5	Damage due to incorrect handling	1	2	17520	0.06	24	1.37
6	Damage due to incorrect storage	1	2	17520	0.06	24	1.37
7	Isolation valve switch set to manual	1	3	26280	0.04	15	0.57
8	Automatic valve passing	2	5	21900	0.05	48	2.19
9	GEM 80 PLC fuse blown	1	20	175200	0.01	18.1	0.10
10	Loss of electrical signal to valve	1	5	43800	0.02	2	0.05
11	air supply fails	10	20	17520	0.06	2	0.11
12	in manual op mode and selected to close	1	1	8760	0.11	1	0.11
13	Manual /auto valve switch selected to manual with valve open	15	20	11680	0.09	4.5	0.39
14	Isolation valve seized open	2	20	87600	0.01	30	0.34
15	drain valves seized closed	1	5	43800	0.02	2	0.05
16	remote emergency stop not released	5	20	35040	0.03	1	0.03
17	no cooling water flow	4	1	2190	0.46	0.5	0.23
18	control panel faulty	1	20	175200	0.01	2	0.01
19	compressor left running and overfills accumulator	5	20	35040	0.03	0.5	0.01
20	level float stuck	3	20	58400	0.02	24	0.41
				Totals	**1.81**	**(A)**	**21.46**
			MTBF =		1000/(A)	552	**(B)**
			MTTR =		(B)/(A)	12	
			Availability		=	0.98	

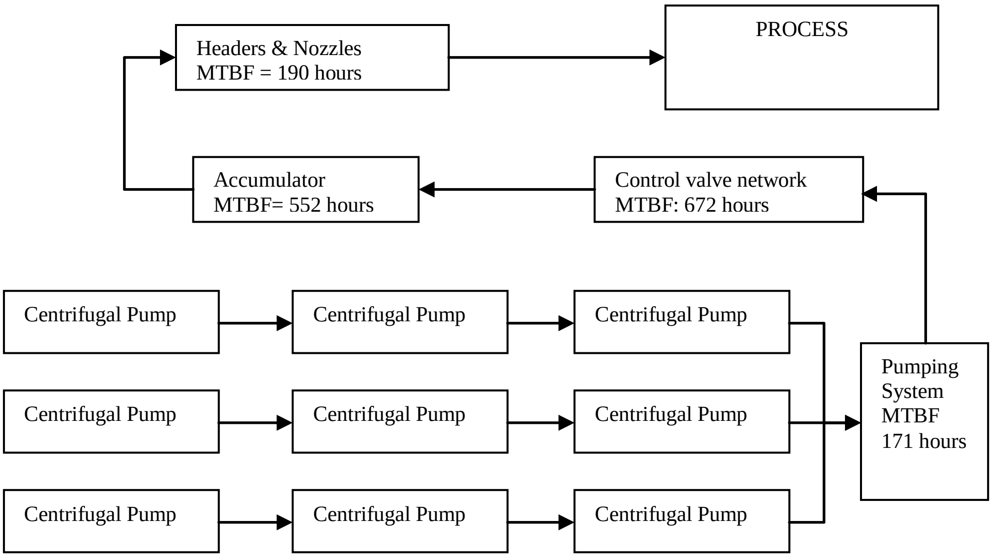


Figure 8-4 Original MTBF Reliability Block Diagram using RCM Data

8.1.2 Pump House Monitoring System (Data Source 2)

Running in parallel to the failure recording systems operational at the Hot Strip Mill is a "pump house monitoring system". This is a condition monitoring system which is focused solely on the water pressure generating side of the system i.e. the series arrangements of motor, gearbox and pumps shown in Figure 8.4. This is an automated monitoring system which continuously logs the operational health of the system. Due to the amount of data being collated this system operates on a rolling four week cycle. In effect this means that the maximum run time data that can be accrued from this system is four operational weeks or 672 hours, after 672 hours the failure data set is deleted. Therefore it was decided that this system is not suitable for a long term analysis method and no further investigation was made into these data sets. It should be noted that references to this data source were found within the RCM data set, the original referenced data is not available for further examination.

8.1.3 Year to Date (YTD) Monitoring System (Data Source 3)

A detailed description of this data monitoring system is presented in Chapter 4. Hot mill engineers introduced this failure/stoppage monitoring system into the Hot Strip Mill in 2007 as a method of improving the plant monitoring system. This data set was not used in the construction of the business case for the descaling system upgrade which was submitted in Quarter 3 of 2007. This was due to the short time period that this data monitoring system had been active. It was noted that the data logging methods used to compile the year to date failure date automatically constructs the failure data sets for each process area. However these data logging methods do not support any method of quickly retrieving the failure data relevant to the area subsystems. This means that data for these subsystems has to be retrieved from the area data set through a manual, time consuming process. In order for the reliability analysis of this system to be carried out required manually accessing failure data which was logged in four separate areas, these areas are identified in the descaling systems reliability block diagram (Figure 8.5).

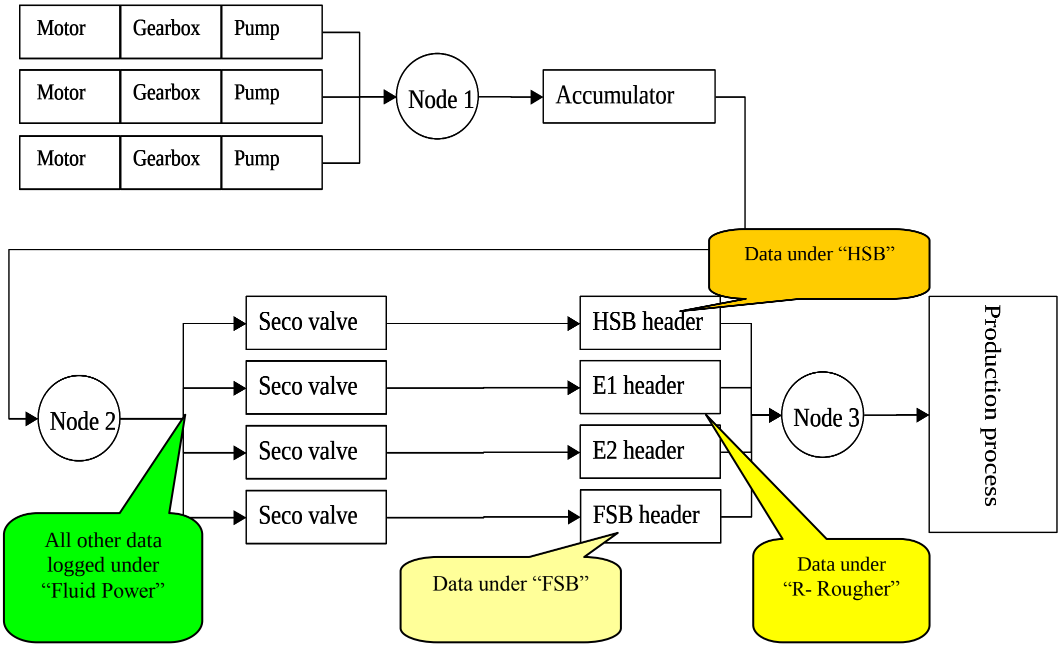


Figure 8-5 Reliability Block Diagram of the Descaling System

8.1.4 Descaling System Analyses 2007-2010

As stated in Section 8.1.1 the original descaling system reliability analysis was carried out using the RCM data set from 2005, summary values from this analysis are presented in Table 8.3 under the 2005 data set heading. The reliability block diagrams in Figures 8.4 and 8.5 are constructed with each reliability block representing a failure data collection point. This comparison can visualise the differences in the failure data which has been recorded in the RCM method compared to the failure data recorded in the year to date recording method. The RBD in Figure 8.5 is more representative of the actual descaling system.

The process of collating data and analysing the descaling system informed the author of the desirability to develop an improved reliability analysis methodology. In addition the investigation highlighted the process improvements which could be attained through replacement of the motor-pump system. Due to the differences in the data set structure it was not possible to perform a direct comparison between the analyses carried out on the 2005 data set against the 2007-2010 data sets. The development TRAM method initiated in this research was used in the construction of the 2007-2010 analysis. The results from the Power Law (IMTBF) analysis are the only suitable method for this examination due to the differences in the failure data sets. As stated in Chapter 4, the year to date (YTD) data set does not allow data sets relevant to the subsystems of an individual area to be easily compiled.

However the ability to access the individual “Sorted” area data sets by using the reliability analysis model produced in this research does improve the formation of the data relevant to the particular subsystem. A data set relevant to the descaling system was withdrawn from the “Sorted” data set for the period 2007 – 2010. This data set was manually compiled into the relative subsystems and analysed using the TRAM method. The resulting calculated values are compared to the initial calculations obtained from the reliability centred maintenance data set from 2005 in Table 8.3. The calculated values for the 2007 – 2010 data sets reflect the reliability indices as of week 52 in 2010.

The IMTBF figures shown in Table 8.3 are a “snapshot” of the systems reliability health in Week 52 - 2010. These calculated values bear no relationship to the earlier RCM values. However when compared to the manually calculated MTBF value over this period it is possible to identify if the system is improving.

For example the Reversing Rougher (R-Rougher) Seco valve shows an IMTBF value of 9752 hours compared to the MTBF (average) value of 8736 hours. The capability of recognising a deteriorating system is highlighted in the FSB- Seco valve which indicates an IMTBF value of 1510 hours compared to the calculated MTBF value of 4368 hours.

Table 8-3 Comparisons of Reliability Indices from the 2005 and 2007-2010 Data Sets

2007-2010 Data set			2005 Data set	
Area	TRAM method IMTBF values, Week 52 2010 (Hours)	Manual calculation MTBF (Hours)	Manual Analysis using RCM data set	MTBF (Hours)
Reversing Rougher (R-Rougher)			Header & Nozzles	190
E1	7844	5824		
E2	No data	34944		
Seco Valve	9752	8736		
HSB				
Header	4125	5824		
Seco Valve				
FSB				
A Leg	3195	2912		
B Leg	1926	4368		
Seco valve	1510	4368		
			Distribution system	1627
Pump House	1357	1519	Pumps	365
			Gear box	338
			Motor	7266
Accumulator	919	2184	Accumulator	552

From a cross check of the MTBF values in Table 8.3 it can be seen that there are considerable discrepancies in the calculated values relevant to each subsystem. This is highlighted when the sections of the Descaling system are compiled in a comparable format as shown in Table 8.4 data comparison table.

Table 8-4 Data Comparison Table

2007-2011 Data	MTBF (Hours)	2005 data	MTBF (Hours)
Header & Nozzles	777	Header & Nozzles	190
		Distribution system	1627
Pump House	1519	Pump House	171
Accumulator	2184	Accumulator	552

It could be assumed that MTBF from both data sets should be of similar magnitude. However it can be seen in the cases of the “Header and Nozzles” and “Accumulator” that there is an approximate factor of four in the difference in their calculated MTBF values. This increases to a factor of approximately ten in the “Pump

House" calculated values. This can be due to several reasons including the differences in the data sets compilation. The 2007-2010 data sets are based on *actual* production line stoppages attributed to the descaling system, whereas the 2005 data set is based on component failure within the descaling system regardless of the occurrence of a line stoppage. In addition estimates were made of the component failure rates in the RCM data set. This highlights the discrepancies present in the formatting of the data sets and indicates the requirement for a more robust data monitoring system.

In the case of the "Pump House" data set it is recognised that data from the pump house monitoring system (Data Source 2) has been included within the RCM data set. This data set includes "alarms" raised by the monitoring system which have been incorporated regardless of whether the operational unit (pump, motor etc) has continued operating. Again the alarm conditions in this operating section need to be reviewed in line with operational requirements.

8.1.5 Descaling System Modification and 2011 Reliability Analysis

The author was responsible for the construction of the business case for this process upgrade to the scaling and continued to contribute to the project until final project sign off. The reliability analysis of the descaling system formed part of the business case for the project. The importance of being able to access accurate reliability information in this case was seen as further justification for the development of the TRAM method. The upgrade to the descaling system consisted of the removal of the motor- gearbox arrangement and the installation of a direct drive, motor to pump configuration. A variable speed drive (VSD) was installed and this now acts as the control for each motor-pump configuration. A reliability block diagram for this new system has been produced to reflect the modifications to this system and is shown in figure 8.6. The Hot Strip Mill operation required a sequential installation of each variable speed drive and its respective electric motor. This has been carried out since January 2011, with the final installation in March 2011. All new equipment was installed with no disruption to the Hot Strip Mill process.

There has been one recorded failure to date due to a faulty optical cable. The reliability testing regime has been extended to incorporate the Descaling system upgrade. This analysis is required to prove the revised reliability status of the upgraded descaling system. It is accepted that due to the short time since project installation there is a limited amount of failure data available for analysis. However early indications are favourable, and the continual monitoring of this system will provide further verification of the systems reliability status.

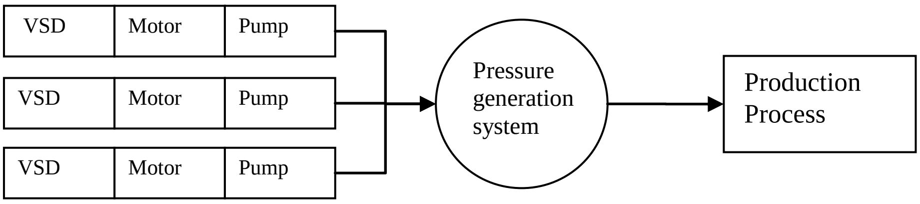


Figure 8-6 Reduced Reliability Block Diagram Descaling System

The revised system has been operational for six months at August 2011, and the latest failure data has been used to calculate the reliability indices for the modified section of the descaling system. The reliability calculations are solely based on the pressurised water supply to the final section “Production Process”. This is considered as the water supply into the Seco water distribution valves (see Figure 8.5.) The descaling systems reliability indices over the period 2007 – 2010 have been compared to the upgraded descaling systems reliability indices in Table 8.5. The upgraded systems operation used the latest failure recording spreadsheet the, Mill Delay 2011 data sheet which was analysed using an updated TRAM method. For convenience sake it is prudent to focus on the areas of the descaling system which have been upgraded for this analysis.

Table 8-5 Comparison of Upgraded Descaling Systems Reliability Indices

	2007-2010 Data IMTBF (Hours)	2007-2010 Data MTBF (Hours)		2011 data IMTBF (Hours)	2011 data MTBF (Hours)
Pump House	1357	1519	Pump House	4032	4320
Accumulator	919	2184			
Total	548	**896**	Total	4032	**4320**

It can be seen from Table 8.5 that the upgrade to the descaling system has considerably improved the reliability performance of the descaling system, with the MTBF values (bold type Table 8.5) rising from 992 hours for 2010 to 4320 hours for 2011. These figures must be reviewed with caution as the descaling system has been ramped into full operational mode and the full upgrade has not been in operation for enough time to collate meaningful failure data. However the continual monitoring of the descaling system through the TRAM method will allow the Tata engineers to correlate these findings at a later date.

The upgrade to the system was instigated to improve the descaling systems reliability and initial confirmation of this is reflected in Table 8.5. Other important consequences include the isolation of the accumulator which has decreased the amount of high pressure water maintained within the system to approximately 3000 litres which will improve system safety. In addition the energy usage required maintaining a large volume of water at a high pressure, plus the efficiency losses due to the gearbox and motor operation have been severely diminished. The upgraded system has reduced the cost of consumed energy by approximately 15% per month. It is believed that the more stable operating requirements offered by the upgraded system will remove the large fluctuations in operating pressures which will be reflected in reduced component wear. In addition the removal of water holding areas such as the accumulator should reduce the formation of rust and scale within the system. This will have a beneficial impact on nozzle performance and the corresponding descaling and product quality.

An improvement in product quality is an additional benefit that should be realised by the system upgrade. This system is expected to produce high volumes of water at the required pressure (up to 185 Bar) to the descaling headers. This produces a high-pressure water jet which is directed at the strip to remove scale from the surface of the metal. If insufficient volume or pressure of water is produced then the descaling operation will be partially successful, and may produce an inferior product. The reliance is then placed on downstream inspection to identify any abnormalities in the product. This is recognised by most modern manufacturing methodologies as the incorrect way to manufacture product with the latest production methods installing monitoring and failsafe methods to ensure that their systems work effectively.

The descaling system operates with two pumping elements in the normal operating mode. The system incorporates a third, redundant, pumping element which is built into the system to ensure effective operation if either of the two operational pumps fail. However this feature can mask inherent defects within the system and makes robust calculation of the descaling system’s reliability indices difficult. The fact that the redundant system is normally designated for reconditioning during its redundant phase means that it will not be available for operation over a certain percentage of its redundancy period. This will mean that a one pumping element operation could occur with a corresponding effect on water pressure and flow which would affect product condition. It is appreciated that redundancy is incorporated into this system to ensure that the continuation of a pumped water supply is maintained, however the redundancy in this operation can allow systematic failures within the system to be covered over by the judicious use of the system's "redundant" section. It could be hypothesised that this method of system operation makes full use of the system's redundancy to ensure continuous production, but there may be additional effects on the systems performance which could be detrimental to the product's quality.

When a failure impinges upon the systems operation, even for a short period, it could take water pressure and flow outside of the stipulated boundaries before the backup systems come into full operation. In effect the system cannot react quickly enough to accommodate all possible failure causes. When this occurs the steel material will be travelling through the mill stands at up to three metres per second. This means that if the pumped water drops outside the stipulated range for three seconds there could possibly be nine metres of steel of inferior quality produced within a 1000 metre steel coil. This production abnormality will be detected retrospectively with a possible re-examination of the coil being required. As can be imagined if defect or downgraded material is produced in sufficient quantities it raises the probability of defective material being supplied to the customer with possible quality ramifications on the steel manufacturing plant.

The use of the TRAM methodology for an in-depth analysis of the descaling system has assisted in identifying the most suitable new machinery for the process upgrade. This has led to the construction of a focused business case which has scoped robust criteria for asset purchase. This has shown that the TRAM methodology can improve the effectiveness of the asset purchasing system. The TRAM method will continue to confirm the upgrade's progress by continually monitoring the systems reliability. The upgraded descaling system has a much improved reaction time through improved monitoring methods and tighter control of operational parameters. These features should improve product quality through minimising water pressure and flow variability and providing advanced notice to operators regarding parameter deviation. In addition the initial use of the reliability analysis methodology in construction of the projects business case has ensured that a robust project proposal was made.

The preceding case file has shown that the judicious use of reliability analysis can support a business proposal to upgrade a process system and verify the upgraded systems performance. The TRAM method provides a long term monitoring method which will continue to monitor this system. The TRAM method is downwardly compatible with all the sub systems in this manufacturing process. It is recognised by the author that the current area classifications are not suitable for automatic retrieval of data relevant to subsystems. Therefore a full review of the data logging methods and area classifications is required to attain the most effective operation of the model.

The next chapter discusses the whole manufacturing scenario at Tata Steel – Port Talbot together with a method of integrating the TRAM method in to the software systems which are operational in this manufacturing plant. This is expanded onto the influences that reliability monitoring can have on the other operational control parameters used at Tata Steel.

9 Reliability Analysis Model - Integration into the steel plant

The Port Talbot steel manufacturing plant is split into four manufacturing sections which form a sequential manufacturing operating. These sections are constructed as stand alone processes and are considered as separate business units, the sections are:

Heavy End:

This areas main focus is primarily for iron making and encompasses three sections. The harbour and stockyards are used for the importation and transference of core materials. The Coke Ovens use the imported coal to manufacture coke intended for the furnaces. This operation also produces thermal energy for the power generation station plus gas fuel which is used in furnaces at other sections of the plant. The Blast Furnaces uses the core materials such as iron ore etc. to manufacture the primary iron which is the core product for the steelmaking process.

Steelmaking process

This facility processes the primary iron through Electric Arc Furnaces and supporting thermal process vessels. These process the iron with different additives to construct the many steel grades which are manufactured at this plant. The steel is processed through Casters of differing configurations which form the cast slabs for use in the next process.

Hot Strip finishing

This processes the cast slab into the hot rolled coils through the Hot Strip Mill, this process accounts for the major deformation within the steel.

The coils can be supplied direct to customer for further processing or transferred to the cold strip mill for further processing

Cold Strip finishing

This is the final stages of manufacture at this facility and will include the rework of the hot strip finished coil to the required specifications. The coil specification is dependant on the steel grade, material dimensions and quality level. All of which require that a multitude of control parameters have to be met before the finished product can be supplied to the customer. When reviewing the operating processes at a large scale manufacturing plant such as this, it is prudent to recall that this plant is currently over 50 years old. It is believed that production will continue at this manufacturing facility for the foreseeable future. Steelmaking is a stable manufacturing process which undergoes incremental improvements rather than evolutionary change. This means that the main process is primarily unchanged since the plants inception. However, with the structured addition of the latest steel manufacturing techniques into the plant, the plant does encompass the latest steelmaking methodologies

This means that processes can be decades old with their main operating systems remaining fundamentally unchanged. Each manufacturing area can contain multiple operating processes with constituent machines being replaced as and when necessary. This results in a curious feature where some operating systems can contain machines and operating units with ages ranging from as new condition to several decades old. The descaling system considered as a case file in Chapter 8 is one such example. This means that it is almost impossible to calculate the actual operating age of any system, and correspondingly that any system installed is expected by default, to last several decades as a minimum.

The next section will deal with the operation and application of the reliability analysis model to the alternative manufacturing areas within this steel plant.

9.1 Reliability Analysis Model -Operating Methodology and Installation Criteria

The intention behind the TRAM method is to monitor all machine systems performance by fulfilling the following criteria:

- The construction of a historical reference to the processes reliability behaviour.
- Acting as a reliability monitoring method indicative of system changes or identifying apparent trends in the system’s behaviour.

The analysis model works in a retrospective manner and it is realised that due to the limitations of the statistical significance requirements the analysis model should not be generically used for reliability growth prediction. It can be proposed that reliability growth prediction using the Power Law process model (IMTBF) can be applied if the Cramer von Mises goodness of fit test indicates statistical significance for the whole data set from model inception or if the goodness of fit test indicates statistical significance for the last year of the system’s operation. The comparison can then be made to a relatively short-term test program.

It is considered that the Cramer von Mises test might not be the most suitable medium for a long term testing regime. Further investigations are required to identify a definitive goodness of fit testing regime suitable for this application. In reality the information generated by the model can always be used as a “comparator” between any numbers of systems being operated under a similar regime. The application of this analysis model to additional manufacturing areas within the same manufacturing facility will allow this comparative aspect of the analysis model to be expanded. This is an intentional design feature of the reliability analysis model and it is expected that this feature will.

- Identify the effect of different operating conditions on similar machinery.
- Identify performance differences between different machines performing similar tasks.
- Identify discrepancies in maintenance regimes and their corresponding effects on similar machinery.
- Identify the differences in quoted reliability figures and the calculated machine reliability indices obtained through the machines working life.

This will allow the identification of the most suitable machinery and the most effective operating parameters for specific applications; in addition the most effective maintenance regimes can be applied. This will allow a “Best Practice” regime to be spread to the whole manufacturing plant. To facilitate this feature the TRAM method has to be readily applicable to the other manufacturing areas in this steel plant. It is envisaged that the integration of the TRAM method into each manufacturing section will follow the flow diagram format depicted in Figure 9.1. To install the analysis model within the additional manufacturing areas in this plant requires access to the new operating area’s failure data set, preferably in an Excel format, or in a format which can be interrogated by SQL and downloaded in an Excel compatible format.

The following additional modifications to the respective templates will also be required:

1. Modification to the SORTED workbook to ensure compatibility with the acquired failure data set notation.
2. Modification to the FRONT PANEL workbook to ensure that the failure data set is accessed correctly by the SORTED workbook, the relevant data sets are transferred to the ANALYSIS Workbook and the calculated results are re-installed in the FRONT PANEL workbook.

3. Modifications to the FRONT PANEL workbook to ensure that all Process mimics and reliability block diagrams are constructed relative to the new operating area.

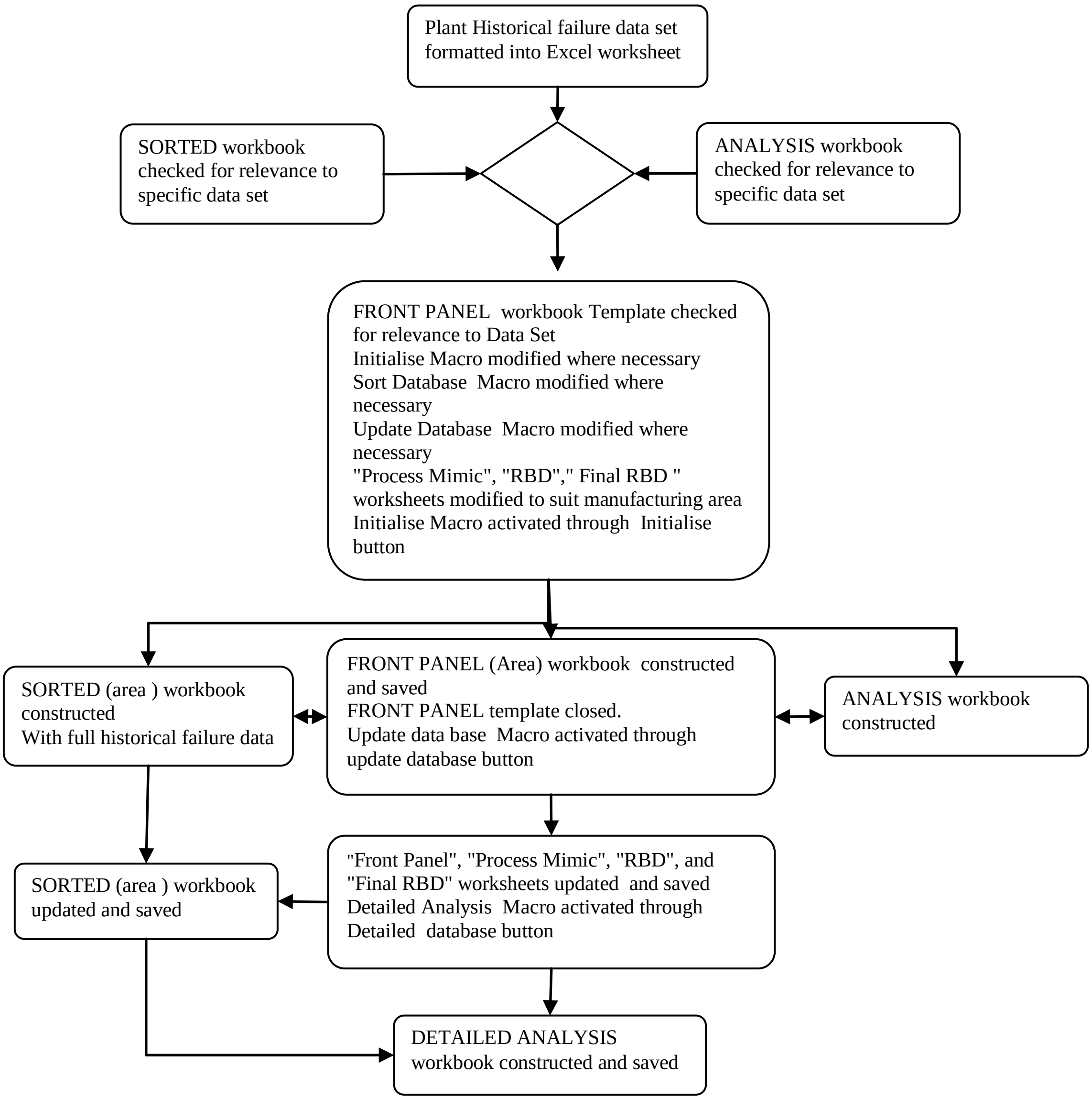


Figure 9-1 Flow diagram of Analysis model Installation and Operating Procedure

As stated earlier one of the remits for the reliability analysis model is that it has to be integrated within the steel plants operational control system. The next section details the asset management framework currently operational at the Port Talbot site and the integration of the reliability analysis model within this framework.

9.2 Asset Management Framework (AMF) at Tata Steel

The current maintenance regimes and asset optimisation processes at the Tata Port Talbot steel works are contained within an operating strategy known as the Asset Management Framework (AMF). This strategy is designed to control all systems or processes from their design stages through to the final stage of operating life –and system decommission.

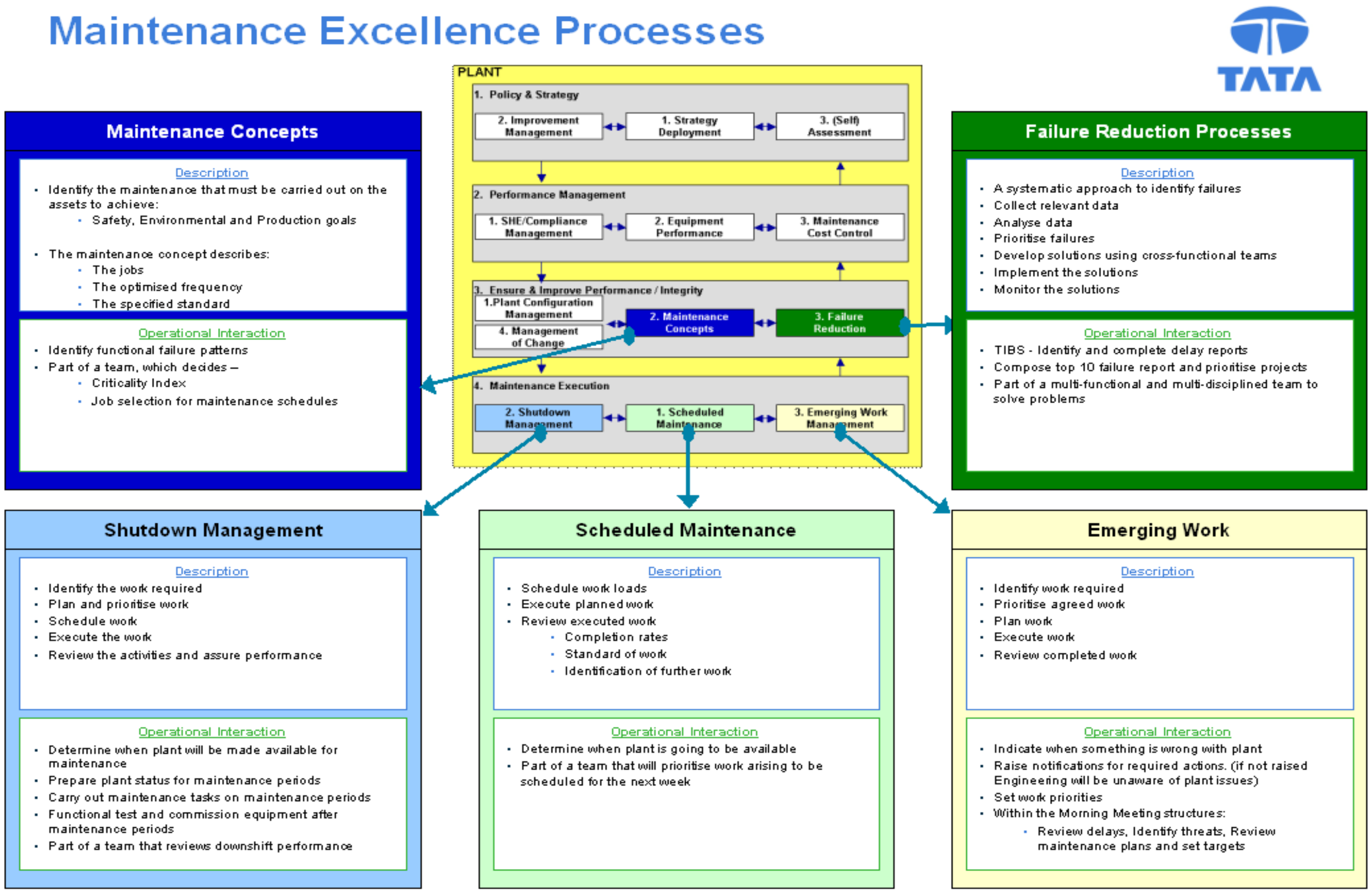
9.3 TRAM Method Integration with AMF

It is the authors' intention is to construct a reliability analysis tool which is compatible with the asset management framework (AMF) which is detailed in the centre of the Maintenance Excellence Process, depicted in Figure 9.2. The intention is to incorporate this model into the Failure Reduction module (section 3.3) of the asset management framework; after all testing regimes have been completed.

The Maintenance Excellence strategy indicated in Figure 9.2 is made up of a number of modules. The diagram illustrates the relationship of the Failure Reduction module to the corresponding modules with its direct links to; maintenance cost control & data assessment, maintenance concepts and emerging work control. Failure data assessment is currently made by dedicated personnel manually deciphering plant data from multiple sources such as shift reports and bespoke data monitoring methods dedicated to the works area (e.g. year to date (YTD) failure sheet). The examining engineers collate this data and complete either or both of the following methodologies:

- Compile a failure reporting and corrective action system report (FRACAS) which can indicate to senior management the future direction for an improvement to the maintenance strategy.
- Initiate a reliability centred maintenance (RCM) activity; this can be supplemental to the FRACAS report or a stand alone exercise.

Both activities are commonplace in reliability engineering. However at this plant the multiple recording systems mean that engineers often have to use personal experience to identify the most suitable course of action.



Maintenance Concepts

Description

- Identify the maintenance that must be carried out on the assets to achieve:
  - Safety, Environmental and Production goals
- The maintenance concept describes:
  - The jobs
  - The optimised frequency
  - The specified standard

Operational Interaction

- Identify functional failure patterns
- Part of a team, which decides –
  - Criticality Index
  - Job selection for maintenance schedules

Failure Reduction Processes

Description

- A systematic approach to identify failures
- Collect relevant data
- Analyse data
- Prioritise failures
- Develop solutions using cross-functional teams
- Implement the solutions
- Monitor the solutions

Operational Interaction

- TIBS - Identify and complete delay reports
- Compose top 10 failure report and prioritise projects
- Part of a multi-functional and multi-disciplined team to solve problems

Shutdown Management

Description

- Identify the work required
- Plan and prioritise work
- Schedule work
- Execute the work
- Review the activities and assure performance

Operational Interaction

- Determine when plant will be made available for maintenance
- Prepare plant status for maintenance periods
- Carry out maintenance tasks on maintenance periods
- Functional test and commission equipment after maintenance periods
- Part of a team that reviews downshift performance

Scheduled Maintenance

Description

- Schedule work loads
- Execute planned work
- Review executed work
  - Completion rates
  - Standard of work
  - Identification of further work

Operational Interaction

- Determine when plant is going to be available
- Part of a team that will prioritise work arising to be scheduled for the next week

Emerging Work

Description

- Identify work required
- Prioritise agreed work
- Plan work
- Execute work
- Review completed work

Operational Interaction

- Indicate when something is wrong with plant
- Raise notifications for required actions. (if not raised Engineering will be unaware of plant issues)
- Set work priorities
- Within the Morning Meeting structures:
  - Review delays, Identify threats, Review maintenance plans and set targets

Figure 9-2 Maintenance Excellence Process

9.4 TRAM Method Implementation

The implementation of the model within the failure reduction module will support the enhancement of the failure reduction strategy. The TRAM method can perform instantaneous failure assessment by examining the current failure data sets and indicating which are the worst performing systems and subsystems in that particular area. In addition the reliability analysis model will indicate trends in each system's performance and identify if a process improvement is required immediately or can be deferred to a later date. The reliability model will track process change points and can identify if any implemented process improvements have been successful or not. This will allow identification of the best working practice and measure the effectiveness of maintenance strategies. In addition through the continuous tracking of individual system performance one can identify if there is long term deterioration. This can support the business case for procurement of replacement machinery or additional repairs to the system.

The Technology Group at the Hot Strip Mill is currently testing the TRAM method. In addition there is a modified TRAM method under construction. This later model will link directly with the latest intranet failure database. In this way the model will be automatically updated with the latest data from the failure database upon opening. The TRAM method is also being trialled at the Blast Furnace area. A modified reliability analysis model has been constructed and is currently being applied to the Blast Furnace failure database. The Blast Furnace failure database has been identified as requiring considerable modification before the TRAM method can be fully utilised. This feature is currently under investigation by Blast Furnace personnel.

9.5 Reliability and its Influences on Manufacturing Parameters

In addition to impinging upon an individual machine or system's operational performance, machine reliability has a major influence on the whole manufacturing operation. One such feature is a detrimental effect on overall equipment efficiency (OEE) where the lack of reliability is manifested as unplanned downtime.

Another example of machine reliability impinging on operational processes is through the effects on product quality. This can be easily identified when a machine suddenly fails and the product undergoing processing is damaged beyond repair.

Another more insidious effect of the lack of reliability is partial system failure which could reduce capability and produce an inferior product.

9.5.1 Operating equipment efficiency (OEE)

Manufacturing processes require a high level of process stability to operate efficiently. This is especially true of the Hot Strip Mill process as even a stoppage of a short duration can render the hot metal product unworkable and make it only suitable for scrap. A lack of process reliability will have a severe effect on the process overall equipment efficiency (OEE) which is fully defined as Performance multiplied by Availability multiplied by Quality, this parameter being expressed as a percentage of overall operating time. The one element of the standard OEE calculation which is most used in the manufacturing context may be defined as machine or process operating time divided by cycle time. From the author’s personal experience it has been identified that some manufacturing facilities use all stoppages in assessing their parameters for OEE classification. These manufacturers will designate such stoppages either as planned downtime, which includes tool changes, planned maintenance, scheduled stoppage and changeovers; or unplanned downtime, which includes system failure, machine failure, product shortage, and scheduling disruptions etc.

Clearly every one of these may be seen as unwanted parameters in the manufacturing process. The drive is to maintain 100% effective utilisation of the equipment at all times. This is a goal which fits in well with continuous improvement activities to drive all downtime to as close to zero as possible. It was identified in Chapter 4 through the examination of the failure monitoring database at the Hot Strip Mill (year to date spreadsheet) that such downtimes can consist of approximately six thousand readings per annum. This data set is a mixture of planned and unplanned stoppages.

In reality it is preferable to utilise planned downtime as much as possible, this allows the process operators to prepare for the downtime event and minimise stoppage length. The TRAM method is relevant to the unplanned process downtime, the model will support the OEE calculated values by interrogating the failure data sheet and segregating the data sets relative to machine system failures. This will allow easier identification of failure root causes and assist the mill engineers in installing timely remedial actions. Where no permanent remedial action can be installed the engineers will be able to instigate a preventative maintenance regime which will circumvent repeat failures. In addition the TRAM method will highlight the proportion of unplanned downtime attributed to production planning and other operational practises, this feature can be used to minimise unproductive practises at the Hot Strip Mill.

9.5.2 Product Quality

The other aspect of manufacturing upon which system or machine reliability has a major influence is product quality. All manufacturing processes are subject to a rigorous degree of control to ensure process accuracy and stability. This can include continuous process monitoring and the full measurement of some product parameters. In addition the use of statistical monitoring methods such as statistical process control (SPC) etc are often utilised to ensure the process remains “in control” and operating effectively. The SPC process will monitor the set parameters of the manufactured product and quantify if the process is “in control” and statistically normal or veering towards the control boundaries. An early indication of machine failure is the deviation of the product parameters. This can create anomalies in the recorded data which are often attributed to special causes.

The reliability monitoring feature of the TRAM method will allow the Tata engineers to identify the least reliable production systems. It can thus support the implementation of improvements similar to the descaling system upgrade and the overall reliability characteristics of the whole production process can be improved. The continual monitoring of all system’s performance will identify if the improvement has been successful or if further action is required. This feature will have similar benefits on product quality through decreasing the process instability in this manufacturing area.

The author constructed The TRAM method to be user friendly; this should ensure that the use of the model will be widespread at the Port Talbot plant. This widespread application can significantly reduce the manpower requirements for analysing stoppage issues. It is estimated that the effective implementation of this analysis model can immediately decrease engineer workload by several hours per week. There is a minimum of ten engineers at the Hot Strip Mill and these personnel are duplicated in the other manufacturing areas at the Port Talbot plant. Therefore this contribution to their working patterns can release a significant amount of hours which can be dedicated to more proactive approach such as continuous improvement activities.

10 Conclusions

Research has been performed into identifying a reliability analysis methodology suitable for repairable systems installed in a challenging manufacturing environment. This research has led to the development of the Tata Reliability Analysis Model (TRAM) method. This method, whilst not using unique reliability analysis methods, Is a novel approach to formatting standard reliability analysis models to analyse and monitor repairable systems deployed in a long term manufacturing scenario. This is a “common sense” approach to improving the condition of manufacturing assets (machinery) through long term monitoring and analysis.

The Contributions of this research to Tata Steel are:

- Developed new methodology for the Reliability Analysis of repairable systems
- Utilised an innovative step of combining three Reliability Analysis methods as complimentary activities
- Constructed an automated Reliability Analysis model which fulfils the project remit. In addition the model is capable of long term monitoring of system reliability
- Delivered the new Reliability Analysis method to Tata Steel. The Reliability Model is installed in the Port Talbot Technology Group with a direct link to the HSM database.

The implementation of this analysis model in the Hot Strip Mill at Port Talbot steel works has led to the following conclusions:

The failure data acquisition system at the Hot Strip Mill will allow the acquisition of all failure data relating to this manufacturing process. Up until this point this data was presented in a format which is not readily transferable to reliability analysis techniques. However an attempt at applying the analysis model to other sections of the Port Talbot plant has highlighted the differences in the failure data recording methods being used. This detail is being used to assist in developing a uniform failure data recording method which can be applied to all the manufacturing units.

In undertaking the review of research to support this work it was identified that there are no readily identifiable long-term applications of reliability modelling techniques suitable for repairable mechanical systems being applied within the world-wide manufacturing environment. One of the main reasons for this is the disparity of the repairable systems under review and the range of operating conditions seen by these systems over a long-term manufacturing period. This means that most of the failure data sets produced are often not statistically significant, a factor which makes the failure data sets unsuitable for many analysis techniques. The TRAM method is a new measure which can be applied to such systems and has been engineered specifically to meets these requirements. This research has shown that the three level analysis approach used does work in these cases and will react to changes in system operation.

The derived reliability analysis method operates by applying the most widely used reliability analysis technique, the Power Law, to all the failure data sets under review. The calculated results obtained from the analysis are compared through the most appropriate reliability values, goodness of fit tests and trend testing. When indicated the additional breakdown of the failure data sets into annual segments allows the identification of the section of the failure data set which is not statistically significant using the two supporting analysis methods which operate simultaneously. The examination of the InMTBF allows the identification of the medium term reliability trends in the system, thereby identifying disparities in the systems data set. The specific measure introduced by this research, the TMTBF allows the identification of short-term trends by the analysis model. This can identify changes in operating and machine conditions that may have influenced the failure data set structure. This is a new and innovative approach introduced by this research that overcomes issue of the non-statistical significance of the failure data sets. The author believes that this issue has up to this point limited the application of reliability analysis to repairable systems. This research has thus increased the application of such approaches to the manufacturing environment.

This research has introduced the application of these analysis methods in an automated model to allow the feature of non- statistical significance to be used as a tool. This feature is an important new element introduced by this research. It represents a major contribution to the establishment and increased utilisation of effective reliability analysis tools. This feature can also identify the inconsistencies in any system’s manufacturing performance through reverse engineering the calculated reliability values one can trace the root failure causes and special circumstances which affect the operational performance of any system. This has important ramifications in an engineering environment which is influenced by many operational parameters. The identification of operational controls which are detrimental to the process operation allows these parameters to be modified and construct a more process friendly operational control system. This could improve operating efficiencies and bring additional benefits in process stability and product quality.

The TRAM methods construction in the form of three Excel workbooks in a self-contained folder allows it to be easily transferable to any other manufacturing area. The analysis method is predominantly automated and it utilises advanced spreadsheet techniques to achieve this feature. The analysis method is user friendly and does not require specialist training to operate.

This analysis method has been tested with four years operational data from the Hot Strip Mill manufacturing area. The analysis has shown that changes in all systems operational status can be easily identified.

It has been established that the ability to perform a robust reliability analysis on any repairable system will be beneficial in the identification, construction and monitoring of any process upgrade. In addition the ability to identify trends in system reliability will facilitate a more efficient maintenance regime. This will enable engineers to be released for new manufacturing issues which could further enhance process efficiency and product quality.

There have been several papers withdrawn from this thesis; these are currently undergoing the review process at several Journals. The papers are:

A repairable mechanical system reliability assessment methodology applied in a steelmaking context.
R.J.Owen, S.Porretta, R.Grosvenor and P.Prickett
Submitted to Reliability Engineering & System Safety (August 2011)

The reliability analysis of mechanical systems; Robert J Owen; Roger Grosvenor; Steve Porretta, Paul Prickett. Submitted to Reliability Engineering & System Safety (January 2011)

Applying Reliability Assessment to Identify and Verify Process Improvements in a Hot Strip Steel Mill Descaling System.
R. Owen, R. Grosvenor, S Porretta and P. Prickett
Submitted to Quality and Reliability Engineering International

10.1 Research Contributions

This research has compiled a combination of three reliability analysis methods, which operate simultaneously and are suitable for the reliability analysis of repairable systems. This approach to reliability analysis will facilitate the use of non-statistically significant failure data sets. This is a new and novel approach to the reliability analysis of repairable systems. The main contributions are:

- Developed a new methodology for the application of reliability analysis techniques to repairable systems within a steel manufacturing facility
- Utilised an innovative step of combining three reliability analysis methods as complimentary activities
- Constructed an automated reliability analysis model which fulfils the project remit. In addition the model is capable of the long term monitoring of repairable system reliability

The new reliability analysis method has been delivered to Tata Steel and is installed in the Port Talbot Technology Group with a direct link to the Hot Strip Mill (HSM) monitoring database.

The three reliability analysis methods will allow manufacturing facilities to identify trends in reliability data and any disruptive influences on their manufacturing processes. This approach utilises advanced spreadsheet capabilities to simplify the reliability analysis techniques. The automation of the reliability analysis spreadsheets allows long term monitoring of reliability trends which can confirm or disprove any remedial actions. This will confirm that the root cause of failures has been identified and the correct remedial action installed. The installation of a short term analysis method into the TRAM method will expand the use of these techniques into the toolkit of plant engineers and facilitate their use by the engineers in their day to day operational toolbox.

Current Reliability analysis software is capable of examining the reliability of individual repairable systems. The TRAM method has progressed from this position and facilitates the reliability analysis of multiple repairable systems simultaneously. In addition the developed model is compatible with the majority of manufacturing control systems used at manufacturing facilities through the use of an intermediate spreadsheet

It is the authors' opinion that this research has bridged the gap between the practical application of reliability analysis techniques to repairable systems in the manufacturing environment and the academic examinations of these analysis techniques. This will facilitate the widespread application of these techniques to the manufacturing environment and assist engineers in developing more robust, data based remedial actions for system failures.

11 Future Work

11.1 Reliability Analysis Model Deployment and Testing

At the end of Quarter 2- 2011 the TRAM method is undergoing trials at two business units (manufacturing areas) within the Port Talbot steel plant. The model is currently undergoing modifications that will allow automatic interrogation of the latest Hot Strip Mill operational performance database. This will allow the model to run with an automatic data input every four weeks.

The TRAM method has been introduced to the reliability monitoring and process-conditioning group at the Blast Furnace (Heavy End area) and is currently being used to supplement and compile the failure reporting and corrective action system reports. It is envisaged that significant modifications to the failure database are required for effective implementation of the TRAM method at this manufacturing area. The Central Engineering Group at Port Talbot is reviewing the TRAM method, with the intention of forming a uniform failure data monitoring and compilation methodology. This is intended to become part of a revised asset management framework, which will be installed at Tata steel.

It is envisaged that it will be beneficial for further Proof of Principle trusting to be implemented once the TRAM method is more mature,. The benefits will be

- Ensuring that the TRAM programming does not become corrupted by interaction with disparate databases
- Ensuring that the TRAM methodology is maintained with the latest developments in the reliability analysis of repairable systems

11.2 Data Set Compilation

In addition to a uniform failure database format it has been identified that the failure logging methodology at the Hot Strip Mill needs review. It was identified in Chapter 4 that the current working practise at the Hot Strip Mill consists of a stoppage area being “rebooted” to clear its “fault” if there is no obvious reason for the stoppage. This can result in a failure being “rebooted” several times over a short period of time before the actual root cause of the stoppage is identified resulting in several stoppages being assigned to one failure cause. This can result in a failure being recorded several times which can give a skewed distribution to the failure data set. Therefore clarification and agreement on the stoppage recording methods will be required for effective compilation of data sets to ensure a robust reliability analysis.

11.3 Model Integration with the Tata operating system

Tata steel has recently introduced a new business enterprises software system into the Port Talbot plant. The current TRAM method uses an intermediate spreadsheet to interact with the control operating systems of the various manufacturing facilities. It is envisaged that the full implementation of the new software system will allow the intermediate spreadsheet stage to be discarded. This will allow direct interaction with the new software system and facilitate transference of the TRAM method to the other manufacturing facilities at the steel plant.

It is recognised that the TRAM model is based on the EXCEL software package. This package has a finite resource in the number of systems that it can interact with. It is envisaged that additional model development may be required as the model interacts with a greater number of databases or subsystems.

11.4 Reliability analysis – Sub system compatibility

The current TRAM method has been designed using a “top down” approach using the actual stoppage data from the manufacturing unit. This approach does not supply detail on partial system failures, only on failures which have resulted in process downtime. This approach does not facilitate sub system analysis.

The latest software system has a recording medium entitled the “functional location” (FLOC) number which assigns a unique code to all plant equipment. This facility is not fully populated to date. The completion of the functional location data base will allow the construction of failure data sets relevant to machines or sub systems. These can be compiled to form a detailed higher level operating system. The adoption of this methodology will allow a “bottom up” approach to the system reliability analysis. The TRAM method will readily adapt to such an approach and will be able to perform a more robust reliability analysis in all cases.

A further benefit of this approach will be the identification of the sequencing and possible interdependency of failures. It was shown in chapter 7 that The Coilers operating parameters can exhibit trends in their failure rates. This reasoning can be applied to their subsystems and could even identify failure trends in individual machines. This would be facilitated by focusing the reapplication of the TRAM method on the machine under investigation at weekly intervals until the failure root cause has been fully analysed and a robust remedial action implemented.

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Appendix A

A.1 Description of Program operations

1) Initialise Button (Macro):
The Initialise Button is the first step in applying the analysis model to any manufacturing area.
This operation uses the sub routine - initialise to operate the “Initialise analysis” macro

```
Private Sub Initialise_Click()
Initialise_Analysis
AreaCode.Value = AreaCode.List(1)
YearSelect.Value = YearSelect.List(0)
End Sub
```

This operation initiates the initialise analysis macro, Sets the area code and the year data to the first items in list

The Initialise Analysis program is fully defined as shown (sample of program definitions)

```
Sub Initialise_Analysis()
Dim Sorted_Book As String           'complete file path of sorted
workbook
Dim Sorted_Book_File As String      'sorted workbook filename
Dim Sorted_Workbook As Workbook     'Sorted workbook
Dim Sorted_File_Path As String      'complete file path for new
sorted workbook
```

The References to the front panel controls are constructed in the program as OLE = Object Linking and Embedding, these are used to link objects in windows programming

```
Dim Area_Combo As OLEObject         'Areas combo box
Dim Init_Btn As OLEObject           'Initialise button
Dim Analyse_Btn As OLEObject        'Analyse button
Dim Sort_Btn As OLEObject           'Sort Database button
Dim Year_Select As OLEObject        'Year combo box
```

The Front workbook is set as the active workbook

```
   Set Front_Workbook = ActiveWorkbook
```

The program constants are defined :

```
Area_Col = "H"           'Column with Areas in Sorted info sheet
Class_Col = "E"          'Column with Classes in Sorted info sheet
Code_Col = "D"           'Column with area code headings in Front
Panel
Info_Sheet = "INFO SHEET" 'Name of info definitions sheet in
sorted database
Front_Sheet = "FRONT PANEL" 'Name of front panel sheet in front
panel
Sorted_File_Cell = "B12"    'Cell containing filename of sorted
database
Plant_Name_Cell = "B15"     'Cell containing name of current plant
area (e.g. "Hot Strip Mill")
Analysis_File_Cell = "B17"  'Cell containing filename of analysis
file
```

```
    Sorted_Book_File = "SORTED.xls"      'Filename of sorted workbook
    Analysis_Book_File = "ANALYSIS.xls" 'Filename of analysis workbook
```

And the current directory is designated as the target for saving new files

```
    Cur_Dir = ActiveWorkbook.Path
```

The file path for opening the file of sorted data is set as the sorted database template file located in the current folder

```
     Sorted_Book = Cur_Dir & "\" & Sorted_Book_File
```

If the Sorted book cannot be found the program is terminated.

```
      Then If Sorted_Book = "False"
        Exit Sub
      End If
```

The Sorted workbook is set as the variable. A check is made to see if the file is already open and if it hasn't been found to flag the file as already open.

```
        File_Open = False
        For Each Workbook In Application.Workbooks
         If Workbook.FullName = Sorted_Book Then
         If File_Open <> True Then
         File_Open = True
          Set Sorted_Workbook = Workbook
         End If
         End If
         Next
```

If the Sorted file is not open then the program opens it

```
        If File_Open = False Then                                 '
        Set Sorted_Workbook = Workbooks.Open(Sorted_Book)
        End If
```

The Sorted workbook is activated and scanning for "Area" starts, the variable i is set at 1.

```
        Sorted_Workbook.Activate
        End_Scan = False
            i = 1
```

The while loop is activated to get the number of available area codes through searching down the Area Column

```
        While End_Scan = False
        If Range(Area_Col & i + 1).Value = "" Then
```

Until an empty cell is found in the column and the while loop ends

```
        Area_Tot = i
         End_Scan = True
```

Otherwise the while loop increments by 1 until completion

```
         Else
             i = i + 1
         End If
         Wend
```

And a reference to the number of area codes is saved in the spreadsheet

```
         Range("G2").Value = Area_Tot
```

The Sorted Workbook is still active and scanning for "Class" starts, the variable i is set at 1

```
End_Scan = False
i = 1
```

The while loop is activated to obtain the number of “Class” codes available through searching down the class column. This procedure continues until an empty cell is found and the while loop ends. Otherwise the while loop will increment by 1 until completion (as above loop)

```
While End_Scan = False
If Range(Class_Col & i + 1).Value = "" Then

    Class_Tot = i
    End_Scan = True
 Else
    i = i + 1
End If
Wend
```

And a reference to the number of class codes is saved in the spreadsheet

```
 Range("D2").Value = Class_Tot
```

The sheet names are compiled from i=1 to all areas, a new sheet for each area is added to the workbook and each sheet is named with an area code until all areas have their respective worksheets in the newly constructed SORTED workbook.

```
 For i = 1 To Area_Tot
Set New_Sheet = Sheets.Add
New_Sheet.Name = Sheets(Info_Sheet).Range(Area_Col &
i).Value
Next
```

The Plant name and abbreviation are defined from their respective cells in the original sorted database file

```
Plant_Name = Sheets(Info_Sheet).Range("K1")
Plant_Abbrv = Sheets(Info_Sheet).Range("K2")
```

The Analysis file is defined and the analysis book filename is set in the current directory

```
"Open Template Analysis File", "Open", False)  'Get desired
filename to load
Analysis_Book = Cur_Dir & "\" & Analysis_Book_File
```

The FRONT PANEL workbook is activated

```
Front_Workbook.Activate
```

And a new filename which contains the plant abbreviation is dedicated to the constructed sorted database

```
Sorted_File_Path = Cur_Dir & "\" & "Sorted Database " &
Plant_Abbrv & ".xls"
```

The reference to the sorted database location in the spreadsheet is saved

```
Range(Sorted_File_Cell).Value = Sorted_File_Path
```

And a reference to the plant abbreviation in the spreadsheet is saved (this is used for titles and filenames)

```
Range(Plant_Name_Cell).Value = Plant_Name
```

A reference to the ANALYSIS workbook file location is saved for in the spreadsheet

```
        Range(Analysis_File_Cell).Value = Analysis_Book
```

For every named area, the program obtains the current area name from the “Info sheet”

```
         For i = 1 To Area_Tot
                    Tag =
            Workbooks(Sorted_Workbook.Name).Sheets(Info_Sheet).Range(A
            rea_Col & i).Value
```

And each row header is set as an area name in the “Front Sheet”

```
      Workbooks(Front_Workbook.Name).Sheets(Front_Sheet).Range(Code_Co
      l & (3 * i + 2)).Value = Tag
```

The listed area names in placed in the hidden B column in the “Front Sheet” for use in the drop-down box

```
      Workbooks(Front_Workbook.Name).Sheets(Front_Sheet).Range("B" &
      (i + 20)).Value = Tag
       Next
```

The references to the Area code combination box, Year combination box, Initialise button, Detailed Analysis button, and Sort Database button on the front panel are created.

```
    Set Area_Combo = Sheets("Front Panel").OLEObjects("AreaCode")
    Set Init_Btn = Sheets("Front Panel").OLEObjects("Initialise")
          Set Analyse_Btn = Sheets("Front
      Panel").OLEObjects("DetailedAnalysis")
    Set Sort_Btn = Sheets("Front Panel").OLEObjects("SortDatabase")
    Set Year_Select = Sheets("Front Panel").OLEObjects("YearSelect")
```

Set the range of data to be placed in the year combination box as the list in hidden column B

```
      Area_Combo.ListFillRange = Range("B20:B" & 20 +
      Area_Tot).Address
```

Activate the SORTED workbook

```
      Sorted_Workbook.Activate
```

Save and close the Sorted database file

```
      ActiveWorkbook.SaveAs (Sorted_File_Path)
      ActiveWindow.Close
```

Clear the copied selection and select cell A1 for cursor placement (aesthetics)

```
       Application.CutCopyMode = False
            Range("A1").Select
```

Hide or show relevant front panel buttons and combo boxes after initialisation

```
      Area_Combo.Visible = True
      Init_Btn.Visible = False
      Analyse_Btn.Visible = True
      Sort_Btn.Visible = True
      Year_Select.Visible = True
```

And Save the FRONT PANEL workbook as Front Panel & the plant’s abbreviated name

```
Front_Workbook.SaveAs (Cur_Dir & "\" & "Front Panel - " &
Plant_Abbrv & ".xls")
End Sub
```

Update Database Macro

The Update Database Button initiates the selection of the Sort Database macro and sets the year selection in the window to the current year by scrolling the worksheet to the current year’s analysis

```
Private Sub SortDatabase_Click()
Sort_Database
YearSelect.Value = Year(Date)
```

The Sort_Database macro is fully defined (selection from definitions)

```
Sub Sort_Database()
Dim Class_Token As String       'Current Class being sorted
Dim Area_Token As String        'Current Area being sorted
Dim Area_Size As Integer        'Total number of areas
Dim Class_Size As Integer       'Total number of Classes
```

The Constants in the Sort_Database macro are fully defined

```
Area_Column = "F"               'Column with failure area in YTD
data sheet
Class_Column = "G"              'Column with failure class in
YTD data sheet
Sorted_Book_Cell = "B12"        'Cell in Front panel containing
sorted book filename
Analysis_Book_Cell = "B17"      'Cell containing analysis book
filename in Front panel
Info_Sheet_Name = "INFO SHEET"  'Name of Info sheet in Sorted
workbook
```

The programs instruction gets the desired filename to load, opens the YTD database and sorts the variables

```
Data_Book = Application.GetOpenFilename("Excel Workbooks ,
*.xls", 1, "Open      Database File", "Open", False)
```

If the Database cannot be found end the program

```
If Data_Book = "False" Then 'End if load cancelled
  Exit Sub
End If
```

Check if the file is already open, If it is open (and it hasn't already been found) then flag the file as and set variable as the open workbook

```
File_Open = False                            '
For Each Workbook In Application.Workbooks
  If Workbook.FullName = Data_Book Then    '
      If File_Open <> True Then
          File_Open = True                 '
          Set Data_Workbook = Workbook     '
      End If
 End If
 Next
```

If the database file is not open, then open it ;

```
If File_Open = False Then
Set Data_Workbook = Workbooks.Open(Data_Book)
End If
```

Activate the data base and store the name of the database sheet for reference

```
Data_Workbook.Activate                      '
Data_Sheet_Name = ActiveSheet.Name
Set Data_Sheet = Sheets(Data_Sheet_Name)
```

Open the Sorted data file, end the program if the filename is not present

```
Sorted_Book =
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range(Sort
ed_Book_Cell)
If Sorted_Book = "" Then
  Exit Sub
End If
```

Set the file to open, check if the file is already open , If it is (and it hasn't already been found) then flag the file as open and set the workbook as the variable

```
File_Open = False                          '
For Each Workbook In Application.Workbooks  '
 If Workbook.FullName = Sorted_Book Then
     If File_Open <> True Then           '
         File_Open = True                '
         Set Sorted_Workbook = Workbook
     End If
 End If
 Next
```

If file is not open then open it;

```
If File_Open = False Then
    Set Sorted_Workbook = Workbooks.Open(Sorted_Book)
 End If
```

Activate the Sorted workbook

```
Sorted_Workbook.Activate
```

Extract the number of areas and the number of classes from the “Info sheet”

```
With Sheets(Info_Sheet_Name)
Area_Size = .Range("G2").Value      '
Class_Size = .Range("D2").Value
End With
```

'The program initialises the "End Search" variable to ensure execution of while loop

```
End_Search = False
```

The start date of the search is set and the program starts the search at row 2 in YTD sheet (row 1 is header row)

```
Start_Date = Sheets(Info_Sheet_Name).Range("B1").Value
 k = 2
```

The While loop is initiated and looks at the main failure database sheet for blank rows

```
While End_Search = False
If
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A
" & k).Value = ""
```

If a blank row is found before the start date of the latest sorted data the program displays the message box with the message “No new data” and ends the program

```
OK_BOX = MsgBox("Database does not need updating",
vbOKOnly, "No new data")
Exit Sub
End If
```

Look for the Start_Date in column A of YTD workbook to find the start point of a new search. If the start date is found, set the current row as a new search row and set End_Search to true to exit the While loop

```
If
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A"
& k).Value > Start_Date Then
      Search_Row_Start = k
      End_Search = True
```

Otherwise increment the search by k to look at the next row, repeat for each Area

```
Else
      k = k + 1
  End If
Wend
For j = 1 To Area_Size
```

Reset Search row to Search_Row_Start and get the current area designation from "Info sheet" in the Sorted database

```
Search_Row = Search_Row_Start
Area_Token = Sheets(Info_Sheet_Name).Range("H" & j).Value
```

Initialise Insert row as 1 and 'Initialise to run the While loop

```
Insert_Row = 1
End_Search = False
While End_Search = False
```

Then look down every row in YTD worksheet to find the next blank row. End the search when a blank row found. This sets the insertion point for new data.

```
If Sheets(Area_Token).Range("A" & Insert_Row + 1) = "" Then '
End_Search = True
```

Otherwise increment the Insert Row to look at the next row

```
Else
Insert_Row = Insert_Row + 1
End If
Wend
```

Initialise the program to run the While loop and begin searching class for its token . For each class get the current class from the "Info Sheet" in the sorted database

```
End_Search = False
While End_Search = False
For i = 1 To Class_Size
Class_Token = Sheets(Info_Sheet_Name).Range("E" & i).Value
Then
```

If the class and area of the row in YTD workbook match the current area being sorted then copy the row for that entry. Open the correct sheet in "Sorted" database select the insert row and paste the data. Increment the insert row so the next array of new data goes in next new row

```
If
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range(Clas
s_Column & Search_Row) = Class_Token And
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range(Area
_Column & Search_Row) = Area_Token
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A"
& Search_Row & ":I" & Search_Row).Copy
     Sheets(Area_Token).Select
     Range("A" & Insert_Row).Select
     ActiveSheet.Paste
     Insert_Row = Insert_Row + 1
     End If
     Next
```

If the row in the YTD worksheet is blank then we have reached end of data , therefore end the search

```
            If
            Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Rang
            e("A" & Search_Row + 1) = "" Then      set
            End_Search = True
```

And save the reference to the End Date of the current search

```
            End_Date =
            Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Rang
            e("A" & Search_Row).Value
            End If
```

Increment the search row

```
             Search_Row = Search_Row + 1
             Wend
             Next
```

Save the end date from the YTD data set in the sorted database info sheet

```
            Sheets(Info_Sheet_Name).Range("B1").Value = End_Date
```

Activate the Sorted workbook and close the YTD worksheet

```
            Data_Workbook.Activate
            ActiveWindow.Close
```

After the SORTED (abbreviated name) workbook is constructed the individual “Area” data sets are sequentially applied through the analysis worksheet
Open the Analysis workbook; end the program if the filename is not present

```
      Analysis_Book =
      Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range(Anal
      ysis_Book_Cell)
      If Analysis_Book = "" Then
      Exit Sub
      End If
```

Check if the file is already open, if it is (and it hasn't already been found),then flag the file as open and set the workbook as the variable.

```
      File_Open = False                          '
      For Each Workbook In Application.Workbooks
      If Workbook.FullName = Analysis_Book Then
      If File_Open <> True Then
      File_Open = True
      Set Analysis_Workbook = Workbook
      End If
      End If
      Next
```

If the file is not open then the program open’s it

```
      If File_Open = False Then
      Set Analysis_Workbook = Workbooks.Open(Analysis_Book)
      End If
```

The program activates FRONT PANEL workbook and enters the current date into the ANALYSIS workbook to define the finishing time of the analysis

```
      Workbooks(Front_Panel_Book).Activate
      Analysis_Workbook.Sheets("INPUT DATA").Range("E2").Value = Date
```

The number of weeks of total sorted data is collated for each area

```
Data_Length = (End_Date -
Sheets(Front_Panel_Sheet).Range("B3").Value) / 28 + 2
For i = 1 To Area_Size
```

The program selects current area to be analysed from the “Info sheet “

```
 Area_Token =
Workbooks(Sorted_Workbook.Name).Sheets(Info_Sheet_Name).Range("H
" & i).Value
```

Copies the 1000 data (date) points from the Sorted data sheet and pastes them into the ANALYSIS workbook

```
 Sorted_Workbook.Sheets(Area_Token).Range("A1:A1000").Copy
 Analysis_Workbook.Sheets("INPUT DATA").Range("A2").PasteSpecial
(xlPasteValues)
```

And copies the corresponding 1000 time points from the Sorted data sheet and paste these into the ANALYSIS work book

```
Sorted_Workbook.Sheets(Area_Token).Range("C1:C1000").Copy
Analysis_Workbook.Sheets("INPUT DATA").Range("B2").PasteSpecial
(xlPasteValues)
```

The program copies the number of analysed data points (MTBF etc) from the ANALYSIS workbook – “Front worksheet” and paste these into the “Front Panel,” worksheet transposing the data values from columns to rows

```
Analysis_Workbook.Sheets("FRONT").Range("B2:D" &
Data_Length).Copy
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range("F"
& 3 * i + 2).PasteSpecial Paste:=xlPasteValues,
Operation:=xlNone, SkipBlanks:=False, Transpose:=True
Next
```

The data is cleared from the ANALYSIS workbook and the book is closed

```
Analysis_Workbook.Sheets("INPUT DATA").Range("A2:B1001").Clear
Analysis_Workbook.Save
Analysis_Workbook.Close
```

The SORTED workbook is saved and closed

```
Sorted_Workbook.Save
Sorted_Workbook.Close
```

The cursor is returned to cell C1 in the “Front panel” worksheet and the FRONT PANEL workbook is saved.

```
Range("C1").Select
Workbooks(Front_Panel_Book).Save

End Sub
```

Detailed Analysis Button:

The Detailed Analysis Button initiates the Detailed Analysis macro for the current area code in the combination box

```
Private Sub DetailedAnalysis_Click()
Detailed_Analysis (AreaCode.Value)
End Sub
```

The Detailed Analysis” macro takes the Area code comes from "Area Code" combination box and uses the following definitions (Sample)

```
Detailed_Analysis(Area_Code As String)
Dim Analysis_Book As String       'Filepath of analysis workbook
Dim Analysis_Workbook As Workbook      'Analysis workbook
```

```
Dim Front_Panel_Book As String    'Filepath of front panel
workbook
Dim Front_Panel_Sheet As String    'Name of Front Panel sheet
Dim Sorted_Book As String          'Filepath of sorted workbook
Dim Sorted_Workbook As Workbook         'sorted workbook
Dim Sorted_Sheet As Worksheet       'Current sorted data sheet
Dim Cur_Dir As String               'Working directory
Cur_Dir = ActiveWorkbook.Path     'Define working directory as
current directory
```

The Front panel workbook and “Front panel” sheet name are defined

```
Front_Panel_Book = ThisWorkbook.Name
Front_Panel_Sheet = "Front Panel"
```

The Analysis book filepath is retrieved from the “Front panel” worksheet

```
Analysis_Book =
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range("B17
")
```

The Analysis workbook is opened , the program ends if the filename is not present

```
If Analysis_Book = "" Then
Exit Sub
End If
```

Checks if the file is already open, If it is (and it hasn't already been found), then flag the file as open and set the workbook as the variable.

```
File_Open = False
For Each Workbook In Application.Workbooks
If Workbook.FullName = Analysis_Book Then
If File_Open <> True Then
File_Open = True
Set Analysis_Workbook = Workbook
End If
End If
Next
```

If the file is not open then the program open’s it

```
If File_Open = False Then
Set Analysis_Workbook = Workbooks.Open(Analysis_Book)
End If
```

The file of Sorted data is opened, the program ends if the filename is not present

```
Sorted_Book =
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range("B12
")
If Sorted_Book = "" Then
Exit Sub
End If
```

Check if the file is already open, If it is (and it hasn't already been found), then flag the file as open and set the workbook as the variable.

```
File_Open = False                          '
For Each Workbook In Application.Workbooks
If Workbook.FullName = Sorted_Book Then
If File_Open <> True Then
File_Open = True
Set Sorted_Workbook = Workbook
End If
Next
```

If the file is not open the program opens it

```
If File_Open = False Then
Set Sorted_Workbook = Workbooks.Open(Sorted_Book
End If
```

The program copies the first 1000 data points from the Sorted worksheet into the Analysis file (column A and C: date and time)

```
       Sorted_Workbook.Sheets(Area_Code).Range("A1:A1000").Copy
       Analysis_Workbook.Sheets("INPUT DATA").Range("A2").PasteSpecial
       (xlPasteValues)

       Sorted_Workbook.Sheets(Area_Code).Range("C1:C1000").Copy
       Analysis_Workbook.Sheets("INPUT DATA").Range("B2").PasteSpecial
(      xlPasteValues)
```

The ANALYSIS workbook is saved with the area code as a suffix

```
       Analysis_Workbook.SaveAs (Cur_Dir & "\" & "Analysis - " &
       Area_Code & " - " & ".xls")
```

The sorted workbook is closed

```
       Sorted_Workbook.Close
```

The ANALYSIS workbook presents the "MTBF Graphs" worksheet in the analysis as an overview when transferring to a new analysis workbook

```
       Analysis_Workbook.Sheets("MTBF graphs").Select '
       End Sub
```

Process Mimic Drop Down tables

Analysis type: This table accesses the calculated results from the “Front Panel” these are inserted in their relevant cells using the Subroutine

```
       Private Sub cboAnalysisType_Change()
       Update_Mimic
       End Sub
```

Week number: This table selects the calculated results from the “Front Panel” within the specified week number. This updates the values in the relevant cells using the Subroutine

```
       Private Sub cboWeekNumber_Change()
        Update_Mimic
       End Sub
```

Year: This table accesses the calculated results from the “Front Panel” these are inserted in their relevant cells using the subroutine;

```
       Private Sub cboYear_Change()
       Update_Mimic
       End Sub
```

In addition the page runs a separate subroutine which updates the relevant cells when the worksheet is activated using the subroutine;

```
       Private Sub Worksheet_Activate()
       Update_Mimic
       End Sub
```

Appendix B

B.1 Full Macros used in analysis model

Initialise Sub Routine

```
Private Sub Initialise_Click()
    Initialise_Analysis                       'Initialise database
    AreaCode.Value = AreaCode.List(1)         'Set area code
    YearSelect.Value = YearSelect.List(0)     'and year select to first
items in list
End Sub

"Initialise Analysis " Macro
Sub Initialise_Analysis()

Dim Sorted_Book As String              'complete file path of sorted
workbook
Dim Sorted_Book_File As String         'sorted workbook filename
Dim Sorted_Workbook As Workbook        'Sorted workbook
Dim Sorted_File_Path As String         'complete file path for new sorted
workbook

Dim Analysis_Book As String            'Filepath for analysis book
Dim Analysis_Book_File As String       'Filename for analysis workbook

Dim Cur_Dir As String                  'Working directory

Dim Front_Panel As String              'Filepath of front panel
Dim Front_Workbook As Workbook         'Front panel workbook

Dim i As Integer                       'counting integer
Dim j As Integer                       'Counting integer
Dim Area_Tot As Integer                'Total number of areas
Dim Class_Col As String                'Column containing classes in info
sheet
Dim Area_Col As String                 'Column containing areas in info
sheet
Dim Code_Col As String                 'Column containing area code
headings in front panel
Dim End_Scan As Boolean                'Flag to stop looking for
areas/classes
Dim New_Sheet As Worksheet             'New sheet when creating sorted
workbook
Dim File_Open As Boolean               'Flag to signify file is open

Dim Sorted_File_Cell As String         'Cell containing sorted file name
Dim Plant_Name_Cell As String          'Cell containing plant name

Dim Plant_Name As String               'Plant name
Dim Plant_Abbrv As String              'abbreviated plant name

Dim OK_BOX As Boolean                  'Arbitrary boolean variable to use
MsgBox object
```

```
'References to front panel controls. OLE = Object Linking and
Embedding
'Used by Windows to send data between applications and programs
Dim Area_Combo As OLEObject         'Areas combo box
Dim Init_Btn As OLEObject           'Initialise button
Dim Analyse_Btn As OLEObject        'Analyse button
Dim Sort_Btn As OLEObject           'Sort Database button
Dim Year_Select As OLEObject        'Year combo box

Set Front_Workbook = ActiveWorkbook

'****************'
'Constants

Area_Col = "H"              'Column with Areas in Sorted info sheet
Class_Col = "E"             'Column with Classes in sorted book info
sheet
Code_Col = "D"              'Column with area code headings in Front
Panel
Info_Sheet = "INFO SHEET"   'Name of info definitions sheet in sorted
database
Front_Sheet = "FRONT PANEL" 'Name of front panel sheet in front panel
Sorted_File_Cell = "B12"    'Cell containing filename of sorted
database
Plant_Name_Cell = "B15"     'Cell containing name of current plant
area (e.g. "Hot Strip Mill")
Analysis_File_Cell = "B17"  'Cell containing filename of analysis file

Sorted_Book_File = "SORTED.xls"      'Filename of sorted workbook
Analysis_Book_File = "ANALYSIS.xls" 'Filename of analysis workbook


'****************'

Cur_Dir = ActiveWorkbook.Path   'Get current directory for saving new
files in current folder

'****************'
'Open file of sorted data

    'Uncomment next 2 lines for manual select of sorted database file
    'OK_BOX = MsgBox("Select sorted database definition file",
vbOKOnly, "Choose File")
    'Sorted_Book = Application.GetOpenFilename("Excel Workbooks ,
*.xls", 1, "Open Destination Sorted Data File", "Open", False)  'Get
desired filename to load

    'Set sorted database template file location in current folder
    Sorted_Book = Cur_Dir & "\" & Sorted_Book_File

    If Sorted_Book = "False" Then 'End if load cancelled
        Exit Sub
    End If

    File_Open = False                            '
    For Each Workbook In Application.Workbooks  ' Check if file is
already open
        If Workbook.FullName = Sorted_Book Then ' If it is
```

```
            If File_Open <> True Then           '(and it hasn't
already been found)
                File_Open = True                ' then flag file as
open
                Set Sorted_Workbook = Workbook  ' and set variable
            End If
        End If
    Next

    If File_Open = False Then                               'If file
is not open
        Set Sorted_Workbook = Workbooks.Open(Sorted_Book)   'then open
it
    End If

    Sorted_Workbook.Activate

    End_Scan = False
    i = 1
    While End_Scan = False                      'Get number of area
codes
    If Range(Area_Col & i + 1).Value = "" Then  'By searching down
Area Column
            Area_Tot = i                        'Until empty cell is
found
            End_Scan = True
        Else
            i = i + 1
        End If
    Wend
    Range("G2").Value = Area_Tot                'Save reference to
number of area codes in spreadsheet

    End_Scan = False
    i = 1
    While End_Scan = False                      'Get number of class
codes (as above)
    If Range(Class_Col & i + 1).Value = "" Then
            Class_Tot = i
            End_Scan = True
        Else
            i = i + 1
        End If
    Wend
    Range("D2").Value = Class_Tot               'Save reference to
number of class codes

    For i = 1 To Area_Tot                       'Fill out sheet names
        Set New_Sheet = Sheets.Add
'Add a new sheet
        New_Sheet.Name = Sheets(Info_Sheet).Range(Area_Col & i).Value
'and name it with the area code
    Next

    'Plant name and abbreviation from sorted database file
    Plant_Name = Sheets(Info_Sheet).Range("K1")
    Plant_Abbrv = Sheets(Info_Sheet).Range("K2")

'****************'
```

```
'Define Analysis file

    'Uncomment next two lines for manual selection of analysis file
    'OK_BOX = MsgBox("Select template analysis file", vbOKOnly,
"Choose File")
    'Analysis_Book = Application.GetOpenFilename("Excel Workbooks ,
*.xls", 1, "Open Template Analysis File", "Open", False)  'Get desired
filename to load

    'Set analysis book filename in current directory
    Analysis_Book = Cur_Dir & "\" & Analysis_Book_File

'***************'

'***************'

    Front_Workbook.Activate

    Sorted_File_Path = Cur_Dir & "\" & "Sorted Database " &
Plant_Abbrv & ".xls" 'New filename for sorted database

    Range(Sorted_File_Cell).Value = Sorted_File_Path    'Save
reference to sorted database location in spreadsheet
    Range(Plant_Name_Cell).Value = Plant_Name           'Save plant
abbreviation in spreadsheet (used for titles and filenames)
    Range(Analysis_File_Cell).Value = Analysis_Book     'Save
reference to analysis workbook file location in spreadsheet

    For i = 1 To Area_Tot 'For each area name

        Tag =
Workbooks(Sorted_Workbook.Name).Sheets(Info_Sheet).Range(Area_Col &
i).Value              'Get current area name

Workbooks(Front_Workbook.Name).Sheets(Front_Sheet).Range(Code_Col & (3
* i + 2)).Value = Tag    'Set row header as area name
        Workbooks(Front_Workbook.Name).Sheets(Front_Sheet).Range("B" &
(i + 20)).Value = Tag            'List area names in hidden B column
for use in drop-down box

    Next

    'Create references to buttons and combo boxes on front panel
    Set Area_Combo = Sheets("Front Panel").OLEObjects("AreaCode")
'Area code combo box
    Set Init_Btn = Sheets("Front Panel").OLEObjects("Initialise")
'Initialise button
    Set Analyse_Btn = Sheets("Front
Panel").OLEObjects("DetailedAnalysis")  'Detailed Analysis button
    Set Sort_Btn = Sheets("Front Panel").OLEObjects("SortDatabase")
'Sort Database button
    Set Year_Select = Sheets("Front Panel").OLEObjects("YearSelect")
'Year combo box

    Area_Combo.ListFillRange = Range("B20:B" & 20 + Area_Tot).Address
'Set range of data in year combo box as list in hidden column B

    Sorted_Workbook.Activate
```

```
    ActiveWorkbook.SaveAs (Sorted_File_Path)    'Save sorted database
file
    ActiveWindow.Close                          'and close

    Application.CutCopyMode = False             'Clear copied
selection
    Range("A1").Select                          'Select cell A1
(aesthetics)

    'Hide or show relevant front panel buttons and combo boxes after
initialisation
    Area_Combo.Visible = True
    Init_Btn.Visible = False
    Analyse_Btn.Visible = True
    Sort_Btn.Visible = True
    Year_Select.Visible = True

    Front_Workbook.SaveAs (Cur_Dir & "\" & "Front Panel - " &
Plant_Abbrv & ".xls") 'Save front panel


End Sub
```

Sort Data base – Subroutine

```
Private Sub SortDatabase_Click()
    Sort_Database                           'Sort Database
    YearSelect.Value = Year(Date)           'Set year select to
current year (scrolls sheet to current year analysis)
End Sub
Section 1 of Macro Sub :Sort Database
```

Update Data base button Macro

```
Dim Class_Token As String       'Current Class being sorted
    Dim Area_Token As String        'Current Area being sorted
    Dim Area_Size As Integer        'Total number of areas
    Dim Class_Size As Integer       'Total number of Classes

    Dim i As Integer                'Indexing integers
    Dim j As Integer
    Dim k As Double
    Dim Insert_Row As Integer       'Count for row to paste
    Dim Search_Row As Integer       'Count for row being searched
    Dim Search_Row_Start As Integer 'Start location of search
    Dim Class_Column As String      'Column containing classes
    Dim Area_Column As String       'Column containing areas
    Dim End_Search As Boolean       'Search terminator
    Dim Tag As String               'Current areas name in search

    Dim Data_Book As String         'Database file name
    Dim Data_Workbook As Workbook   'Database workbook
    Dim Data_Sheet As Worksheet     'Database Worksheet
    Dim Data_Sheet_Name As String   'Database worksheet name

    Dim Sorted_Book As String       'Sorted workbook file path
    Dim Sorted_Workbook As Workbook 'Sorted workbook
    Dim Sorted_Sheet As Worksheet   'Current sorted worksheet
    Dim Sorted_Sheet_Name As String 'Current sorted worksheet name
```

```
    Dim Sorted_Book_Cell As String  'Cell containing sorted workbook
filename

    Dim Analysis_Book As String         'Analysis Workbook filepath
    Dim Analysis_Workbook As Workbook   'Analysis workbook

    Dim Front_Panel_Book As String      'Front panel filepath
    Dim Front_Panel_Sheet As String     'Front panel worksheet name

    Dim Info_Sheet_Name As String       'Name of Info Sheet in sorted
workbook

    Dim File_Open As Boolean        'Flag to check if file is open

    Dim New_Sheet As Worksheet      'Reference to new worksheet
    Dim Sorted_Data As String       'Filename for result spreadsheet
    Dim Start_Date As Date          'Last date of previous sort (start
date of current search)
    Dim End_Date As Date            'Last date of current search (will
become start date of next search)
    Dim Data_Length As Integer      'Total number of weeks in complete
sorted database

    Front_Panel_Book = ThisWorkbook.Name    'Create references to
front panel workbook
    Front_Panel_Sheet = "Front Panel"       'and worksheet

'****************'
'Constants

    Area_Column = "F"               'Column with failure area in YTD
    Class_Column = "G"              'Column with failure class in YTD

    Sorted_Book_Cell = "B12"        'Cell in front panel containing
sorted book filename
    Analysis_Book_Cell = "B17"      'Cell containing analysis book
filename in front panel
    Info_Sheet_Name = "INFO SHEET"  'Name of info sheet in sorted book

'****************'

'****************'
'Open YTD database and sort variables
    Data_Book = Application.GetOpenFilename("Excel Workbooks , *.xls",
1, "Open Database File", "Open", False)  'Get desired filename to load

    If Data_Book = "False" Then 'End if load cancelled
        Exit Sub
    End If

    File_Open = False                           '
    For Each Workbook In Application.Workbooks  ' Check if file is
already open
        If Workbook.FullName = Data_Book Then   ' If it is
            If File_Open <> True Then           '(and it hasn't
already been found)
                File_Open = True                ' then flag file as
open
                Set Data_Workbook = Workbook    ' and set variable
```

```
            End If
        End If
    Next

    If File_Open = False Then                           'If file is
not open
        Set Data_Workbook = Workbooks.Open(Data_Book)   'then open it
    End If

    Data_Workbook.Activate                      '
    Data_Sheet_Name = ActiveSheet.Name          'Store name of
database sheet for reference
    Set Data_Sheet = Sheets(Data_Sheet_Name)
'****************'



'****************'
'Open file of sorted data
    Sorted_Book =
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range(Sorted_Boo
k_Cell)

    If Sorted_Book = "" Then 'End if filename not present
        Exit Sub
    End If

    File_Open = False                           '
    For Each Workbook In Application.Workbooks  ' Check if file is
already open
        If Workbook.FullName = Sorted_Book Then   ' If it is
            If File_Open <> True Then           '(and it hasn't
already been found)
                File_Open = True                ' then flag file as
open
                Set Sorted_Workbook = Workbook    ' and set variable
            End If
        End If
    Next

    If File_Open = False Then                           'If file is
not open
        Set Sorted_Workbook = Workbooks.Open(Sorted_Book)   'then open
it
    End If


    Sorted_Workbook.Activate
'****************'



'****************'
    With Sheets(Info_Sheet_Name)
        Area_Size = .Range("G2").Value      'Extracting number of
areas
        Class_Size = .Range("D2").Value     'and number of classes
from info sheet
    End With
```

```
'****************'


    End_Search = False                                      'Initialse
"End_Search" variable to ensure execution of While loop
    Start_Date = Sheets(Info_Sheet_Name).Range("B1").Value  'Set start
date of search
    k = 2                                                   'Start
search at row 2 in YTD sheet because row 1 is header row
    While End_Search = False
        If
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A" &
k).Value = "" Then 'Look down main failure database sheet for blank
rows
            OK_BOX = MsgBox("Database does not need updating",
vbOKOnly, "No new data")         'If blank row found before start date
of new sort, then display message
            Exit Sub
'And stop running
        End If

        If
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A" &
k).Value > Start_Date Then 'Look for Start_Date in column A of YTD to
find start of new search
            Search_Row_Start = k                'If start date found,
set current row as new search row
            End_Search = True                   'And set End_Search
false to exit While loop
        Else
            k = k + 1                           'Otherwise increment k
to look at next row
        End If
    Wend

    For j = 1 To Area_Size                      'For each Area

        Search_Row = Search_Row_Start           'Reset Search row to
Search_Row_Start

        Area_Token = Sheets(Info_Sheet_Name).Range("H" & j).Value
'Get current area from info sheet in sorted database

        Insert_Row = 1                          'Initialise Insert row
as 1
        End_Search = False                      'Initialise to run
While loop
        While End_Search = False
            If Sheets(Area_Token).Range("A" & Insert_Row + 1) = ""
Then 'Look down every row in YTD to find next blank row
                End_Search = True
'End search when blank row found to set insertion point of new data
            Else
                Insert_Row = Insert_Row + 1
'Otherwise increment Insert Row to look at next row
            End If
        Wend

        End_Search = False           'Initialise to run While loop
```

```
        While End_Search = False    'Begin searching class for token
            For i = 1 To Class_Size
'For each class
                Class_Token = Sheets(Info_Sheet_Name).Range("E" &
i).Value  'get current class from Info Sheet in sorted database

                If
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range(Class_Colu
mn & Search_Row) = Class_Token And
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range(Area_Colum
n & Search_Row) = Area_Token Then            'If class and area of row
in YTD match current then

Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A" &
Search_Row & ":I" & Search_Row).Copy
'copy row for that entry
                    Sheets(Area_Token).Select
'Open correct sheet in Sorted Database
                    Range("A" & Insert_Row).Select
'Select Insert Row
                    ActiveSheet.Paste
'and paste data
                    Insert_Row = Insert_Row + 1
'increment insert row so next new data goes in next new row
                End If
            Next

        If
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A" &
Search_Row + 1) = "" Then      'If row in YTD is blank then reached
end of data set
            End_Search = True
'So end search
            End_Date =
Workbooks(Data_Workbook.Name).Sheets(Data_Sheet_Name).Range("A" &
Search_Row).Value  'and save reference to End Date of current search
        End If

            Search_Row = Search_Row + 1
'Increment search row

        Wend

    Next

    Sheets(Info_Sheet_Name).Range("B1").Value = End_Date
'Save end date in sorted database info sheet

    Data_Workbook.Activate      'Activate and
    ActiveWindow.Close          'close YTD file

****************

 'Open Analysis Workbook
    Analysis_Book =
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range(Analysis_B
ook_Cell)
```

```
    If Analysis_Book = "" Then 'End if filename not present
        Exit Sub
    End If

    File_Open = False                           '
    For Each Workbook In Application.Workbooks  ' Check if file is
already open
        If Workbook.FullName = Analysis_Book Then   ' If it is
            If File_Open <> True Then           '(and it hasn't
already been found)
                File_Open = True                ' then flag file as
open
                Set Analysis_Workbook = Workbook    ' and set variable
            End If
        End If
    Next

    If File_Open = False Then                           'If file is
not open
        Set Analysis_Workbook = Workbooks.Open(Analysis_Book)   'then
open it
    End If

'****************'

    Workbooks(Front_Panel_Book).Activate
'Activate front panel
    Analysis_Workbook.Sheets("INPUT DATA").Range("E2").Value = Date
'Enter current date into Analysis workbook to define finish time of
analysis

    Data_Length = (End_Date -
Sheets(Front_Panel_Sheet).Range("B3").Value) / 28 + 2 'Number of weeks
of total sorted data


    For i = 1 To Area_Size  'For each area
        Area_Token =
Workbooks(Sorted_Workbook.Name).Sheets(Info_Sheet_Name).Range("H" &
i).Value   'Set current area from info sheet

        Sorted_Workbook.Sheets(Area_Token).Range("A1:A1000").Copy
'Copy 1000 data (date) points from sorted data sheet
        Analysis_Workbook.Sheets("INPUT
DATA").Range("A2").PasteSpecial (xlPasteValues)             'And paste
them into analysis book

        Sorted_Workbook.Sheets(Area_Token).Range("C1:C1000").Copy
'Copy corresponding 1000 time points from sorted data sheet
        Analysis_Workbook.Sheets("INPUT
DATA").Range("B2").PasteSpecial (xlPasteValues)             'and paste
them into analysis book

        Analysis_Workbook.Sheets("FRONT").Range("B2:D" &
Data_Length).Copy
'Copy number of analysed data points (MTBF etc) from analysis book

Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range("F" & 3 *
i + 2).PasteSpecial Paste:=xlPasteValues, Operation:=xlNone,
```

```
SkipBlanks:=False, Transpose:=True   'And paste them into Front Panel,
transposing from columns to rows

    Next

    Analysis_Workbook.Sheets("INPUT DATA").Range("A2:B1001").Clear
'Clear data in analysis book
    Analysis_Workbook.Save
'Save analysis book (must save to avoid "save file before closing?"
prompt
    Analysis_Workbook.Close
'close analysis book

    Sorted_Workbook.Save
'Save and
    Sorted_Workbook.Close
'close sorted workbook

    Range("C1").Select
'Select C1 in front panel (aesthetics: hides cursor when returning to
front panel)
    Workbooks(Front_Panel_Book).Save
'and save

End Sub
```

Detailed Analysis Subroutine

```
Private Sub DetailedAnalysis_Click()
    'Run Detailed Analysis macro for current area code in combo box
    Detailed_Analysis (AreaCode.Value)
End Sub

 Macro Sub : Detailed Analysis
Sub Detailed_Analysis(Area_Code As String)  'Area code comes from
"Area Code" combo box when called from "Detailed Analysis" button
    Dim Analysis_Book As String            'Filepath of analysis
workbook
    Dim Analysis_Workbook As Workbook      'Analysis workbook

    Dim Front_Panel_Book As String          'Filepath of front panel
workbook
    Dim Front_Panel_Sheet As String         'Name of Front Panel sheet

    Dim Sorted_Book As String               'Filepath of sorted
workbook
    Dim Sorted_Workbook As Workbook         'sorted workbook
    Dim Sorted_Sheet As Worksheet           'Current sorted data sheet

    Dim Cur_Dir As String                   'Working directory

    Cur_Dir = ActiveWorkbook.Path           'Define working directory
as current directory

    Front_Panel_Book = ThisWorkbook.Name    'Define front panel
workbook and
    Front_Panel_Sheet = "Front Panel"       'front pane sheet name
```

```
    Analysis_Book =
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range("B17")
'Get analysis book filepath from front panel

    '****************'
'Open Analysis Workbook
    If Analysis_Book = "" Then 'End if filename not present
        Exit Sub
    End If

    File_Open = False                           '
    For Each Workbook In Application.Workbooks  ' Check if file is
already open
        If Workbook.FullName = Analysis_Book Then   ' If it is
            If File_Open <> True Then           '(and it hasn't
already been found)
                File_Open = True                ' then flag file as
open
                Set Analysis_Workbook = Workbook    ' and set variable
            End If
        End If
    Next

    If File_Open = False Then                           'If file is
not open
        Set Analysis_Workbook = Workbooks.Open(Analysis_Book)   'then
open it
    End If
'****************'


'****************'
'Open file of sorted data
    Sorted_Book =
Workbooks(Front_Panel_Book).Sheets(Front_Panel_Sheet).Range("B12")

    If Sorted_Book = "" Then 'End if filename not present
        Exit Sub
    End If

    File_Open = False                           '
    For Each Workbook In Application.Workbooks  ' Check if file is
already open
        If Workbook.FullName = Sorted_Book Then   ' If it is
            If File_Open <> True Then           '(and it hasn't
already been found)
                File_Open = True                ' then flag file as
open
                Set Sorted_Workbook = Workbook    ' and set variable
            End If
        End If
    Next

    If File_Open = False Then                           'If file is
not open
        Set Sorted_Workbook = Workbooks.Open(Sorted_Book)   'then open
it
    End If
'****************'
```

```
    'Copy first 1000 data points from sorted worksheet into analysis
file (column A and C: date and time)

    Sorted_Workbook.Sheets(Area_Code).Range("A1:A1000").Copy
    Analysis_Workbook.Sheets("INPUT DATA").Range("A2").PasteSpecial
(xlPasteValues)

    Sorted_Workbook.Sheets(Area_Code).Range("C1:C1000").Copy
    Analysis_Workbook.Sheets("INPUT DATA").Range("B2").PasteSpecial
(xlPasteValues)

    'Save analysis workbook with area code
    Analysis_Workbook.SaveAs (Cur_Dir & "\" & "Analysis - " &
Area_Code & " - " & ".xls")

    Sorted_Workbook.Close 'Close sorted workbook
    Analysis_Workbook.Sheets("MTBF graphs").Select 'Select "MTBF
Graphs" sheet in analysis workbook to present overview when jumps to
new analysis workbook

End Sub
```

Year Select Subroutine

```
Private Sub YearSelect_Change()
'When "Year Select" combo box is changed, scroll sheet to current year
    Dim Year As String
    Dim Cell_Year As String
    Dim OK_BOX As Boolean


    Year = YearSelect.Value
    'Switch statement uses references to cells within correct year.
Cell is then selected to scroll
    'If the year does not line up properly, adjust cell references
    Select Case Year
        Case "2007"
            Cell_Year = "M2"
        Case "2008"
            Cell_Year = "Z2"
        Case "2009"
            Cell_Year = "AM2"
        Case "2010"
            Cell_Year = "AZ2"
        Case "2011"
            Cell_Year = "BM2"
        Case "2012"
            Cell_Year = "BZ2"
        Case "2013"
            Cell_Year = "CM2"
        Case "2014"
            Cell_Year = "CZ2"
        Case "2015"
            Cell_Year = "DM2"
        Case "2016"
            Cell_Year = "DZ2"
```

```
        Case "2017"
            Cell_Year = "EM2"
        Case Default
            Cell_Year = "A1"
    End Select

    Range(Cell_Year).Select
End Sub
```

Process Mimic Subroutines

```
'When any selection box is changed, or when the process mimic sheet is
selected
'update the process mimic

Private Sub cboAnalysisType_Change()
    Update_Mimic
End Sub

Private Sub cboWeekNumber_Change()
    Update_Mimic
End Sub

Private Sub cboYear_Change()
    Update_Mimic
End Sub
Private Sub Worksheet_Activate()
    Update_Mimic
End Sub
```

Update Mimic Macro

```
Sub Update_Mimic()
    Dim Abs_Week As Integer      'absolute week number from 1/1/2007
    Dim Front_Sheet As String    'Front sheet name
    Dim Mimic_Sheet As String    'Mimi sheet name
    Dim RBD_Sheet As String      'RBD Sheet name

    Dim OK_BOX As Boolean        'Boolean used to create a message box
    Dim Data As Double           'New data value for mimic cell
    Dim Prev_Data As Double      ' Data value in previous cell in front
panel

    Dim New_Colour As String     'Name of new colour being applied to
cell
    Dim Red As String            'Range containing a Red cell for new
colour
    Dim Orange As String         'Orange cell
    Dim Green As String          'Green cell
    Dim Grey As String           'Grey cell

    Dim Year As Integer          'Year number
    Dim Week As Integer          'relative week number (week number in
year)
    Dim Analysis As String       'Analysis type

    Dim End_Search As Boolean    'Used to terminate a while loop
```

```
    Dim Data_Col As Integer     'Row and column containing data
    Dim Data_Row As Integer     'Row is offset depending on analysis
type
    Dim Abs_Data_Row As Integer 'Absolute row number of data in front
panel

    Dim Week_Row As Integer     'Row containing absolute week numbers
in Front Panel
    Dim i As Integer            'Counting integer

    Dim Mimic_Cell As String    'Cell of area in mimic
    Dim RBD_Cell As String      'cell of area in RBD

    Dim Areas As Integer        'Number of areas

    ' Definitions of cell locations in Mimic and RBD sheets
    Dim A_FURNACE_Cell As String
    Dim B_FURNACE_Cell As String
    Dim COIL_HANDLING_Cell As String
    Dim COIL_BOX_Cell As String
    Dim COILER_4_Cell As String
    Dim COILER_5_Cell As String
    Dim COILERS_Cell As String
    Dim CRANES_Cell As String
    Dim F5_Cell As String
    Dim F6_Cell As String
    Dim F7_Cell As String
    Dim F8_Cell As String
    Dim F9_Cell As String
    Dim F10_Cell As String
    Dim F11_Cell As String
    Dim FINISHING_Cell As String
    Dim FLUID_Power_Cell As String
    Dim FSB_Cell As String
    Dim FURNACES_Cell As String
    Dim HSB_Cell As String
    Dim HSF_Cell As String
    Dim ROTS_Cell As String
    Dim R_ROUGHER_Cell As String
    Dim SLAB_YARD_Cell As String
    Dim VSB_Cell As String

    Dim RBD_A_FURNACE_Cell As String
    Dim RBD_B_FURNACE_Cell As String
    Dim RBD_COIL_HANDLING_Cell As String
    Dim RBD_COIL_BOX_Cell As String
    Dim RBD_COILER_4_Cell As String
    Dim RBD_COILER_5_Cell As String
    Dim RBD_COILERS_Cell As String
    Dim RBD_CRANES_Cell As String
    Dim RBD_F5_Cell As String
    Dim RBD_F6_Cell As String
    Dim RBD_F7_Cell As String
    Dim RBD_F8_Cell As String
    Dim RBD_F9_Cell As String
    Dim RBD_F10_Cell As String
    Dim RBD_F11_Cell As String
    Dim RBD_FINISHING_Cell As String
```

```
    Dim RBD_FLUID_Power_Cell As String
    Dim RBD_FSB_Cell As String
    Dim RBD_FURNACES_Cell As String
    Dim RBD_HSB_Cell As String
    Dim RBD_HSF_Cell As String
    Dim RBD_ROTS_Cell As String
    Dim RBD_R_ROUGHER_Cell As String
    Dim RBD_SLAB_YARD_Cell As String
    Dim RBD_VSB_Cell As String



'********************************

    'Cell locations for values in Mimic sheet
    A_FURNACE_Cell = "D16"
    B_FURNACE_Cell = "D23"
    COIL_HANDLING_Cell = "Q10"
    COIL_BOX_Cell = "J24"
    COILER_4_Cell = "Q25"
    COILER_5_Cell = "R25"
    COILERS_Cell = "P10"
    CRANES_Cell = "G10"
    F5_Cell = "M16"
    F6_Cell = "M17"
    F7_Cell = "M22"
    F8_Cell = "M23"
    F9_Cell = "M24"
    F10_Cell = "M25"
    F11_Cell = "M26"
    FINISHING_Cell = "M10"
    FLUID_Power_Cell = "J10"
    FSB_Cell = "K17"
    FURNACES_Cell = "D10"
    HSB_Cell = "F23"
    HSF_Cell = "R10"
    ROTS_Cell = "P16"
    R_ROUGHER_Cell = "H24"
    SLAB_YARD_Cell = "B13"
    VSB_Cell = "F17"

    'Cell locations for values in RBD sheet
    RBD_A_FURNACE_Cell = "D4"
    RBD_B_FURNACE_Cell = "D12"
    RBD_COIL_HANDLING_Cell = "M33"
    RBD_COIL_BOX_Cell = "Q8"
    RBD_COILER_4_Cell = "M19"
    RBD_COILER_5_Cell = "M23"
    RBD_COILERS_Cell = "C29"
    RBD_CRANES_Cell = "G33"
    RBD_F5_Cell = "C21"
    RBD_F6_Cell = "D21"
    RBD_F7_Cell = "E21"
    RBD_F8_Cell = "F21"
    RBD_F9_Cell = "G21"
    RBD_F10_Cell = "H21"
    RBD_F11_Cell = "I21"
    RBD_FINISHING_Cell = "K33"
    RBD_FLUID_Power_Cell = "I33"
```

```
    RBD_FSB_Cell = "B21"
    RBD_FURNACES_Cell = "E8"
    RBD_HSB_Cell = "I8"
    RBD_HSF_Cell = "F29"
    RBD_ROTS_Cell = "J21"
    RBD_R_ROUGHER_Cell = "N8"
    RBD_SLAB_YARD_Cell = "B8"
    RBD_VSB_Cell = "L8"

    Areas = 25      'Number of areas
    Week_Row = 3    'Row containing absolute week numbers in Front
Panel

    Front_Sheet = "Front Panel"     'Name of front panel sheet
    Mimic_Sheet = "Process Mimic"   'Name of process mimic sheet
    RBD_Sheet = "RBD"               'Name of RBD sheet

    'Locations of references (coloured cells) for each colour
    Red = "E37"
    Orange = "E38"
    Green = "E39"
    Grey = "E40"

'**********************************
                                    'Val() takes numerical value from
string in combo box for
    Year = Val(cboYear.Value)       'Year
    Week = Val(cboWeekNumber.Value) 'Week number within Year
    Analysis = cboAnalysisType.Value 'Analysis type

    Abs_Week = (Year - 2007) * 52 + Week    'Absolute week number from
1/1/2007

    End_Search = False
    Data_Col = 6 'F = 6th number of alphabet

    'Find week number in front panel and return column number
containing data
    While End_Search = False
        If Sheets(Front_Sheet).Cells(Week_Row, Data_Col) = Abs_Week
Then    'Look for week number
            End_Search = True
' End search if week is found
        Else
'Otherwise
            Data_Col = Data_Col + 1
' Look in next column

            If Data_Col >= 256 Then
'Cap search at 256th (final) column
                End_Search = True
'End Search
                OK_BOX = MsgBox("Week not found", vbOKOnly, "Error")
'And return error message
            End If
        End If
    Wend
```

```
    'Find row offset for analysis type using switch statement on combo
box option
    Select Case Analysis
    Case "IMTBF"
        Data_Row = 0
    Case "InMTBF"
        Data_Row = 1
    Case "TMTBF"
        Data_Row = 2
    Case Else
        Data_Row = 0
    End Select


    For i = 1 To Areas                        'For every area type

    Select Case i                             'Get target cell for each
area in Mimic and RBD
        Case 1
             Mimic_Cell = A_FURNACE_Cell
             RBD_Cell = RBD_A_FURNACE_Cell
        Case 2
             Mimic_Cell = B_FURNACE_Cell
             RBD_Cell = RBD_B_FURNACE_Cell
        Case 3
             Mimic_Cell = COIL_HANDLING_Cell
             RBD_Cell = RBD_COIL_HANDLING_Cell
        Case 4
             Mimic_Cell = COIL_BOX_Cell
             RBD_Cell = RBD_COIL_BOX_Cell
        Case 5
             Mimic_Cell = COILER_4_Cell
             RBD_Cell = RBD_COILER_4_Cell
        Case 6
             Mimic_Cell = COILER_5_Cell
             RBD_Cell = RBD_COILER_5_Cell
        Case 7
             Mimic_Cell = COILERS_Cell
             RBD_Cell = RBD_COILERS_Cell
        Case 8
             Mimic_Cell = CRANES_Cell
             RBD_Cell = RBD_CRANES_Cell
        Case 9
             Mimic_Cell = F5_Cell
             RBD_Cell = RBD_F5_Cell
        Case 10
             Mimic_Cell = F6_Cell
             RBD_Cell = RBD_F6_Cell
        Case 11
             Mimic_Cell = F7_Cell
             RBD_Cell = RBD_F7_Cell
        Case 12
             Mimic_Cell = F8_Cell
             RBD_Cell = RBD_F8_Cell
        Case 13
             Mimic_Cell = F9_Cell
             RBD_Cell = RBD_F9_Cell
        Case 14
             Mimic_Cell = F10_Cell
```

```
            RBD_Cell = RBD_F10_Cell
        Case 15
            RBD_Cell = RBD_F11_Cell
            Mimic_Cell = F11_Cell
        Case 16
            RBD_Cell = RBD_FINISHING_Cell
            Mimic_Cell = FINISHING_Cell
        Case 17
            RBD_Cell = RBD_FLUID_Power_Cell
            Mimic_Cell = FLUID_Power_Cell
        Case 18
            RBD_Cell = RBD_FSB_Cell
            Mimic_Cell = FSB_Cell
        Case 19
            RBD_Cell = RBD_FURNACES_Cell
            Mimic_Cell = FURNACES_Cell
        Case 20
            RBD_Cell = RBD_HSB_Cell
            Mimic_Cell = HSB_Cell
        Case 21
            RBD_Cell = RBD_HSF_Cell
            Mimic_Cell = HSF_Cell
        Case 22
            RBD_Cell = RBD_ROTS_Cell
            Mimic_Cell = ROTS_Cell
        Case 23
            RBD_Cell = RBD_R_ROUGHER_Cell
            Mimic_Cell = R_ROUGHER_Cell
        Case 24
            RBD_Cell = RBD_SLAB_YARD_Cell
            Mimic_Cell = SLAB_YARD_Cell
        Case 25
            RBD_Cell = RBD_VSB_Cell
            Mimic_Cell = VSB_Cell
        Case Else
            RBD_Cell = "A1"
            Mimic_Cell = "A1"
    End Select

    Abs_Data_Row = Data_Row + (3 * i + 2)    'Row containing correct
analysis type = first row of that area + analysis type offset

    'If the current week or previous week contains data, assign a
colour, else make it grey
    If Sheets(Front_Sheet).Cells(Abs_Data_Row, Data_Col).Value <> ""
Or Sheets(Front_Sheet).Cells(Abs_Data_Row, Data_Col - 1).Value <> ""
Then
        Data = Sheets(Front_Sheet).Cells(Abs_Data_Row, Data_Col).Value
'Value of data in current analysis week and area
        Prev_Data = Sheets(Front_Sheet).Cells(Abs_Data_Row, Data_Col -
1).Value 'Data in previous week in area

        If Data < Prev_Data * 0.95 Then             'If statements
apply Red, Orange or Green colours by copying a colour from a
reference cell, depending if the data has deteriorated, stayed the
same (within 5%) or improved
            New_Colour = Red
        Else
            If Data > Prev_Data * 1.05 Then
```

```
                New_Colour = Green
            Else
                New_Colour = Orange
            End If
        End If

    Else                    'If there is no data, make the cell grey
        New_Colour = Grey
    End If

    'In the mimic sheet and the RBD sheet, copy the value and correct
colour into the relevant area cell
    Sheets(Mimic_Sheet).Range(Mimic_Cell).Value =
Sheets(Front_Sheet).Cells(Abs_Data_Row, Data_Col).Value
    Sheets(Mimic_Sheet).Range(Mimic_Cell).Interior.Color =
Sheets(Mimic_Sheet).Range(New_Colour).Interior.Color

    Sheets(RBD_Sheet).Range(RBD_Cell).Value =
Sheets(Front_Sheet).Cells(Abs_Data_Row, Data_Col).Value
    Sheets(RBD_Sheet).Range(RBD_Cell).Interior.Color =
Sheets(Mimic_Sheet).Range(New_Colour).Interior.Color

    Next    'go on to next area

    Sheets(RBD_Sheet).Range("I4").Value = "Year: " & Year & "   Week:
" & Week & "   Analysis Type: " & Analysis 'Add title to RBD sheet
with current year, week and analysis type for reference

End Sub
```