A METHODOLOGY FOR EVALUATING THE IMPACT OF ROTARY MILL INSTALLATIONS ON THE RELIABILITY PROFILE OF SOUTH AFRICAN PLATINUM CONCENTRATOR PLANTS

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A Research Report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg 2004

DECLARATION

I hereby declare this project report to be my own unaided effort. It is being submitted in partial fulfilment for the requirements for the Master of Science Degree in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted previously for any other degree or examination at any other University.

Mark Greyling

___________day of ______________________2004

ABSTRACT

The primary objective of this study was to develop a methodology for evaluating how the reliability profile of the typical South African Platinum concentrator plant is affected by firstly the size of the primary milling units incorporated in the circuit and secondly by the way that the primary milling units are configured. A methodology, together with a set of general expressions is presented which considers the Platinum concentrator as a stochastic process where the behaviour of the primary mill is a direct measure of the failure pattern of the overall concentrator. The reliability, availability and maintainability (RAM) of the primary mill, and hence the overall concentrator, is then determined by a combination of three different Markov models where each Markov model is used to evaluate and measure a separate set of reliability parameters. This approach effectively overcomes the computational complexity associated with large Markov models. The results of two case studies used to validate the methodology do indicate that the reliability, availability and maintainability profiles of large single stream Platinum concentrators could be fundamentally different from the conventional multiple stream primary mill configurations.

DEDICATION

I dedicate this work to my wonderful wife Miemie for all her patience, support, understanding and unconditional love during my selfish journey of redemption.

ACKNOWLEDGEMENTS

This work represents the most challenging endeavour of my career. The successful completion of this study would not have been possible without the support of a number of wonderful people to whom I owe a great deal.

Firstly I would like to thank my wonderful wife and my two lovely children for all their love, support and encouragement during the past few years.

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CONTENTS Page

DECLARATION 2

ABSTRACT 3

DEDICATION 4

ACKNOWLEDGEMENTS 5

LIST OF FIGURES 9

LIST OF TABLES 12

1. INTRODUCTION 13

1.1. Background. 15
  1.1.1. Redundancy Implications 18
  1.1.2. Mechanical Reliability Implications 19

1.2. Problem Statement: 20

1.3. Research Objectives 21

1.4. Delimitations 21

2. LITERATURE REVIEW 24

2.1. Fundamental Concepts 24
  2.1.1. Reliability 24
  2.1.2. Mean Time To Failure 29

2.2. Simple Network Systems 29
  2.2.1. Series Systems 30
  2.2.2. Parallel Systems 32
  2.2.3. Redundancy 35
  2.2.4. Partially Redundant Systems 35

2.3. Repairable Systems 37
  2.3.1. Behaviour of a Repairable System 38
  2.3.2. Availability 40
  2.3.3. Markov Process Analysis 46
  2.3.4. Frequency and Duration 60
  2.3.5. Trend Analysis 63

2.4. The development of Rotary Mill Sizes in the Mineral Processing Industry 66

3. EVALUATION MODEL & METHODOLOGY 69

3.1. Factors that Influence the Reliability of Primary Mills 70
- 3.1.1. Primary mill design and construction (mechanical reliability) 70
- 3.1.2. Milling & Flotation Circuit Configuration 73
- 3.1.3. Maintenance & operation 76

3.2. Primary Mill Reliability Evaluation Model 77
- 3.2.1. Evaluating a Primary Mill as a Single Component 79
- 3.2.2. Evaluating a Primary Mill as a collection of sub-components or unit processes 84
- 3.2.3. Evaluating a set of primary mills in parallel as a partially redundant system 91

3.3. Primary Mill Reliability Evaluation Methodology 96

4. MODEL VALIDATION 99

4.1. Case Study 1: Plant A; Large Single Stream Primary Mill 100
- 4.1.1. General Information 100
- 4.1.2. Original Data Set 101
- 4.1.3. 2-State; Single component Markov Analysis 105
- 4.1.4. 11-State, Single Component Markov Analysis 108

4.2. Case Study 2: Plant B; Multiple Stream Primary Mills 113
- 4.2.1. General Information 113
- 4.2.2. Original Data Set 115
- 4.2.3. 2-State; Single component Markov Analysis 115
- 4.2.4. 11-State, Single Component Markov Analysis 120
- 4.2.5. 3-State; m-out-of-n Markov Analysis 126

4.3. Comparison of Plant A and Plant B 129
- 4.3.1. Primary Mill Reliability and Maintainability 129
- 4.3.2. Transient Behaviour 131
- 4.3.3. Failure Modes 132
- 4.3.4. Overall System Performance 134

5. CONCLUDING REMARKS 135

5.1. Final Conclusions & Recommendations 140

6. BIBLIOGRAPHY 143

7. REFERENCES 146

8. APPENDIX 1 DERIVATION OF THE PROBABILITY EXPRESSIONS FOR A 2-STATE, SINGLE UNIT, PRIMARY MILLING CIRCUIT...... 149

9. APPENDIX 2 DERIVATION OF THE PROBABILITY EXPRESSIONS FOR AN 11-STATE, SINGLE UNIT, PRIMARY MILLING CIRCUIT . 159

10. APPENDIX 3 DERIVATION OF THE PROBABILITY EXPRESSIONS FOR A 3-STATE, M-OUT-OF-N PARALLEL CONFIGURATION OF PRIMARY MILLS.. 167

10.1. 2x Primary mills in parallel – 4-state Markov process 167

10.2. 2x Primary mills in parallel – 3-state Markov process 174

10.3. 5x Primary mills in parallel; 4-out-of-5, 3-state Markov process 180

10.4. 5x Primary mills in parallel; 3-out-of-5, 3-state Markov process 186

11. APPENDIX 4 VISUAL BASIC® CODE FOR RECORDING MILL DOWNTIME DATA IN MICROSOFT EXCEL®.................................. 196

12. APPENDIX 5: RESPONDENT LETTER.. 219

13. APPENDIX 6 PLANT A DOWNTIME DATA 224

14. APPENDIX 7 PLANT B DOWNTIME DATA 239

LIST OF FIGURES

Figure 1.1: System configuration of older type of concentrator 18

Figure 1.2: Modern concentrator of similar capacity.. 19

Figure 2.1: The relationship between *t, f(t), F(t)*, and *R(t)* (adapted from Grosh, 1989) 25

:Figure 2.2: Bathtub Curve (adapted from Frankel, 1984).. 28

Figure 2.3: Simple series system.. 30

Figure 2.4: Simple parallel system.. 33

Figure 2.5: Chronological behaviour of a simple repairable system 39

Figure 2.6: State-space diagram for a simple 2-state process.................................... 47

Figure 2.7: Single component repairable system (Billinton, 1983) 52

Figure 2.8: Power Plant Model with Possible State Transitions (Perman *et al 1997*) 57

Figure 2.9: Flowchart for the reliability modelling of an LHD Machine (Samanta *et al,* 2004) 58

Figure 2.10: Reliability Block Diagram of LHD sub-systems (Samanta *et al, 2004*) 59

Figure 2.11: Happy and Sad systems (Ascher & Feingold, 1984)............................ 63

Figure 3.1: Example of the main components of a large modern mill with wrap-around motor.(FFE, 2001) 72

Figure 3.2: Process Flow of a typical Platinum Concentrator.................................. 73

Figure 3.3: System configuration of older type of concentrator 75

Figure 3.4: Reliability Block Diagram of a single primary mill 79

Figure 3.5: State-Space diagram of single primary mill. 80

Figure 3.6: RBD of single unit primary milling circuit... 86

Figure 3.7: State-space diagram of an 11-state primary mill..................................... 87

Figure 3.8: State-space diagram for 3-state, m-out-of-n parallel System 92

Figure 3.9: Combined Reliability Block Diagram 96

Figure 3.10: Primary Mill Reliability, Availability, and Maintainability (RAM) evaluation flowchart.. 98

Figure 4.1: Basic configuration of Plant A 101

Figure 4.2: Cumulative failures vs. cumulative operating time. 103

Figure 4.3: RBD and State-space diagram for Plant A 105

Figure 4.4: Transient behaviour of Plant A primary mill 106

Figure 4.5: Overall system reliability of Plant A 106

Figure 4.6: System Maintainability of Plant A 107

Figure 4.7: RBD of Plant A primary mill 108

Figure 4.8: 11- State Space diagram of Plant A primary mill.................................. 109

Figure 4.9: Failure mode reliabilities of Plant A primary mill 111

Figure 4.10: Failure mode maintainabilities for Plant A primary mill. 112

Figure 4.11: Basic configuration each section of Plant B 114

Figure 4.12: RBD and State-space diagram for each primary mills of Plant B 115

Figure 4.13: Average transient behaviour of Plant B primary mills 118

Figure 4.14: Average primary mill reliability of Plant B 119

Figure 4.15: System Maintainability of Plant A 120

Figure 4.16: RBD of Plant B primary mills 121

Figure 4.17: 11- State Space diagram of Plant B primary mills. 121

Figure 4.18: Average Failure mode reliabilities of Plant B primary mills 124

Figure 4.19: Average failure mode maintainabilities for Plant B primary mills...... 125

Figure 4.20: 3-State space diagram for a section of Plant B 126

Figure 4.21: Primary Mill reliability profiles 130

Figure 4.22: Primary mill maintainability profiles...130

Figure 4.23: Transient state probability profiles for Plant A and Plant B...............131

Figure 8.1: Single Primary mill state-space diagram 149

Figure 9.1: RBD of single unit primary milling circuit...160

Figure 9.2: State-space diagram of an 11-state primary mill 161

Figure 10.1: 4x State-space diagram for two mills in parallel. 167

Figure 10.2: 3x State-space diagram for two mills in parallel. 174

Figure 10.3: 3x State-space diagram for 4-out-of-5 mills in parallel......................180

Figure 10.4: 3x State-space diagram for 3-out-of-5 mills in parallel......................186

Figure 10.5: State-space diagram for 3-state, m-out-of-n parallel System 192

LIST OF TABLES

Table 3.1: State categories and description 85

Table 3.2: Departure and return rates 94

Table 4.1: General information of Plant A primary mill 100

Table 4.2: Summary of original data set. 102

Table 4.3: Summary of censored data set. 104

Table 4.4: Summary of 11-state Markov analysis for Plant A primary mill 110

Table 4.5: General information of Plant B primary mill 113

Table 4.6: Summary of original data set for Mills 1-7 116

Table 4.7: Summary of original data set for Mills 8-14 117

Table 4.8: Summary of average 11-state Markov analysis for Plant B primary mills 123

Table 4.9: Summary of 4-out-of-7 system reliability 127

Table 4.10: Summary of 3-state Markov analysis 128

Table 4.11: Failure and repair rates of Plant A & B primary mills 129

Table 4.12: Primary Mill mechanical reliabilities 132

Table 4.13: Downstream Reliabilities 133

Table 4.14: Summary of system performance 134

Table 9.1: State categories and description 159

Table 10.1: Departure and return rates 172

Table 10.2: Departure and return rates 178

Table 10.3: Departure and return rates 184

Table 10.4: Departure and return rates 190

Table 10.5: General expressions for departure and return rates 194

1. INTRODUCTION

The South African Platinum Mining industry is currently undergoing a significant expansion phase. This has resulted in the design and construction of a large number of new mines and mineral processing plants.

During 1997, the global market for Platinum Group metals changed from a supply surplus to a supply deficit. Ever since then the fundamental economic factors supporting the market price mechanism for Platinum Group metals, and in particular Platinum and Palladium, have been very favourable. This positive assessment of market fundamentals has motivated the majority of the South African Platinum mining companies to adopt large growth and expansion strategies in an effort to exploit the favourable commodity market to its maximum.

The world's two largest, and most important producers - Anglo Platinum and Impala Platinum - are both based in South Africa and is estimated to have produced 34% and 18% respectively of the total world supply in 2000 (HSBC, 2001). The positive market fundamentals and elevated prices has resulted in most of the established PGM producers experiencing huge increases in operating cash flows and are using this as their primary form of funding for their expansion projects. Anglo Platinum, for example, announced that it will be investing R13 billion over the next five to seven years to increase its production by 1.5 million ounces to 3.5 million ounces per annum (Anglo Platinum Annual Report, 2000). In similar fashion Implats, the world's next largest producer, has announced that it intends to increase production at a rate of 10% per annum for the next five years and to this end is envisaging a capital expenditure of R1.0 billion for the 2001 financial year (Implats Annual

Report, 2000). At these levels, the demand growth is equivalent to medium sized platinum mine coming on line every six months (Cramer, 2000)

Rotary Mills play a pivotal role in the design and configuration of South African Platinum processing plants, or concentrators as they are more commonly known. The demands for increased milling capacity of lower grade ores, the limited availability of capital, and the continuous drive towards lower operating costs have all resulted in the design and size of the rotary mills employed in modern Platinum concentrators being fundamentally different to those of older, more conventional installations. The modern tendency is to move away from multiple, low capacity rotary milling streams which have been configured in parallel, towards single stream milling and flotation configurations employing rotary mills with significantly larger capacities in order to achieve the same nominal plant throughput capacity.

Two modern developments have fundamentally changed the design of modern rotary mills and their impact on the configuration of the downstream processing circuits. These are:

- The development of highly refined materials of manufacture allowing the physical manufacturing constraints of older mill components to be overcome and increasingly larger rotary mills to be produced.

- The intense pressure by the end-users to make major savings in capital expenditure and operating costs by installing fewer mills with much higher capacities.

The net effect of these two fundamental changes has been twofold. Firstly, it is now possible to achieve much larger system capacities with significantly fewer mills. In most cases the conventional, multiple stream configurations are now being replaced by single stream operations. However, this move to large scale, single stream milling installations has reduced the overall system redundancy, as it relates to the number of primary mills, of modern concentrators. It may therefore be deduced that if the reliability of the modern milling units has not improved concurrently, then the reduced level of redundancy will compromise the overall system reliability profile of modern mineral processing plants.

1.1. Background.

The economic exploitation of minerals through mining and mineral processing still serve as the primary source of inorganic materials used to support modern economic advancement (Kelly, 1989). Virtually no mineral can be directly mined in the final saleable form, where the term mining generically refers only to the activities associated with the primary extraction of the mineral-bearing rock from the crust of the earth. Rather, it requires several stages of further preparation and processing, either physical or chemical or both, to produce a final saleable product.

The primary purpose of mineral processing, as a sub component of the overall mineral production value chain, is to separate the valuable mineral of economic importance from the bulk of the associated gangue (waste) minerals. Even though this beneficiation process can take many forms, comminution, or milling, forms the most important upfront component of nearly all mineral-processing operations (Napier-Munn, 1999). It is for this same reason that most mineral processing plants are commonly referred to as “mills” or “concentrators”. In most cases comminution equipment, and specifically rotary mills, are the largest, the most expensive, the most energy intensive, and most complex of all metallurgical equipment to be incorporated into the design of mineral processing plants (Wills,1992), and forms the central pieces of equipment in the final configuration of the entire mineral processing plant and equipment.

For economic and financial reasons that fall outside the scope of the this study, it is a general rule that mineral processing plants, or concentrators, be designed as continuous operations i.e. to operate 24hrs per day, 7 days per week, 365 days per annum. This design approach is necessary to maximise economies of scale of operations that are capital intensive and operating cost sensitive. These installations are also typically expected to have a useful life of up to 25 years or longer (Svalbonos, 1996). It is therefore obvious that mineral processing plants, and in particular the major pieces of processing equipment employed in these plants such as the rotary mills, pumps, flotation cells etc. have to be designed and configured in the most robust and reliable manner.

The primary performance criteria of a typical Platinum concentrator installation are as follows (adapted from Clifton, 1974):

- It must be able to maintain an acceptable consistency of throughput rate i.e. minimum short-term deviation from design throughput rate.

- It must be able to sustain continuity of production i.e. the frequency and duration of both planned and unplanned equipment and process stoppages must be kept to an absolute minimum.

- It must ensure maximum mineral extraction efficiency for which the first two criteria listed above are considered absolute prerequisites.

- Operating costs per unit ore processed must be strictly controlled.

Platinum concentrators are invariably designed as repairable systems. It is therefore necessary to make allowances for planned or preventative system maintenance downtime when determining what the instantaneous throughput capacity of the system, and hence what the capacities of the major metallurgical equipment should be in order to achieve the required long-term production targets. The larger the downtime allowance, the larger the instantaneous capacity of the process has to be in order to achieve a specified long-term production target.

These downtime allowances are generally made with the expectation that system maintenance and repair time will happen on a planned and scheduled basis. Also implicit in this expectation is the assumption that the system, or process, will function at full operating capacity without failure for the entire period between planned maintenance shutdowns, i.e. have a very high level of operational reliability and availability. It follows that any unplanned system breakdowns or failures will reduce the overall production availability and hence reduces the effective throughput capacity of the plant. For example; it was estimated in 1995 that the cost associated with unplanned downtime of the mill at the Escondida Copper plant in Chile was $60,000 per hour (Danecki, 1996).

1.1.1. Redundancy Implications

It is a fundamental principle of reliability engineering that redundancy is an effective way of improving the reliability of a complex system (Lewis, 1996). As already explained above the design and configuration of conventional, older style Platinum concentrator was determined mostly by the maximum nominal capacities of the rotary mills available at the time. The physical size and capacities of the conventional rotary mills were greatly restricted by manufacturing methods and materials. The result was that the overall capacities of conventional concentrators normally exceeded the unit capacities of the individual mills. This capacity constraint was historically overcome by configuring the rotary mills in multiple, parallel processing streams, thereby providing the overall system with a high level of intrinsic redundancy. This multiple stream configuration is shown graphically in Figure 1.1 below.

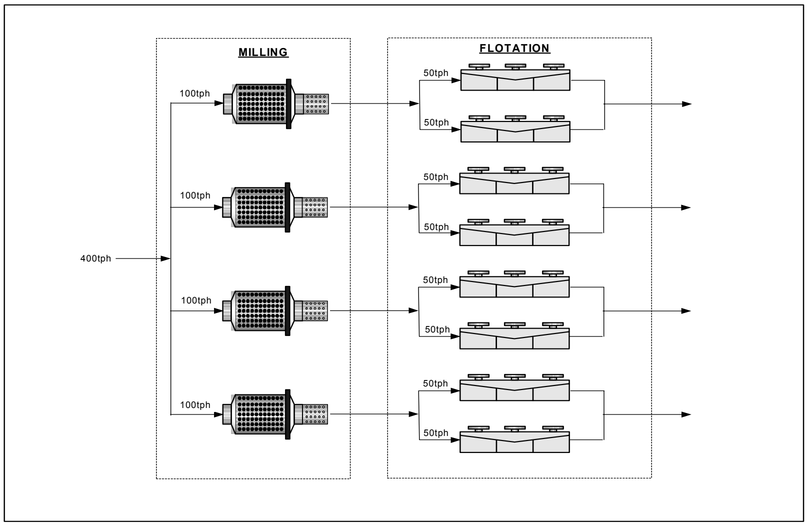


Figure 1.1: System configuration of older type of concentrator

By comparison, the configuration of the typical modern mineral processing circuit depicted in Figure 1.2 below is intuitively not expected to possess the same level of mainstream redundancy and flexibility. In this case a single stream configuration offers the same overall system capacity as the older type of multiple stream configurations shown in Figure 1.1 above.

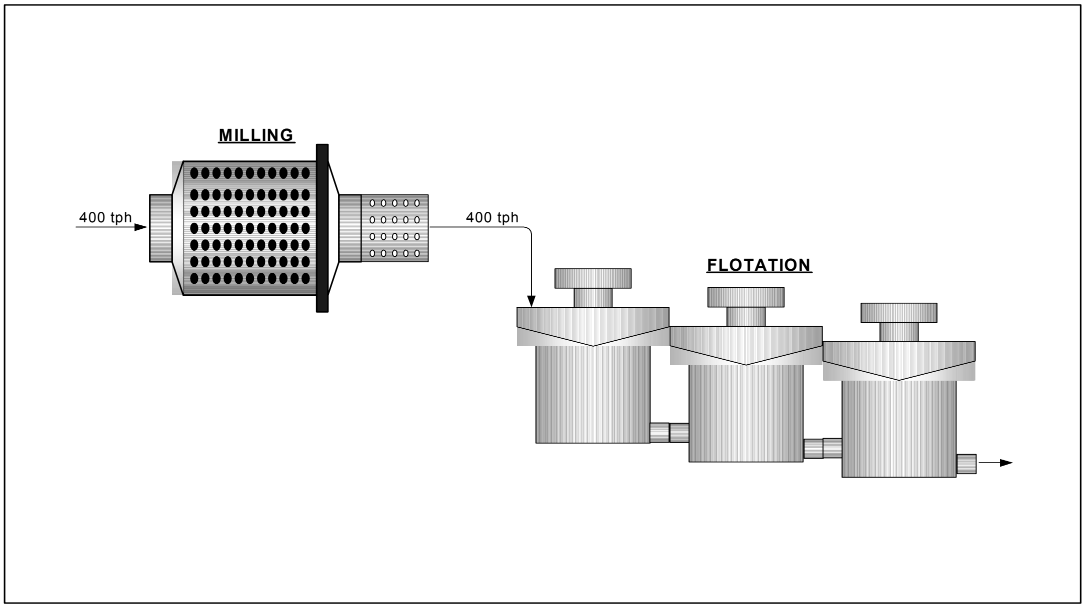


Figure 1.2: **Modern concentrator of similar capacity.**

1.1.2. Mechanical Reliability Implications

The smaller size of the conventional older style rotary mills and associated processing equipment required lower levels of automated process control systems, relatively simple lubrication systems, simple electrical machinery and switch-gear, and definitely more simple design of the major mechanical parts such as bearings etc. In fact these older machines were so robust that they were considered more prone to operator error and abuse than they were to pure mechanical or electrical mode of failures (Peters, 1991). It was therefore extremely difficult to distinguish between operator error and pure mechanical breakdown as the primary mode of random equipment failure of these plants.

In contrast to this the design and operation of modern, high capacity rotary mills is significantly more complex and sophisticated. For example; the trunnion bearings of these large mills are exposed to enormous loadings and they require highly sophisticated and complex lubrication systems to function. These lubrication systems contain a multitude of condition monitoring and protection devices which, in themselves, are also prone to failure. Furthermore the sheer size of the steel fabrications and castings that make up the mill shell and ends also extend the strength of the manufacturing materials to their utmost i.e. even the major steel components are subjected to potentially higher levels of fatigue failure.

1.2. Problem Statement:

The primary objective of any mineral processing engineer employed in the South African Platinum mining industry, who is tasked with the design of a new Platinum concentrator, is to maximise the system performance and reliability of the overall mineral processing plant while minimising capital expenditure and operating cost. For reasons already explained above it is important for the mineral process engineer to have a very detailed understanding and methodology with which to evaluate how the reliability of the rotary mills and their sub-systems will impact on the configuration, and hence, the overall system reliability of the mineral processing plant.

The problem faced by the modern mineral processing design engineer may be summarised as follows:

- To what degree is the reliability and availability of the overall mineral processing plant compromised, if at all, by selecting a single, large capacity, rotary mill compared to a multiple parallel stream configuration consisting of several smaller primary milling units?

- How does the mechanical reliability of large modern rotary mill installations compare with the reliability of the older, smaller milling units?

1.3. Research Objectives

The primary purpose of this study is to develop a methodology for evaluating the influence of the size, capacity and number of primary rotary mills on the reliability profile of mineral processing plants in the South African Platinum mining industry.

1.4. Delimitations

Reliability may be broadly defined as the probability that a system or component will perform its intended function for a specified period under a given set of conditions (Lewis, 1996). As the primary component of most mineral processing circuits, the function of any rotary mill is twofold. Firstly, it must be able to sustain the designed throughput, or milling rate, for a designed duration after allowance has been made for maintenance.

Secondly, it must be able to achieve the required rock size reduction. This latter part of the mill functionality is directly concerned with the detailed science of mineral extraction efficiency and will therefore not form part of the scope of the proposed study. The proposed study will rather focus on the throughput reliability of the mineral processing system as measured by the ability of the rotary mills to remain in operation for any specified periods under a given set of operational conditions.

Any engineering system will have an inherent level of reliability which is derived from the basic configuration design and equipment selection. The inherent reliability refers to the probability that the system will operate at a specified level of performance for a specified time under ideal conditions (Frankel, 1984). However, the actual operating conditions will seldom be comparable to ideal design conditions and actual reliability will therefore deviate from the ideal design reliability. The degree in which the actual system performance deviates from the ideal for any specific concentrator is primarily a function of the general operational and maintenance philosophies applied by the management of the specific plant. These are primarily management functions and will not form part of the scope of this study. The impact on the reliability of the specific concentrators will not be evaluated in detail for the purpose of this study.

The physical design of large diameter rotary mills is the subject of detailed and complex mechanical engineering. This study will be done from a mineral process engineering perspective and will therefore not attempt to address detailed mechanical and structural engineering design aspects such fabrication methods, machining standards etc.

It is further assumed that rotary mills constitute the central components of any modern Platinum concentrator and that their reliabilities profiles will serve as the best direct measure of the reliability performance of the overall processing system. The reliability estimation of large diameter rotary mills will be the focus of the proposed study.

2. LITERATURE REVIEW

2.1. Fundamental Concepts

2.1.1. Reliability

Reliability may be formally defined as the probability that a component or system of complements will perform its specified function for a specified period of time, under specified conditions, given that it was functioning properly at the start of the time period (Frankel, 1984).

Lewis (1996) states that if a random variable **t** is defined as the time-to-system-failure, then the probability density function PDF, ***f(t)*** has the following meaning:

$$f\left(t\right)\Delta t = P\left\{t < \mathbf{t} \leq \Delta t\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.1)$$

Eq. 2.1 has the meaning that the probability that failure will occur at some time between t and $t + \Delta t$.

When Δt tends to zero the cumulative distribution function CDF $F(t)$ becomes the following:

$$F\left(t\right) = P\left\{\mathbf{t} \leq t\right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.2)$$

where Eq. 2.2 is the probability that failure will take place at a time equal to, or less than t.

It is now possible to define the reliability function $R(t)$ as follows:

$$R(t) = P\left\{\mathbf{t} > t\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.3)$$

and Eq. 2.3 is understood to mean the probability that a system operates without failure for a duration equal to *t*.

A system that has not failed for **t** $\leq t$ must fail at some **t** $>$ t. It therefore follows that:

$$R(t) = 1 - F(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.4)$$

The relationship between the different performance functions discussed thus far are shown graphically in Figure 2.1 below.

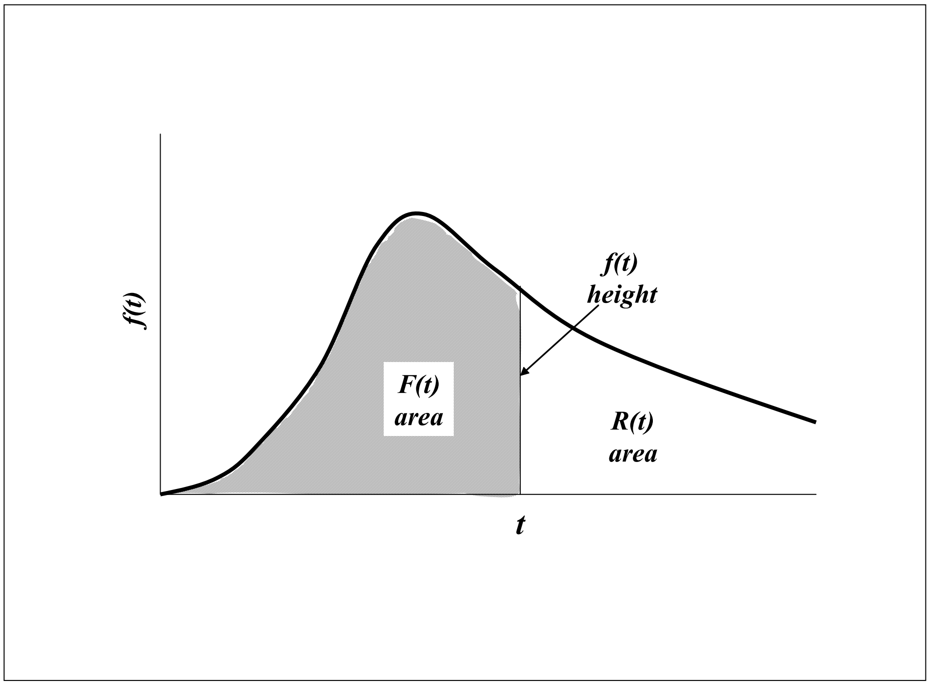


Figure 2.1: The relationship between *t, f(t), F(t),* and *R(t)* (adapted from Grosh, 1989)

Grosh (1989) explains that it is convenient to introduce another conditional probability function defined as the failure probability per unit time at time t, on condition that failure has not yet occurred at time t.

This function is called the hazard rate, or simply the failure rate (as opposed to failure density) and is defined as

$$h(t)=\frac{f(t)}{R(t)}=\frac{f(t)}{1-F(t)} \qquad \text{…………………………………………….(2.5)}$$

Bradley (1993) points out the importance of distinguishing between the average failure rate *Ø(t)* and instantaneous hazard rate $h(t)$. The difference is explained by means of an analogy. If one takes 5 hours to travel 500km the average speed would be 100km/hr. However, the instantaneous speed would probably have been higher or lower than 100km/hr at various stages of the journey. The average speed of 100mh/hr corresponds to the average failure rate *Ø(t)* while the instantaneous speed readings at specific points of time during the course of the journey corresponds to the instantaneous failure rate, or hazard rate, $h(t)$.

It is possible, and is quite commonly encountered, to have a constant hazard rate. In such a case $h(t)$ would be equal to *Ø(t)* and is hence equal to a constant λ. In the case of a constant hazard rate the four descriptive functions become:

$$h(t)=\lambda \text{ ………………………………………………………………..(2.6)}$$

$$R(t)=e^{-\lambda t} \text{ ………………………………………………………(2.7)}$$

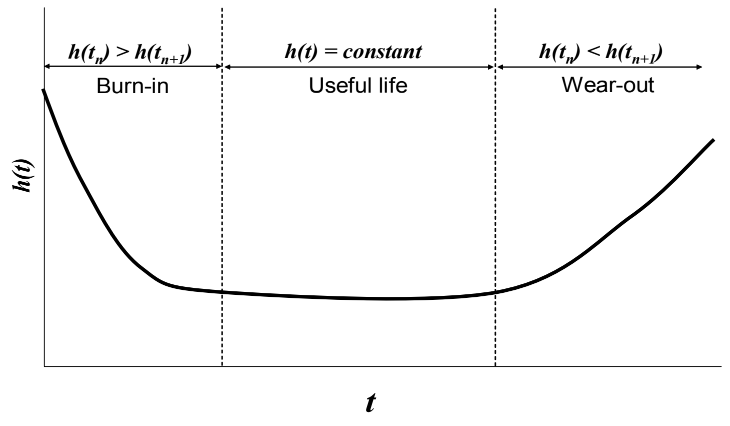
$$F(t) = 1 - e^{-\lambda t} \quad \text{……………………………………..……………….(2.8)}$$

$$f(t) = \lambda e^{-\lambda t} \quad \text{………………………………………..……………………(2.9)}$$

Wolstenholme (1999) points out that the hazard function *h(t)* has a high level of importance in reliability evaluations because it carries direct information and interpretation about the nature of the failures of the components or system under investigation. It is also important to note that the hazard function can adopt several different forms.

1. *h(t)* is a constant λ: This is the reliability function of the exponential distribution with rate parameter λ. An exponential distribution corresponds to a component or system that exhibits "no ageing". The component or system is "as new" at any instant in time and any failure is fully random.
2. *h(t)* is an increasing function of *t*: Here the component or system is experiencing ageing through wear or fatigue.
3. *h(t)* is an decreasing function of *t* : More typical of a system where inferior, of sub standard, components fail soon after start-up and are replaced with components of improved quality and reliability.

These various forms of the hazard function are shown graphically in Figure 2.2 below.



:Figure 2.2 Bathtub Curve (adapted from Frankel, 1984)

The primary objective of this study is of comparative nature i.e. comparing the reliabilities of large single stream milling circuits and multiple stream milling circuits during their useful life phases. This will be achieved by comparing the downtime data of several different full-scale Platinum concentrators, some of which will be old (>10yrs) and some relatively new (<3yrs). It is therefore quite probable that the profiles of the hazard functions of these plants fall are in different phases of their respective bathtub curves. Some of the newer plants may still be in their burn-in phase while some of the older plants may already be in their wear-out phase. It will be important to establish in which phase of the bathtub curve each of the plants are and only to compare those that are considered to be within their useful-life phases.

2.1.2. Mean Time To Failure

Lewis (1996) defines the mean time to failure (MTTF) as the expected value *E{t}* of the failure time t. It can be shown that

$$MTTF = \int_0^\infty R(t)\,dt \qquad (2.10)$$

In the case of a constant hazard rate

$$MTTF = 1/\lambda \qquad (2.11)$$

2.2. Simple Network Systems

In practice a system is commonly represented as a reliability network in which the individual components are connected either in series, or parallel, or a combination of both. Billinton (1983) describes the difference between series and parallel systems as follows:

- A reliability network is considered to be connected in series when **all** the components must function for system success. The failure of any one of the individual components will cause the entire system to fail. A series system is also termed no-redundant.

- A reliability network is considered to be connected in parallel when **all** the components must fail for system failure. A parallel system will contain some level of either full or partial redundancy.

2.2.1. Series Systems

The reliability block diagram of a two-component series system is shown in figure 2.3 below.

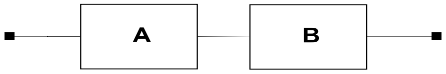


Figure 2.3 Simple series system

Let R_A and R_B be the probability of successful operation of components A and B respectively and let F_A and F_B be the probability of failure of the components A and B respectively. Since success and failure are mutually exclusive and complementary

$R_A + F_A = 1$ and $R_B + F_B = 1$

According the definition of series systems both A and B must be functional for system success. Therefore the probability of system success is given by

$$R_S = R_A \bullet R_B$$

If there are n components in series the generalised from of the equation becomes

$$R_s = \prod_{i=1}^{n} R_i \quad \text{..........(2.12)}$$

If the probabilities of success are made dependent on time i.e. the probability of surviving for a period of time t, then for an n-component system with hazard rates $h_1(t), h_2(t), \ldots\ldots\ldots h_n(t)$ equation 2.12 becomes

$$R_s(t) = \prod_{i=1}^{n} exp\left[-\int_0^t h_i(t)\,dt\right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.13)$$

In the special case of $h(t)$ being a constant λ Eq. 2.13 reduces to

$$R_s(t) = \prod_{i=1}^{n} exp - \lambda_i t = exp\left(-\sum_{i=1}^{n} \lambda_i t\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.14)$$

The most important point that follows from equations 2.12, 2.13, and 2.14 is firstly that the system reliability decreases rapidly as the number of components in series increases, and secondly that the system reliability is directly influenced by the reliabilities of the individual components.

It can be shown that the hazard rate of s series system can be represented by a single equivalent hazard rate $h_e(t)$. Then Equation 2.13 becomes

$$R_s(t) = \prod_{i=1}^{n} exp\left[-\int_0^t h_i(t)\,dt\right] = exp\left[-\int_0^t h_e(t)\,dt\right] \ldots\ldots\ldots\ldots\ldots\ldots(2.13a)$$

and in the case of exponential hazard rates Equation 2.14 becomes

$$R_s(t) = exp\left(-\sum_{i=1}^{n} \lambda_i t\right) = exp(-\lambda_e t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.14a)$$

It is clear from Eq. 2.13a that no simple relationship between $h_e(t)$ *and* $h_i(t)$can be derived from the general case when the distributions of the individual hazard rates is not known. However, in the special case of all series components having constant hazard rates

$$\lambda_e = \sum_{i=1}^{n} \lambda_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(2.14b)}$$

which shows that the equivalent failure rate of such a series system is simply the summation of the failure rates of the individual components.

This fact is of particular relevance to the evaluation of the reliability of large single-stream milling configurations. In this case there is no main-stream milling redundancy and the overall concentrator circuit may be viewed as a collection of different unit processes configured in series. When comparing the reliability profile of a single-stream concentrator with that of a multiple stream plant it will be important to establish whether any difference is due to the inherent mechanical reliabilities of the milling units (large vs. small) themselves being different, or due to the reliabilities of the upstream and/or downstream unit operations being different i.e configuration implications

2.2.2. Parallel Systems

Consider the reliability block diagram of a simple 2-component parallel system as shown in Figure 2.4 below.

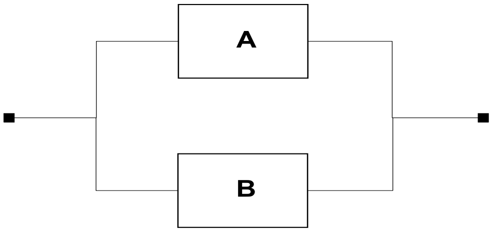


Figure 2.4: Simple parallel system

Let R_A and R_B be the probability of successful operation of components A and B respectively and let F_A and F_B be the probability of failure of the components A and B respectively.

Based on the assumption of full redundancy it is only necessary for either one of component A or B to function to achieve system success. The probability of the 2-component system success is then

$$R_P = 1 - F_A \bullet F_B = R_A + R_B - R_A \bullet R_B \quad \text{………………………………(2.15)}$$

For an n-component parallel system the generalised form of Eq. 2.15 becomes

$$R_p = 1 - \prod_{i=1}^{n} F_i \quad \text{…………………………………………………………...(2.16)}$$

and

$$F_p = \prod_{i=1}^{n} F_i \quad \text{…………………………………………………………………(2.17)}$$

If the probabilities of success and failure are made dependent on time i.e. the probability of surviving for a period of time t, then for an n-component parallel system with hazard rates $h_1(t), h_2(t),\ldots\ldots\ldots h_n(t)$ equations 2.16 and 2.17 become

$$R_p(t)=1-\prod_{i=1}^{n}\left(1-exp\left[-\int_0^t h_i(t)dt\right]\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.18)$$

and

$$F_p(t)=\prod_{i=1}^{n}\left(1-exp\left[-\int_0^t h_i(t)dt\right]\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.19)$$

If the special case of constant hazard rates is considered then, for an n-parallel system, equations 2.18 and 2.19 become.

$$R_p(t)=1-\prod_{i=1}^{n}\left(1-exp\left(-\lambda_i t\right)\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.20)$$

and

$$F_p(t)=\prod_{i=1}^{n}\left(1-exp\left(-\lambda_i t\right)\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.21)$$

In contrast to the series system, it is not possible to derive a single equivalent failure rate to represent a parallel system. Also, the resulting distribution of a parallel system consisting of exponentially distributed component reliabilities is itself non-exponential and the resulting hazard rate is no longer constant but rather a function of time.

2.2.3. Redundancy

Bradley (1993) defines redundancy as the provision of more than component or sub-system in order to accomplish a given function. Per definition redundancy is applicable to systems with parallel configurations.

Redundancy can be active or standby. Active redundancy refers to a system where all the circuit streams are energised/functioning during normal operation and where failure of one or more of the circuit streams will not result in system failure. Standby redundancy on the other hand refers to a system configuration where an alternative standby component, or sub-system, is provided that is idle during normal operations and is only becomes energised when the main sub-system or component fails.

2.2.4. Partially Redundant Systems

Partial redundancy refers to systems which require some proportion of the components somewhere between the extremes of full series and parallel (full redundancy) to operate. Partially redundant systems are commonly referred to as *k-out-of-n* active redundancy systems. This simply means that k out of a total number of n components must function to achieve system success.

It follows therefore that a partially redundant system may adopt different states i.e *0, 1, 2, 3, ………, n* components operating. In the special case of identical components the probability of each state of such a system can be estimated using the binomial expansion

$$(n-k)^n = \sum_{k=0}^{n} \frac{n!}{k!(n-k)!} p^k q^{n-k} \text{……………………………………}(2.22)$$

where n = total number of components in parallel

k = number of operating components required for system success.

In the case of time dependant probabilities Eq. 2.22 becomes

$$\left(R(t)+F(t)\right)^{n} \qquad (2.23)$$

In the special case of exponential distributions (constant failure rate)

$$R(t)=e^{-\lambda t} \quad \text{and} \quad F(t) = 1-e^{-\lambda t}$$

and the binomial expansion for estimating the probability of system success for a k-out-of-n system of identical components becomes

$$\left[e^{-\lambda t}+\left(1-e^{-\lambda t}\right)\right]^{n} \qquad (2.24)$$

In the more general case when the components do not have identical failure rates the probability of each system state can be estimated according to

$$\left(R_1(t)+F_1(t)\right)\left(R_2(t)+F_2(t)\right)\ldots\left(R_n(t)+F_n(t)\right) \qquad (2.25)$$

The concept of partial redundancy is applicable to the majority of multi-stream Platinum concentrators. As already explained the design and configuration of conventional, older style Platinum concentrators was determined mostly by the maximum nominal capacities of the rotary mills available at the time. The physical size and capacities of the conventional rotary mills were greatly restricted by manufacturing methods and materials. The result was that the overall capacities of conventional concentrators normally exceeded the unit capacities of the individual mills. This capacity constraint was historically overcome by configuring the rotary mills in multiple, parallel processing streams. It was, and still is, also common practice to apply a relatively generous safety factor when sizing and selecting the rotary mills during the design phase i.e. the absolute maximum capacity of the individual milling units is invariably higher than the actual design capacity (assuming of course that all the metallurgical parameters that determine the grindability of the ore was correctly tested and evaluated beforehand). The practical implication of this, in the case of a multi-stream plant, is that the feed rates to the online milling streams can be temporarily increased to compensate, either fully or partially, for milling streams that are down. In other words; a multi-stream Platinum concentrator may be viewed as a partially redundant system where a certain k-out-of-n milling streams are required to be operational in order to sustain overall system success i.e. sustain an acceptable throughput rate.

2.3. Repairable Systems

Ascher (1984) defines a repairable system as one which, after failing to perform one or more of its functions satisfactorily, can be restored to a fully satisfactory level of performance by any method other than replacing the entire system.

These repairs to a repairable system are collectively referred to as maintenance. Lewis (1994) states that for most repairable systems there are two classes of maintenance namely preventative and corrective maintenance. The objective of preventative maintenance is to extend, or sustain, the long term system reliability by retarding the effects of wear, corrosion, fatigue etc.

This is achieved by performing routine maintenance activities such as parts replacement, lubrication replacement etc **before** failure occurs. The primary criterion for measuring the effectiveness of preventative maintenance is the long term reliability of the system.

In contrast to this the term corrective maintenance refers to those activities required to restore a system to a functional level **after** it has failed. Lewis (1994) states that the effectiveness of corrective maintenance is measured by the availability of the system where availability is seen as the probability that the system is able to function when required.

2.3.1. Behaviour of a Repairable System

The discussions of failures in all the preceding sections are based on the assumption that when a component or system fails, it is repaired or replaced instantly, or that the time taken to repair or replace it is negligibly small compared to the operating time. However, this assumption is not always valid because in the case of some repairable systems the time taken to perform repairs and maintenance is significant relative to normal operating time and must be taken into account when evaluating the overall reliability of the system.

The chronological behaviour of simple repairable system is shown as a time line in figure 2.5 below. In the preceding sections the mean-time-to-failure MTTF was defined as the average of the operating times taken from the moment that a system or component started operating to the moment that it failed. These times are shown as m_1, m_2, m_3…. in figure 2.5. The reciprocal of the MTTF was described as the failure rate λ , assuming that the failures follow a negative exponential distribution. Similarly the repair rate μ is the reciprocal of the mean-time-to-repair MTTR where the MTTR is the average of the repair times taken from the moment that the system failed to the moment that it is returned to an operable state. These repair times are shown as $r_1, r_2, \ldots\ldots$ in figure 2.5.

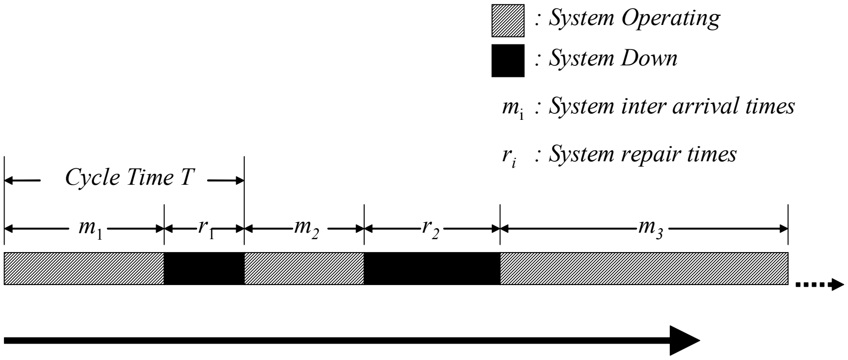


Figure 2.5: Chronological behaviour of a simple repairable system

The majority of repairable systems can be considered discrete in space and continuous in time. This means that they can exist continuously in one of several clearly identifiable system states until a transition occurs that transfers them discretely to another system state where they then continuo existing until another transition occurs and so forth. The two most common system states are the operating state and the failed state.

Very simply

$$\lambda = \frac{no.\ of\ \ failures\ in\ a\ given\ time\ period}{total\ \ period\ \ of\ \ time\ in\ the\ operating\ state} \text{ …………………………(2.26)}$$

and

$$\mu = \frac{no.\ of\ \ repairs\ in\ a\ given\ time\ period}{total\ \ period\ \ of\ \ time\ in\ the\ \ failed\ state} \text{ …………………………...(2.27)}$$

It is important at this point to distinguish between mean-to-to-failure MTTF and mean-time-between-failure MTBF. By convention MTTF is used to describe the failure characteristics of non-repairable systems and components while MTBF is reserved for repairable systems and replaceable components.

2.3.2. Availability

It is inevitable in the case of Platinum concentrators that failures will occur and hence corrective repairs or maintenance will be necessary. It will therefore not only be important to estimate the probability of failure, but also to consider two additional reliability parameters namely the number of failures that occur, and the time taken to implement corrective maintenance or repairs. These reliability parameters are called availability and maintainability respectively.

Lewis (1994) defines availability is the probability that a system is available for use at a given point in time and maintainability as the basic measure of how quickly a system can be repaired after a failure has occurred. Availability and maintainability are important parameters because they serve as the quantitative basis for analysis repairable systems.

In general the Poisson distribution can be used to represent the probability of a discrete event happening a specified number of times in a given period of time when the rate at which the event occurs is constant over time. Let $P_x(t)$ be the probability that of x number of failures occurring in the time period (0, *t*) and assuming $h(t) = \lambda$, a constant, then

$$P_x(t) = \frac{(\lambda t)^x e^{-\lambda t}}{x!} \quad \text{...(2.28)}$$

Bradley (1993) adapts Eq. 2.28 to derive an expression for estimating the probability of not completing a single repair within a specified time limit.

$$\begin{aligned} P(0) &= \frac{(\mu t_m)^0 e^{-\mu t_m}}{0!} \\ &= e^{-\mu t_m} \end{aligned} \quad \text{...(2.29)}$$

where

μ = the repair rate (assumed to be constant)

t_m = the repair time constraint

It then follows that the probability M of completing one or more repairs is

$$M(t_m) = 1 - e^{-\mu t_m} \quad \text{...(2.30)}$$

Eq 2.30 is also known as the maintainability expression. Also from Eq 2.8 the probability of one or more failures occurring within a specified time period is

$$F(t) = 1 - e^{-\lambda t}$$

From Eq 2.8 and Eq 2.29 the probability of not completing the repair after a failure has occurred is

$$= e^{-\mu t_m}\left(1 - e^{\lambda t}\right)\text{...}(2.31)$$

Therefore the probability A_e of completing a repair and restoring the system to an operable state is

$$A_e = 1 - e^{-\mu t_m}\left(1 - e^{\lambda t}\right)\text{...}(2.32)$$

Bradley (1993) refers to expression 2.32 as the equipment availability.

Lewis (1994) applies a slightly different procedure for developing the different expressions for point, interval, and steady-state availabilities.

Let $A(t)$ = the probability that a system is performing satisfactorily at specific point in time t.

and $A^*(T)$ = the value of the point availability averaged over an interval period of time.

Then

$$A^*(T) = \frac{1}{T}\int_0^T A(t)dt \quad \text{……………….……………………………………(2.33)}$$

It is often found that the point availability will assume a time-independent value if the interval T is large enough. In such cases it is then possible to define the steady-state availability as

$$A^*(T) = \lim_{T\to\infty}\frac{1}{T}\int_0^T A(t)dt \quad \text{…………………..…………………………….(2.34)}$$

Assuming that the distribution of repair times is characterised by a constant repair rate then

$$v(t) = \mu \quad \text{……………………….…………………………………(2.35)}$$

and the probability density function of repair times is then exponential

$$m(t) = \mu e^{-\mu t} \quad \text{………………………………………………….……(2.36)}$$

and then the mean-time-to-repair is

$$MTTR = {}^{1}\!/_{\mu} \quad \text{…………………………………………...………..(2.37)}$$

Now consider a two state system where state 1 represents the operational state, and state two the failed state. Then let $A(t)$ and $\tilde{A}(t)$, the availability and unavailability respectively, be the probabilities that the system is either in the operational or in the failed state at time t, where t is measured from the instant that the system first starts to operate. Therefore at the moment that the system starts to operate

$A(t) = 1$ and $\tilde{A}(t) = 0$

It follows that

$$A(t) + \tilde{A}(t) = 1 \qquad (2.38)$$

First consider the change in $A(t)$ between t and Δt. Since $\lambda\Delta t$ is the conditional probability of failure during Δt, given that the system is available at t, the loss of availability during Δt is equal to $\lambda\Delta tA(t)$ Similarly $\mu\Delta t$ is the conditional probability that the system is repaired during Δt given that is unavailable at t, and hence the gain in availability is equal to $\mu\Delta t\tilde{A}(t)$

$$A(t+\Delta t) = A(t) - \lambda\Delta tA(t) + \mu\Delta t\tilde{A}(t) \qquad (2.39)$$

Rearranging terms and eliminating $\tilde{A}(t)$ then Eq 2.39 may be written as a differential equation

$$\frac{d}{dt}A(t) = -(\lambda+\mu)A(t) + \mu \qquad (2.40)$$

Using an integrating factor of $e^{\lambda+\mu}$ and assuming the initial condition $A(0) = 1$ then

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} \cdot e^{-(\lambda+\mu)t} \qquad (2.41)$$

Now inserting Eq 2.41 into Eq 2.34 yields the expression for interval availability

$$A^{*}(t)=\frac{\mu}{\lambda+\mu}+\frac{\lambda}{(\lambda+\mu)^{2}T}\cdot\left(1-e^{-(\lambda+\mu)T}\right)\text{.................................}(2.42)$$

The estimation of steady-state availability is obtained by letting T go to infinity

$$A^{*}(\infty)=\frac{\mu}{\lambda+\mu}\text{ ....}(2.43)$$

Also note that for constant repair rates $A^*(\infty) = A(\infty)$ and since MTTF = $1/\lambda$ and MTTR = $1/\mu$

$$A(\infty)=\frac{MTTF}{MTTF+MTTR}\text{ ....}(2.44)$$

Lewis (1994) makes the point that Eq 2.44 is generally an acceptable estimation of availability if averaged over a reasonable period T of time.

It is common practice in the Platinum mining industry to measure availability on a monthly basis. Monthly availability is generally calculated as

$$A(month)=\frac{Total\ calender\ time\text{ - }Downtime\ due\ to\ repairs\ \&\ maintenance}{Total\ calender\ time}$$

Availability calculated in this manner may yield the same result as Eq 2.44 under conditions of constant failure rates and constant repair rates over a period of a normal calendar month. However, it is unlikely to be the same if considered on a weekly or even daily basis. It will therefore be prudent to characterise the availabilities of the Platinum concentrators surveyed for purposes of this study.

2.3.3. Markov Process Analysis

The majority of the reliability evaluation techniques described above are based on the assumption that repairs are instantaneous, or the duration of repairs is negligible relative to operational times. These techniques are therefore not applicable when this assumption is not valid.

A technique known as Markov analysis or modelling has been found to be very applicable in such cases (Billinton, 1983, Lewis, 1994). The Markov approach can be applied if the system behaviour conforms to selected criteria of a stochastic process. In short these criteria are (Tijms, 1994):

- The behaviour of the system must have a lack of memory i.e. all the future states of the system must be independent of all the past states except the immediately preceding one.
- The process must be stationary or homogeneous. This means that the behaviour of the system must be the same at all point in time i.e the probability of making a transition from one state to another must be constant over time.
- The different states in which the system can be must be discrete and clearly identifiable

These three criteria then allows the Markov approach to be applied to engineering systems whose behaviour in space and time follow a probability distribution that is characterised by a constant hazard rate i.e. Poison and exponential distributions. Space is normally represented by the discrete and identifiable states in which the system can occur, while time may either be discrete or continuous.

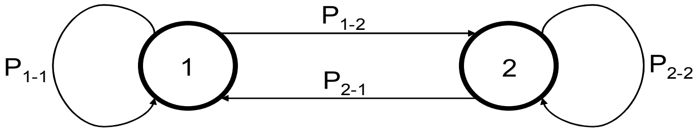


Figure 2.6: State-space diagram for a simple 2-state process

The basic concepts of the Markov approach are explained by considering the simple 2-state process shown graphically in figure 2.6 above. The system has two clearly identifiable states namely state 1 and state 2. The different probabilities of remaining or leaving a particular state are also shown where:

P_{1-2} : the probability of passing from state 1 to state 2
P_{1-1} : the probability of remaining in state 1
P_{2-1} : the probability of passing from state 2 to state 1
and P_{2-2} : the probability of remaining in state 2

It is important to note that the sum of the probabilities of remaining or moving from a state must be unity. Assuming that the system starts in a specific state at t=0 and that its transition from one state to another follows a discrete time path, then it can be shown that the probability of being in a particular state will change after each time interval until it reaches an equilibrium. The different state probabilities encountered during the initial time intervals is known as the transient behaviour, or time-dependent values of the state probabilities and is very dependent on the system conditions at start-up. The equilibrium values of the state probabilities that are reached after the system has been allowed to run for a large number of time intervals is known as the limiting-state or time-independent values and, in contrast to the values during transient behaviour, are totally independent of the initial conditions.

A system for which the limiting state values are independent of the initial conditions is known as ergodic. It is a further requirement of an ergodic system that every state of the system must be reachable, either directly or indirectly, from all other states. If this is not possible and the system contains states that cannot be left once they have been entered into, and the relevant states are known as absorbing states.

It is possible to describe and evaluate the different states for a specific system in terms of a matrix known as the stochastic transitional probability matrix, of which a generic example is shown below. The element P_{ij} of the matrix is defined as the transitional probability of moving from i-th state to the j-th state.

$$\begin{array}{c|ccccc|} & 1 & 2 & 3 & \cdots & n \\ 1 & P_{11} & P_{12} & P_{13} & \cdots & P_{1n} \\ 2 & P_{21} & P_{22} & P_{23} & \cdots & P_{2n} \\ 3 & P_{31} & P_{32} & P_{33} & \cdots & P_{3n} \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ n & P_{n1} & P_{n2} & P_{n3} & \cdots & P_{nn} \end{array}$$

In general Platinum concentrators may be viewed as continuous Markov processes i.e. they can exist continuously in one of several discretely identifiable states until a transition occurs which takes them into another state in which they then exist continuously until the next transition occurs.

Tijms (1994) provides the following formal definition and description for the continuous Markov Process:

Definition. *A continuous-time stochastic process* $\{X(t),\ t\geq 0\}$ *with discrete state space* I *is said to be a continuous-time Markov chain if*

$$P\left\{X\left(t_n\right)=i_n \,\middle|\, X\left(t_0\right)=i_0 ,\ldots,X\left(t_{n-1}\right)=i_{n-1}\right\}$$
$$=P\left\{X\left(t_n\right)=i_n \,\middle|\, X\left(t_{n-1}\right)=i_{n-1}\right\}$$

for all $0 \leq t_0 < \cdots < t_{n-1} < t_n \text{ and } i_0,\ldots,i_{n-1},i_n \in I$

When considering a time-homogeneous Markov chain for which the transition probability $P\{X(t+u)=j \mid X(u)=i\}$ is independent of u > 0. Then

$$p_{ij}(t)=P\{X(t+u)=j \mid X(u)=i\}$$

It is then possible to construct a jump process whereby a stochastic system with a discrete state I jumps from one state to another according to the following rules:

1. If the system jumps to state i, it remains in state i an exponentially distributed time with mean $1/v_i$ independently of how the system reached state i and how long it took to get there.
2. If the system leaves state i, it jumps to state j with a probability p_{ij} $(j \neq i)$ independently of the duration of the stay in state i where $\sum_{j \neq i} p_{ij} = 1$ for all $i \in I$

Assumption *In any finite time interval the number of jumps is finite with probability = 1.*

Then define a continuous-time stochastic process $\{X(t), t \geq 0\}$ by

$X(t)$ = the state of the system at time t, $t \geq 0$, where the process is said to be right-continuous.

Now consider a process $\{X(t)\}$ In view of the assumption made above and the memory less property of the exponentially distributed times, the probability of two or more state transitions within a time Δt is negligibly small compared to Δt as $\Delta t \to 0$.

Then for $i \in I$

$$P\{X(t+u) = j \mid X(t) = i\} = \begin{cases} v_i \Delta t \times p_{ij} + o(\Delta t) & \text{for all } j \neq i \\ 1 - v_i \Delta t + o(\Delta t) & \text{for all } j = i \end{cases}$$

as $\Delta t \to 0$. Further denote $q_{ij}(j \neq i)$ by the quantity

$$q_{ij} = v_i p_{ij}, \quad i, j \in I, \quad j \neq i$$

The numbers q_{ij} are called the infinitesimal transition rates of the continuous-time Markov chain $\{X(t)\}$. Although $q_{ij}\Delta t$ can be interpreted as the probability of moving from state I to state j in the next Δt, the q_{ij} values themselves are not probabilities but rather transition rates.

Note that the q_{ij} values determine the v_{ij} and p_{ij} values by

$$v_{ij} = \sum_{j \neq i} q_{ij}$$

and

$$p_{ij} = \frac{q_{ij}}{v_{ij}}$$

Billinton (1983) provides a much more understandable derivation of the time-dependent probabilities of a continuous Markov process from the perspective of a reliability application. Consider a single component repairable system of which the state-space diagram is shown in figure 2.7 below.

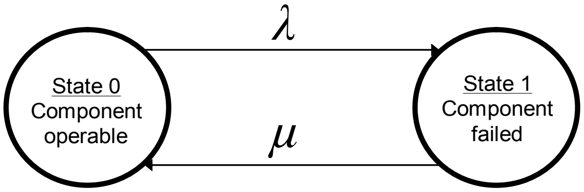


Figure 2.9 Single component repairable system (Billinton, 1983)

Define

$P_0(t)$ = probability that the component is operable at time t

$P_1(t)$ = probability that the component is in the failed state at time t

λ = failure rate

μ = repair rate

where λ and μ are defined as in Eq's 2.26 and 2.27 respectively. Then from Eq 2.9 the density function for a component with a constant hazard rate of λ was given as

$$f(t) = \lambda e^{-\lambda t}$$

It is therefore possible to describe the density functions of the operable and failed states for the system shown in Figure 2.7 above as

$$f_0(t) = \lambda e^{-\lambda t} \quad \text{………………………………………………………………} (2.45)$$

and

$$f_1(t) = \mu e^{-\mu t} \quad \text{……………………………………………………...…….}(2.46)$$

respectively.

Referring once again to Eq's 2.26 and 2.27 leads to an important definition

$$transition\ rate = \frac{no.\ of\ times\ a\ transition\ occurs\ from\ a\ given\ state}{total\ combined\ time\ spent\ in\ the\ given\ state}$$

Consider the system shown in figure 2.7 above and allowing for an incremental time interval *dt* that is sufficiently small so that the probability of two or more transitions occurring during this interval is negligible. Then the probability of being in the operating state after this time interval *(t+dt)* is

[Probability of being operative at time t, AND not failing in time dt]
\+ *[probability of being failed at time t AND of being repaired in time dt]*

This is expressed mathematically as

$$P_0(t+dt) = P_0(t)(1-\lambda dt) + P_1(t)(\mu dt) \quad \text{………………………………..}(2.47)$$

and

$$P_1(t+dt) = P_1(t)(1-\mu dt) + P_0(t)(\lambda dt) \quad \text{……………………………...…}(2.48)$$

By simplifying and rearranging it can be shown that

$$P_0'(t) = -\lambda P_0(t) + \mu P_1(t) \quad \text{……………………………………………….} (2.49)$$

and

$$P_1'(t) = \lambda P_0(t) - \mu P_1(t) \quad \text{……………………………………….…………(2.50)}$$

Eq's 2.49 and 2.50 are linear differential equations with constant coefficients that can be solved by Laplace transform (see appendix 1) method to ultimately yield

$$P_0(t) = \frac{\mu}{\lambda+\mu} + \frac{e^{-(\lambda+\mu)t}}{\lambda+\mu}\left[\lambda P_0(o) - \mu P_1(o)\right] \quad \text{…………….……….(2.51)}$$

and

$$P_1(t) = \frac{\lambda}{\lambda+\mu} + \frac{e^{-(\lambda+\mu)t}}{\lambda+\mu}\left[\mu P_1(o) - \lambda P_0(o)\right] \quad \text{………………………(2.52)}$$

based on the fact that $P_1(0) + P_0(0) = 1$.

Equations 2.51 and 2.52 therefore represent the time-dependent probabilities of finding the system in the operating state and failed state given that the system started in either the operating state or failed state respectively.

Expressions for the time-independent or limiting state probabilities can also be derived from Eq's 2.51 and 2.52. Firstly define the limiting state probabilities as P_0 and P_1 for the operating state and the failed state respectively; then by letting $t \rightarrow \infty$

$$P_0 = P_0(\infty) = \frac{\mu}{\lambda+\mu} \quad \text{…………………………………………….…………(2.53)}$$

and

$$P_1 = P_1(\infty) = \frac{\lambda}{\lambda+\mu} \quad \text{…………………………………………………...(2.54)}$$

Equations 2.53 and 2.54 are also known as the steady-state availability and steady-state unavailability.

The approach described above is based on defining a limiting state probability vector α which remains unchanged when multiplied by the stochastic transitional probability matrix.

$$\alpha P = \alpha \quad \text{………………………………………………..……………(2.55)}$$

If α is $\begin{bmatrix} P_0 & P_1 \end{bmatrix}$ then the expression fro the system shown in figure 2.7 above becomes

$$\begin{bmatrix} P_0 & P_1 \end{bmatrix} \cdot \begin{bmatrix} 1-\lambda \Delta t & \lambda \Delta t \\ \mu \Delta t & 1-\mu \Delta t \end{bmatrix} = \begin{bmatrix} P_0 & P_1 \end{bmatrix} \quad \text{……………………..……….(2.56)}$$

which when written in explicit from equals Eq’s 2.47 and 2.48. These equations can be solved using either matrix solution techniques, or any other relevant method to provide explicit expressions for the individual state probabilities.

Bradley (1991) points out that the practical application of the Markov process method has been somewhat limited for mainly the following reasons:

- The state transition matrices very rapidly assume large proportions as the systems become larger and more complex.
- The computational effort and complexity required to analyses even a moderately sized system can be substantial.

These opinions are shared by Billinton (1983). He points out that the maximum number of states in which a system can reside is equal to 2^n where n is the number of individual components in the system. For example, if the system consists of five components, then it can adopt a maximum of $2^5 = 32$ different states. The derivation of the expressions for the different state probabilities will therefore require a 32×32 matrix to be solved.

The comments and opinion expressed above by Bradley and other others is certainly valid for the reliability analysis of repairable systems at component level where the number of components are typically large. However, these limitations can be overcome to a certain degree by considering large systems as a collection of sub-systems, or unit processes and defining a limited number of critical states.

Perman *et al* (1997) applied Markov chain analysis to the reliability evaluation of a large electric power station. The main thrust of their work was an attempt to overcome the restrictions created by the traditional Markov method whereby the state holding times have to be exponentially distributed. In their view exponential distributions does not always fit actual operating data very well. Instead they propose using semi-Markov process methods and estimating the reliability indices using Weibull distributions. However, the most important part of their work, as it relates to the purposes of this study, is the way that they modelled a Slovenian coal-fired electric power plant called Šoštanj as system of unit processes where the interaction of the different states could lead to the overall system being either operational or failed. The different system states for the power plant and the possible transitions between them are shown graphically in Figure 2.8 below.

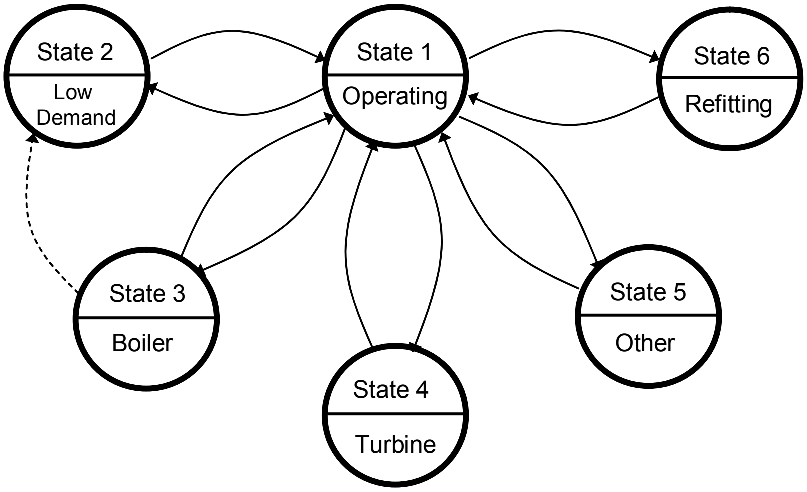


Figure 2.3: Power Plant Model with Possible State Transitions (Perman *et al 1997*)

The six system states used for their model are defined as

1. Operating state (up)
2. Stoppage due to low power demand (up)
3. Boiler failure (down)
4. Turbine failure (down)
5. Stoppages due to states other than no's 3 & 4 down.
6. Refitting (down).

The method of dividing a large, complex plant into a simplified network of sub-systems was found by the investigators to be an effective way of preventing the computational complexities that are normally associated with large Markov chains.

Samanta et al (2004) followed a similar approach in evaluating the reliability, availability, and maintainability (RAM) of a load haul dump truck used in an underground coal mining operation. They list a number of different methods that have been used by other investigators to model the failures of similar types of repairable machines. The different methods are; a renewal process, a homogenous Poisson Process, a non-homogenous Poisson Process, a Proportional Hazard process, and a Markov Process. They elected to model the LHD as a Markov process with due acknowledgement of the fact that failures of the sub-systems of such a machine can never be predicted precisely as they are very dependent on the highly variable operating conditions in an underground mining environment, as well as the maintenance philosophy applied by the maintenance crews.

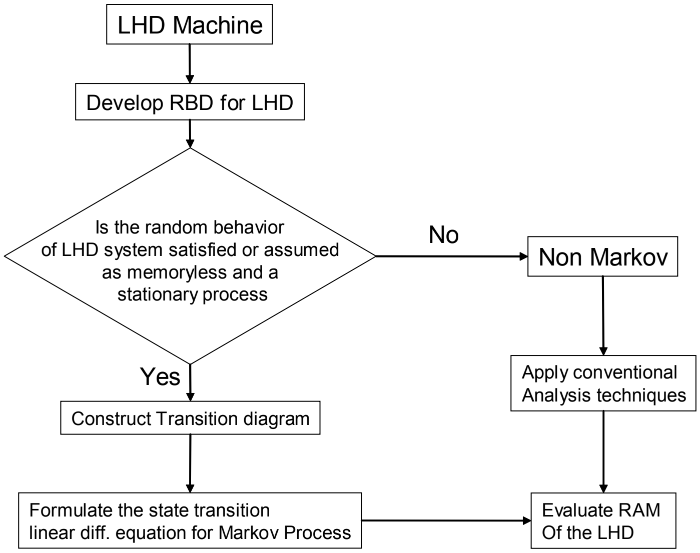


Figure 2.4: Flowchart for the reliability modelling of an LHD Machine (Samanta *et al*, 2004)

The basic procedure followed by Samanta *et al* is shown as a flowchart in figure 2.9 above.

By dividing the LHD truck into a collection of sub-systems then allows the overall machine to be represented as a simple series system represented by the reliability block diagram in figure 2.10 above.

By analysing approximately three years of breakdown and maintenance data of a specific LHD allowed the investigators draw significant conclusions regarding the RAM of the machine. Specific sub-systems that were the main contributors to an overall low level reliability were identified which could then be investigated in more detail.

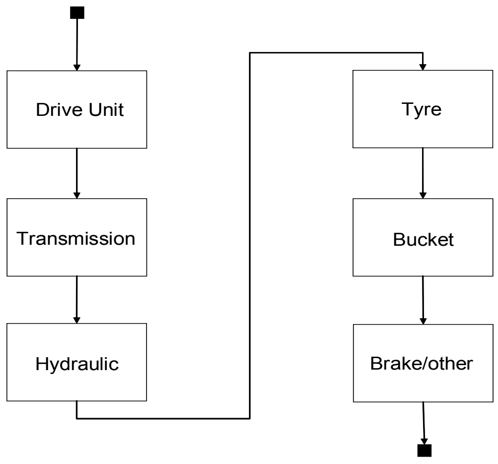


Figure 2.5: Reliability Block Diagram of LHD sub-systems (Samanta *et al, 2004*)

2.3.4. Frequency and Duration

Billinton (1983) comments that evaluating the reliability, availability, and maintainability RAM of a repairable system may not be sufficient for a thorough understanding of the performance of the specific system. He suggests two additional indices namely the frequency of encountering a specific state and, once entered, the duration of residing in the state. He refers to these additional indices as the “frequency and duration technique. This technique is based on, and forms a natural extension to the Markov process technique described in section 2.3.3 above.

The value of this technique becomes very evident when considering two separate systems; one with reliability indices of λ and μ and the other with indices of 2λ and 2μ. The availability and unavailability is the same for both systems but the one fails twice as much as the other and is repaired twice as fast i.e. the frequency of transitions, and duration of residing in a state is different. This could have a significant impact on the operation and effectiveness of the system. This is particularly true for Platinum concentrators where the number of plant stoppages has been shown to have a deleterious effect on the efficiency of Platinum recovery

The essence of this technique is best explained in terms of single repairable component. (refer figure 2.7). The probability of remaining in the operable state is then given by

$$P_0 = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} \qquad (2.55)$$

and the probability of remaining in the failed state is given by

$$P_1 = \frac{\lambda}{\lambda+\mu} = \frac{r}{m+r} \quad \text{......(2.56)}$$

where

λ = failure rate of the component
μ = repair rate of the component
m = average operating time of the component
r = average repair time of the component.

Referring to Figure 2.5 the system cycle time is *T* and is equal to the sum of the mean time to failure MTTF and mean time to repair MTTR. The cycle time is better known as the mean time between failures MTBF and must be distinguished from the mean time to failure MTTF. Only in cases where the MTTR is very small compared to operating time is it possible to assume that MTTF and MTBF are similar.

It is then possible to define the following relationships

$$m = MTTF = \frac{1}{\lambda} \quad \text{......(2.57)}$$

$$r = MTTR = \frac{1}{\mu} \quad \text{......(2.58)}$$

$$T = MTBF = m + r = \frac{1}{f} \quad \text{......(2.59)}$$

where f is the cycle frequency i.e. frequency of encountering a specific system state.

From equation 2.55 and 2.56 the probability of remaining in any state of the system is equal to the mean residence time of that state divided by the mean cycle time for that state to occur. This concept is applicable to all repairable systems no matter how many states exist. Therefore if $P(S)$ is the probability of residing in state S and $m(S)$ is the mean time spent in state S, and $T(S)$ is the mean time between encounters of state S then

$$P(S) = \frac{m(S)}{T(S)} \qquad (2.60)$$

also from Eq 2.55

$$P_0 = \frac{m}{m+r} = \frac{m}{T} = \frac{1}{\lambda T} = \frac{f}{\lambda} \qquad (2.61)$$

and from Eq 2.56

$$P_1 = \frac{r}{m+r} = \frac{r}{T} = \frac{1}{\mu T} = \frac{f}{\mu} \qquad (2.62)$$

From Eq's 2.61 and 2.62

$$f = P_0\lambda = P_1\mu \qquad (2.63)$$

which, when stated in words, means

the frequency of encountering the up state = $P_0\lambda$ *= (the probability of being in the upstate) x (rate of departure from the upstate) =* $P_1\mu$ *= (probability of not being in the state) x (rate of entry into the state)*

This concept is only applicable to long-term or steady-state conditions of the system and is not valid for time-dependent probabilities or frequencies.

2.3.5. Trend Analysis

Asher and Feingold (1984) provide the example of a happy and a sad system (see Figure 2.11 below). These two systems have the same failure rates if calculated in the conventional manner, but clearly the reliability of the happy system is improving and that of the sad system is deteriorating.

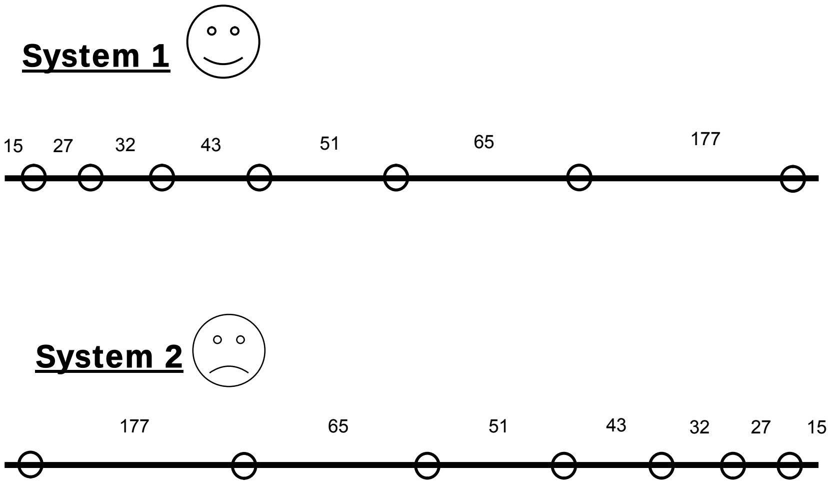


Figure 2.6: Happy and Sad systems (Ascher & Feingold, 1984)

Crowder *et al* (1991) also refer to the happy and sad systems of Ascher and Feingold, and emphasises the importance of the reliability of the behaviour of the inter-arrival failure times. Not only is the long term trend of failure time of importance but there may also be other structures that are of interest. For example, suppose that repairs are not always adequate. Then the failure time line will exhibit clusters of failures in short succession of each other.

Conventional reliability estimation techniques are based on independent and identically distributed (IID) lifetimes and hence any factors that lead to the departure from this assumption must be considered in the reliability evaluation of repairable system.

Crowder et al (1991) also defines the rate of occurrence of failures (ROCOF) as

$$\begin{aligned} v(t) &= \frac{d}{dt} E\{N(t)\} \\ &= A\alpha t^{\alpha-1} \end{aligned} \quad \text{………………………………………………….………(2.64)}$$

where

$N(t)$ = the number failure in the time interval $(0,t)$

From Eq 2.64, if $0<\alpha<1$ then the ROCOF is decreasing, if $\alpha=1$ then the ROCOF is constant, and if $\alpha>1$ then ROCOF is increasing.

Plotting the cumulative number of failures against the cumulative operating time is a simple but effective way of detecting long term trends. Any departure from linearity is indicative of inter-arrival times that are not IID.

Wolstenholme (1999) provides an alternative method called the Laplace test for detecting trends in failures. The central limit theorem sates that the statistic $\sum_{i=1}^{n-1} T_i / (n-1)$ has an approximate normal; distribution with a mean $T_n / 2$ and variance $T_n^2 / [12(n-1)]$.

So the statistic

$$U = \frac{\sum_{i=1}^{n-1} \frac{T_i}{n-1} - \frac{T_n}{2}}{T \sqrt{\frac{1}{12(n-1)}}} \quad \text{...(2.65)}$$

may be used to test the null hypothesis H_0 of zero trend i.e. $\alpha = 1$ in $A\alpha t^{\alpha-1}$ against either increasing or decreasing ROCOF.

2.4. The development of Rotary Mill Sizes in the Mineral Processing Industry

The diameter and installed power is typically used as the primary measures of the size and capacity of rotary mills.

Rotary mills are also classified by the nature of the grinding media used for size reduction. According to this classification there are four main types of mills namely, fully autogenous mills (using only the native rock), semi-autogenous mills (using a combination of steel balls and rock), ball mills (using a full charge of steel balls), and finally rod mills using large steel rods (Napier-Munn, 1999).

Allis-Chalmers, then a major supplier of rotary mills, manufactured and installed the first 4.0m diameter ball mill with 1800kw installed power during 1956. By the end of the 1970's the largest ball mills had grown to 5.5m in diameter with 3100kW installed power while the largest semi-autogenous (SAG) mill during the same period had a diameter of 11m and an installed power of 8950kW (Roloff, 1979). The largest gear driven SAG mill ever, at a diameter of 10.4m by 5.5m long and 13.4MW-installed power, went into operation at the Escondida Copper mine in Chile (Danecki, 1996). In 2002, the largest gear-and pinion driven ball mill at 7.32m by 9.6m and 10.4MW-installed power was commissioned at Rustenburg Platinum Mines in South Africa.

The need for increasing mill sizes is being driven by the demand for increased milling capacities for the treatment of lower grade ore, and stricter limitations on capital budgets (Roloff, 1979). This has resulted in modern mills using heavier and more complex components and fabrications than ever before (Svalbonas, 1996). The sheer size of the fabrications, and the enormous workload, make modern rotary mills more susceptible to fatigue and fracture failures despite the use of stricter specifications and standards for design and testing procedures. These failures may occur anywhere from start-up to as late as 12 years of service (Svalbonas, 1996).

The conclusion that may be reached at this stage is that the available mineral processing literature points to a high level of awareness among the mill manufacturers of the increased dependency by mineral process engineers and operators on the reliability of rotary mills for the overall performance of large mineral processing plants. However, nowhere in the literature could any concrete evidence be found of direct efforts made towards quantifying and parameterising the reliability of modern rotary mills and the impact that they in turn have on the reliability profile of the overall mineral processing system.

The focus of classical reliability engineering is on the understanding of failures, their prediction, and prevention. There is a close relationship between manufacturing and processing performance variability, and the modes of failure. Variability due to original manufacturing methods normally lead to failures soon after commissioning of the machine and are known as “infant mortality failures” The variability due to ongoing changes in the process or operating parameters lead to random failures because they are not dependent on the age of the machine. The final mode of failure is directly related to the age of the machine or system, and is known as aging or wear-out failures (Lewis, 1996). The failure modes of rotary mills are expected to be no different. It is expected to be possible to predict the probability of an infant mortality failure due to the manufacturing and fabrication process by applying modern analysis techniques such as finite analysis, and by revising inspection standards (Knecht, 1996). However, the other two modes of failure can only be quantified by analysing data of field failures. As described above, the environment of the typical mineral processing plant is highly variable and may serve as the main reason why the principles of classical reliability theory have not been applied extensively in the analysis of random and wear-out failures of rotary mills.

It is accepted that the area of classical field data analysis and interpretation of reliability data obtained from sophisticated systems such as electronics, aeronautical, weapons systems etc, has been widely researched to the point where these principles and theories can be adapted and applied to the prediction of reliability and availability of mineral processing systems.

3. EVALUATION MODEL & METHODOLOGY

The primary objective of this study is to develop a methodology which can be used to determine how the reliability of modern, high capacity, single stream, primary milling installations compare with the reliability of conventional low capacity, multiple stream, primary milling installations of South African Platinum concentrators. The methodology must allow the two main research questions associated with primary milling installations, to be answered namely :

- How does the inherent mechanical reliability of the large modern milling units compare to that of the older, conventional milling units?
- How does the configuration reliability of a modern, single stream milling installation compare to that of the conventional, multiple stream configurations?

The purpose of this chapter is to describe the available literature researched by this investigator towards developing a methodology with which to evaluate the above-mentioned research questions. The first section of this chapter provides more detail of the different primary milling configurations found in typical South African Platinum concentrators and the practical issues that impact on their reliabilities. The next section then seeks to develop a generic reliability block diagram (RBD) of these primary milling installations that will serve as the basis for the quantitative reliability evaluation for the purposes of this study. Three general expressions for quantifying the different reliability parameters of primary milling circuits as continuous-time Markov process will be presented. Later chapters will then focus on applying these expressions and methodology on firstly performing a hypothetical case study, and then later be applied to empirical case studies. The last section of this chapter will provide more detail on the method of treating and evaluating the empirical case studies.

3.1. Factors that Influence the Reliability of Primary Mills

The first stage of the Platinum extraction process involves reducing the size (milling) of the ore particles until the majority of the Platinum containing minerals are exposed, or liberated, allowing them to be recovered by means of flotation into a concentrate. The primary milling step is undoubtedly the most critical part of this process.

3.1.1. Primary mill design and construction (mechanical reliability)

Structurally these primary mills consist of large, cylindrical steel vessels that are supported in a horizontal position. These vessels are then rotated about their horizontal axis which allows the contained ore particles to be reduced in size by a combination of impact and abrasion processes. The cylindrical mill shell is protected by renewable liners. These liners are manufactured from wear resistant material, typically steel castings or rubber, or a combination of both. The inspection and replacement of these shell liners forms one of the most important maintenance functions that require the entire milling unit to be stopped for significant periods of time on a routine basis.

The mill shell is supported on both ends by end plates, each with a hollow trunnion. These end plates are manufactured as large steel castings that are then machined and drilled to be bolted onto the mill shell. The foundry process of manufacturing these large castings also holds certain physical limitations which can impact on the final integrity of the mill ends. In general it may be stated that it becomes more difficult to ensure the quality and integrity of these mill ends as the size of the mill end increases. Despite improved manufacturing techniques and materials it can still be expected that the mill ends of the large modern primary mills will be more prone to structural defects and failures than the smaller, conventional mills.

The trunnions at each end of the mill rest on large trunnion bearings and support the full static and dynamic loading of the mill. The trunnion bearings of the older, smaller type mills were made of either white metal castings enclosed by a fabricated steel housing, or of large roller bearings. In most cases both these types of bearings are grease lubricated i.e. a simple lubrication system. The enormous trunnion bearing loadings of the large modern mills prevents simple grease lubrication systems from being used. Instead, pump driven oil lubrication systems have to be applied. These oil pumping systems consist of reservoirs, oil filters, dedicated cooling systems etc. and require sophisticated monitoring and protection devices to function.

The conventional mills are almost exclusively rotated, or driven by a single pinion that meshes with a girth gear bolted to one end of the mill. The pinion, in turn is driven by standard type of squirrel gage electrical motor via a reduction gearbox. However, there is a structural limitation on the maximum amount of power/torque that can be transmitted by a single pinion drive. Very large mills therefore require multiple pinion drives, or even wrap around motors (see figure 3.1), and very complex load sharing systems and devices in order to overcome these limitations.

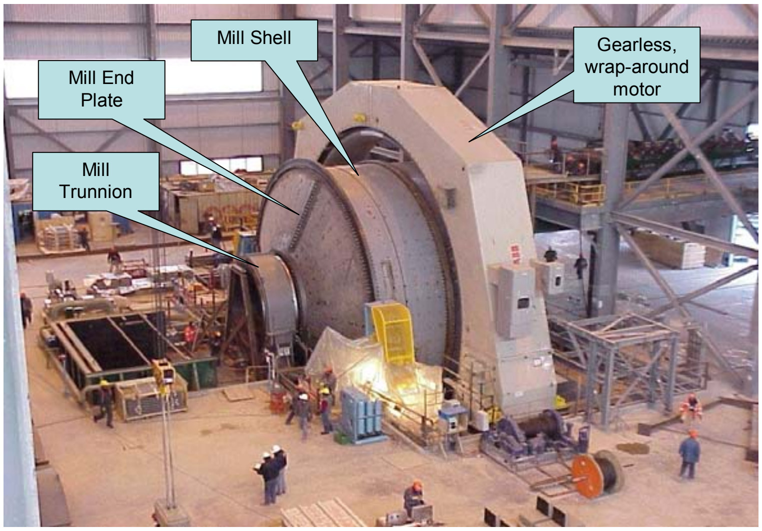


Figure 3.1: Example of the main components of a large modern mill with wrap-around motor.(FFE, 2001)

In summary it is very clear from the above description that the construction of the large modern mills is significantly more complex, and contains substantially more components, than the older type mills. It may therefore be expected that the inherent reliability of the older, conventional mills is different than that of the modern, large. However, the objective of this study does not include a detailed failure mode and effect analysis, at component level, of the two different types of mills. Instead, only the average pattern of operating and repairs times will be evaluated and compared.

3.1.2. Milling & Flotation Circuit Configuration

As already mentioned, a typical Platinum concentrator may be viewed as a system consisting of different unit processes of which primary milling are arguably the most critical. It is important to note that the primary mill, or mills, of the typical Platinum concentrator may have to be stopped due to failures of the other unit processes, either upstream or downstream. A simplified process flow sheet of a typical Platinum concentrator is shown if figure 3.2 below.

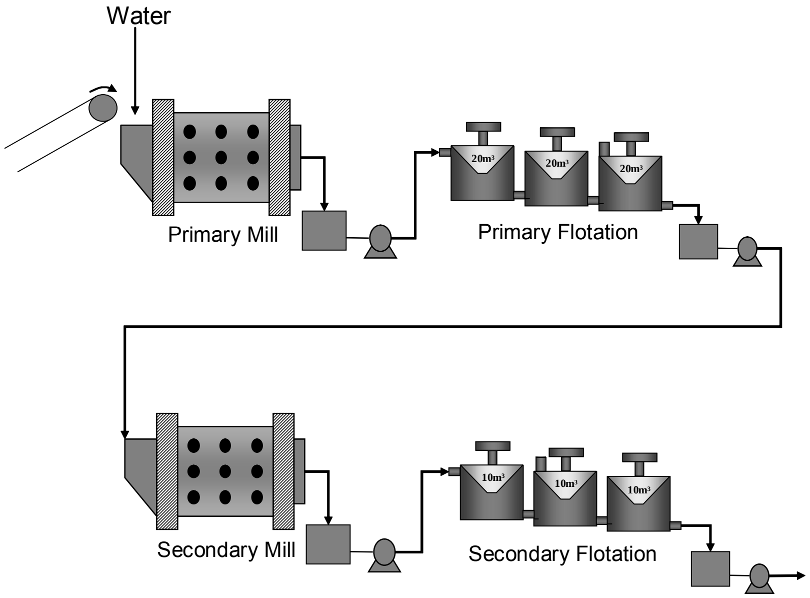


Figure 3.2: Process Flow of a typical Platinum Concentrator

Platinum bearing ore is usually transported by rail or other means from the mining operations to the concentrators where it is stored in some sort of storage bin. It is then removed from the storage bin and fed by conveyor to the primary mill in a strictly controlled manner. Water is introduced into the milling operation and the resultant slurry is then pumped to the primary flotation section. Reagents and air is introduced into the flotation cells (reactors) from which an enriched platinum bearing concentrate is recovered. The semi-barren tailing slurry from the primary flotation section is usually pumped to a secondary milling and flotation section for improved overall extraction efficiency (so-called mill-float-mill-float or MF2). The barren tailings from the concentrator process is then pumped to the final tailings dams for final disposal. The important point to note for the purposes of this study is that the primary mill/s is part of a system where, apart from its own inherent reliability, the failure of several other machines, or unit process, either upstream or downstream can cause the primary mill/s to be stopped, or taken off-line while repairs are being done. It is also important to point out that the size and capacities of the other processing equipment are normally related to the size, and number of primary mills employed in the circuit. The size and capacities of flotation cells and pumps used in a high capacity, single stream circuit will be substantially larger than the similar types of equipment used in a multiple stream circuit.

Clearly the way that the different unit processes are configured will have an impact on the reliability profile of the overall milling and flotation circuit. As already explained in section 1.1.1 above the design and configuration of conventional, older style Platinum concentrator was determined mostly by the maximum nominal capacities of the rotary mills available at the time. The physical size and capacities of the conventional rotary mills were greatly restricted by manufacturing methods and materials. The result was that the overall capacities of conventional concentrators normally exceeded the unit capacities of the individual mills. This capacity constraint was historically overcome by configuring the rotary mills in multiple, parallel processing streams as shown in a highly simplified manner in Figure 3.3 below.

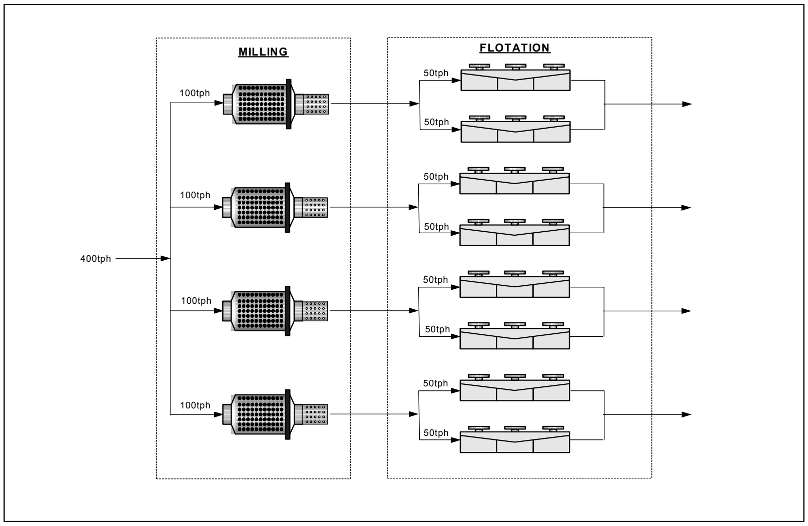


Figure 3.3: **System configuration of older type of concentrator**

One additional factor must be recognised when considering the reliability profile of the typical older Platinum concentrator circuit as shown in figure 3.3 above. This relates to the actual throughput capacity of the individual primary mills and its associated processing leg. The variable nature of the ore being treated requires a relatively generous safety factor to be applied when sizing the equipment during the original design phase. In almost every case the instantaneous throughput of each primary milling circuit can be adjusted to either exceed, or be below the original design capacity. In practice, when one or two mills are taken off line from a multiple stream circuit, this flexibility then allows the operators to step up the throughput rates of the remaining units in order to continue operating at the overall required throughput rate (ignoring the negative impact on recoveries). From a reliability perspective this implies that a typical multi-stream Platinum concentrator will always have a certain degree of partial redundancy i.e. stopping a limited number of primary mills will not result overall system failure and is a very important factor to considered when evaluating the reliability profile of such a plant.

By comparison, the configuration of the typical, single stream modern mineral processing circuit depicted in figure 3.2 below is intuitively not expected to possess the same level of mainstream redundancy and flexibility. In this case any maintenance or failure event that requires the primary mill to be stopped means that the entire plant has to be stopped i.e. system failure means primary mill failure and *vica versa*.

3.1.3. Maintenance & operation

As already mentioned any engineering system will have an inherent level of reliability which is derived from the basic configuration and equipment design. This refers to the ability of the system to operate at a specified level of performance for a specified time under ideal conditions (Frankel, 1984). However, the actual operating conditions of a Platinum concentrator will seldom be comparable to ideal design conditions and actual reliability will therefore deviate from the ideal design reliability. The degree in which the actual system performance deviates from the ideal for any specific Platinum concentrator is primarily a function of the general operational and maintenance philosophies and must be considered on a case specific basis

Possibly the most important factor to consider would be the quality of the maintenance performed on a specific mill. There are several maintenance related issues that would have a major impact on the measured reliability profile of any specific milling circuit. Some of these issues could be for example:

- Is preventative maintenance being practiced or not?
- Is there enough maintenance personnel?
- Have the maintenance personnel been adequately trained?

- Is the spares holding adequate?
- Etc

The evaluation of plant maintenance is an entirely separate field of study and, with due acknowledgement of its importance, will not be evaluated as part of this study. Instead, this investigator will simply adopt the view that, in general, maintenance practices on different Platinum concentrators will be the same, and any deviations will primarily be due to the nature and scale of the specific operation.

3.2. Primary Mill Reliability Evaluation Model.

Any primary mill may be classified as a repairable machine or component, that invariably forms part of a repairable system. This classification serves as the primary basis for the set of reliability evaluation techniques that are relevant to the analysis of primary mills for purposes of this study.

This investigator has elected to consider the chronological behaviour of the typical primary mill as a stochastic process. The criteria for a process to be classified as a stochastic was given in section 2.3.3. but is summarised again as follows:

i. The behaviour of the system must have a lack of memory i.e. all the future states of the system must be independent of all the past states except the immediately preceding one.

ii. The process must be stationary or homogeneous. This means that the behaviour of the system must be the same at all point in time i.e. the probability of making a transition from one state to another must be constant over time.

iii. The different states in which the system can be must be discrete and clearly identifiable

This investigator openly acknowledges that the general applicability of these criteria to a typical Platinum concentrator plant can be strongly debated. As stated in the chapter 2, no evidence could be found in the public literature of detailed reliability studies having been performed specifically on mineral processing plants. However, several references exist to power generation plants and underground mining equipment being successfully subjected to stochastic process evaluation techniques where the degree of success is measured to the ability of being able to identify pieces of equipment, or unit processes, which were the main contributors to poor reliability.

This study is based on the premise that if stochastic process evaluation techniques, such as Markov process analysis, can assist in providing a benchmark for comparative purposes of the reliability profiles of mineral processing plants, as opposed to producing statistically precise reliability determinations, then these techniques are certainly applicable for the purposes of this study.

3.2.1. Evaluating a Primary Mill as a Single Component

It has already been explained above that the primary mill is the most critical component in any Platinum concentrator circuit. The analysis of the operational behaviour of the primary mill will therefore serve as a direct measure of the behaviour of the overall circuit.

If the chronological behaviour of a single primary mill is considered, regardless of whether it is part of a multiple or single stream plant, then at any point in time it will either be operating or be stopped. It will therefore behave as a continuous Markov process i.e. it will be continuous in time and alternate discretely between the operating and failed states.

The primary mill may then be represented very simply as a single cell reliability block diagram as shown in figure 3.4 below. Also if the operating state is designated as State 0 and the failed state as State 1, then the state-space diagram is represented by figure 3.5 below.

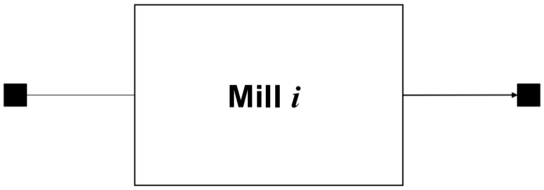


Figure 3.4: Reliability Block Diagram of a single primary mill

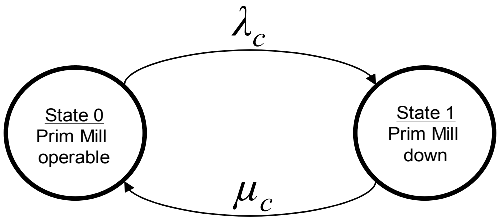


Figure 3.5: State-Space diagram of single primary mill.

Define the following for the single primary mill system

$P_0(t)$ = probability that the primary mill is operable at time t

$P_1(t)$ = probability that the primary mill is down at time t

λ_c = failure rate

μ_c = repair rate

Therefore

$\lambda_c dt$ = Probability of failing in $(t+dt)$

$1-\lambda_c dt$ = Probability of not failing in $(t+dt)$

$\mu_c dt$ = Probability of being repaired in $(t+dt)$

$1-\mu_c dt$ = Probability of not being repaired in $(t+dt)$

Consider the system shown in figure 3.5 above and allowing for an incremental time interval dt that is sufficiently small so that the probability of two or more transitions occurring during this interval is negligible. Then the probability of being in the operating state after this time interval *(t+dt)* is

[Probability of being operative at time t, AND not failing in time dt]
\+ *[probability of being failed at time t AND of being repaired in time dt]*

This is expressed as

$$P_0(t+dt)=P_0(t)(1-\lambda_c dt)+P_1(t)(\mu_c dt) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3.1)$$

Similarly the probability of being in the failed state after this time interval *(t+dt)* is

[Probability of being failed at time t, AND not being repaired in time dt]
\+ *[probability of being operative at time t AND of failing in time dt]*

$$P_1(t+dt)=P_1(t)(1-\mu_c dt)+P_0(t)(\lambda_c dt) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2)$$

By rearranging and simplifying it can be shown that Eq's 3.1 and 3.2 are

$$\left.\frac{P_0(t+dt)-P_0(t)}{dt}\right|_{dt\to 0}=P_0'(t)=\mu_c P_1(t)-\lambda_c P_0(t) \ldots\ldots\ldots\ldots..(3.3)$$

and

$$\left.\frac{P_1(t+dt)-P_1(t)}{dt}\right|_{dt\to 0}=P_1'(t)=\lambda_c P_0(t)-\mu_c P_1(t) \ldots\ldots\ldots\ldots(3.4)$$

Together Eq's 4.4 and 4.6 form a set of linear differential equations with constant coefficients that may be presented in matrix format as

$$\left[P_0'(t) \quad P_1'(t)\right]=\left[P_0(t)t \quad P_1(t)\right]\cdot\begin{bmatrix}-\lambda & \lambda \\ \mu & -\mu\end{bmatrix} \text{……………………..……} (3.5)$$

where $\left[P_0(t) \quad P_1(t)\right]$ is known as the state-probability vector.

Eq 3.5 can now be solved to give (see Appendix 1 for full derivation)

$$P_0(t)=\frac{\mu_c}{\lambda_c+\mu_c}\cdot\left[P_1(0)+P_0(0)\right]+\frac{e^{-(\lambda_c+\mu_c)t}}{\lambda_c+\mu_c}\cdot\left[\lambda_c P_0(0)-\mu_c P_1(0)\right] \text{………} (3.6)$$

and

$$P_1(t)=\frac{\lambda_c}{\lambda_c+\mu_c}\cdot\left[P_1(0)+P_0(0)\right]+\frac{e^{-(\lambda_c+\mu_c)t}}{\lambda_c+\mu_c}\cdot\left[\mu_c P_1(0)-\lambda_c P_0(0)\right] \text{……….} (3.7)$$

According to the Laws of probability

$$P_0(t)+P_1(t)=1 \text{………………………………………………………} (3.8)$$

Assuming the system starts in the operating state at $t=0$ then

$$P_0(0)=1 \text{……………………………………………………………} (3.9)$$

and

$$P_1(0)=0 \quad \text{……(3.10)}$$

Then Eq's 3.6 and 3.7 reduce to

$$P_0(t)=\frac{\mu_c}{\lambda_c+\mu_c}+\frac{\lambda_c}{\lambda_c+\mu_c}\cdot e^{-(\lambda_c+\mu_c)t} \quad \text{……(3.11)}$$

$$P_1(t)=\frac{\lambda_c}{\lambda_c+\mu_c}-\frac{\lambda_c}{\lambda_c+\mu_c}\cdot e^{-(\lambda_c+\mu_c)t} \quad \text{……(3.12)}$$

respectively. Eq's 3.11 and 3.12 can now be used to evaluate the transient behaviour of the system given that it started in the operating state.

Letting $t \to \infty$ reduces Eq 3.11 to

$$P_0(\infty)=\frac{\mu_c}{\lambda_c+\mu_c} \quad \text{……(3.13)}$$

which is the steady-state availability of the system. From this it follows that

System reliability $R_c = e^{-\lambda_c t}$ ……(3.14)

System Maintainability $M_c = 1-e^{-\mu_c t}$ ……(3.15)

Mean time to failure $MTTF_c = {}^{1}\!/_{\lambda_c}$ ……(3.16)

Mean time to repair $MTTR_c = {}^{1}\!/\!{}_{\mu_c}$ ……………………………………….…(3.17)

Mean time between failure $MTBF_c = MTTR_c + MTTF_c$

$$= {}^{1}\!/\!{}_{\lambda_c} + {}^{1}\!/\!{}_{\mu_c} = \frac{\lambda_c + \mu_c}{\lambda_c \mu} \qquad \text{………………}(3.18)$$

Frequency of encountering the failed state $f_c = P_1 \mu_c$ ……………

$$= \frac{\lambda_c}{\lambda_c + \mu_c} \cdot \frac{\mu_c}{1} = \frac{\lambda_c \mu_c}{\lambda_c + \mu_c} \qquad \text{……………...}(3.19)$$

3.2.2. Evaluating a Primary Mill as a collection of sub-components or unit processes

The expressions derived in section 3.2.1 above for evaluating a primary mill as a single component does not allow any evaluation of the possible reasons for failure. This can be achieved by considering the primary mill as a collection of components connected in series i.e. the failure of any one of the components, unit processes will result in system failure. In this case however, the components, or sub processes are the actual reasons for failure, and not physical components as is usually the case.

For the purposes of this study, a generic list of ten possible reasons why a primary mill will fail or be stopped was compiled and categorised as is shown in Table 3.1 below.

State no.	Description	Code
0	Normal operating	N
1	Planned maintenance	PM
2	Ore shortage	OS
3	Feed conveyor breakdown	FC
4	Major mill mechanical breakdown	M
5	Downstream pumping/piping breakdown	PP
6	Downstream process equipment breakdown	PE
7	Electrical failure or outage	E
8	PLC/SCADA failure	PLC
9	Water shortage	W
10	Other	O

Table 3.1: State categories and description

The primary mill and the possible reasons for failing are then considered to be in a series configuration i.e. failure of any one of the different components (failure modes) will cause overall system failure. The reliability diagram of this configuration is shown in Figure 3.6 below.

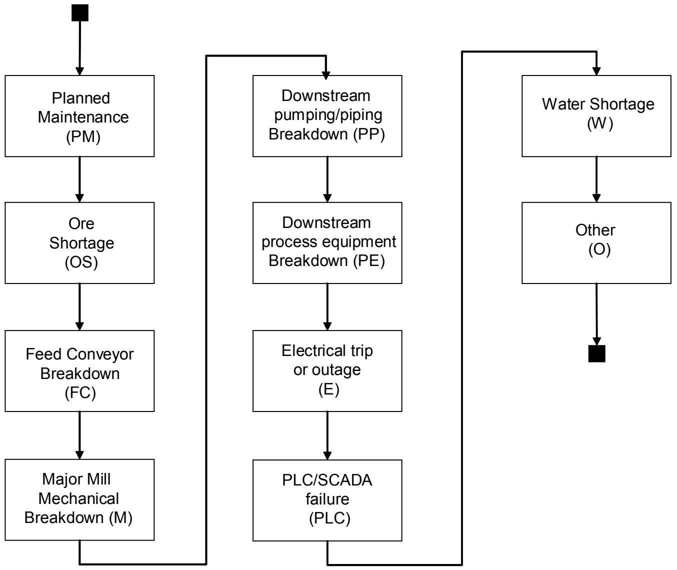


Figure 3.6: RBD of single unit primary milling circuit

The system failure rates and repair rates are defined as follows for the different failure modes as described in Table 3.1 above.

$$\lambda_i = \frac{no.\,of\ failures\ due\ to\ a\ specific\ reason\ in\ a\ given\ time\ period}{total\ period\ of\ time\ spent\ in\ the\ operating\ state} \quad \ldots\ldots(3.20)$$

and

$$\mu_i = \frac{no.\,of\ repairs\ in\ a\ specific\ failure\ mode\ in\ a\ given\ time\ period}{total\ period\ of\ time\ in\ the\ failed\ state} \quad \ldots\ldots(3.21)$$

The state-space diagram associated with the RBD in Figure 3.6 is shown in Figure 3.7 below.

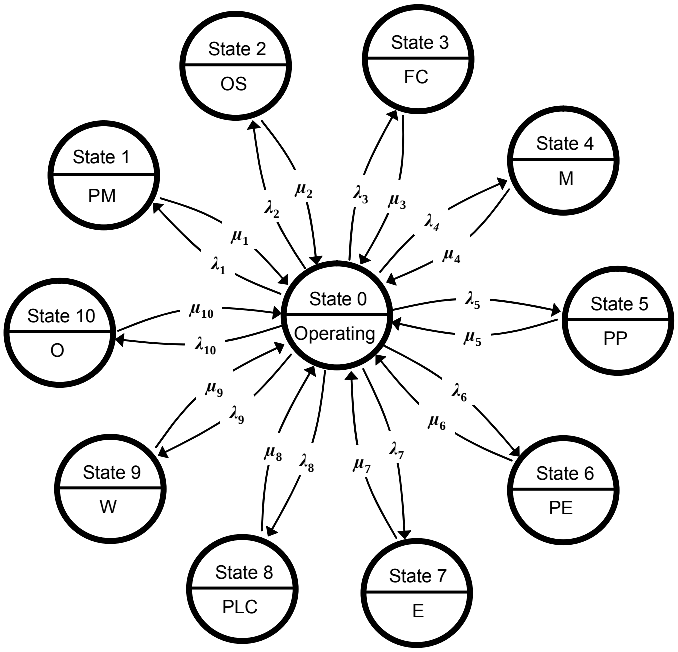


Figure 3.7: State-space diagram of an 11-state primary mill

Define

$P_0(t)$ = probability that the primary mill is operable at time t

$P_i(t)$ = probability that the primary mill is down at time t due to any one of the defined failure modes

λ_i = failure rate due to a specific failure mode

μ_i = repair rate in a specific failure mode

Therefore

$\lambda_i dt$ = Probability of failing due to a specific failure mode in $(t+dt)$ $1 \le i \le 10$

$1-\sum_{i=1}^{10} \lambda_i dt$ = Probability of not failing in $(t+dt)$ $1 \le i \le 10$

$\mu_i dt$ = Probability of being repaired in $(t+dt)$ $1 \le i \le 10$

$1-\mu_i dt$ = Probability of not being repaired in $(t+dt)$ $1 \le i \le 10$

Consider the system shown in figure 3.7 above and allowing for an incremental time interval *dt* that is sufficiently small so that the probability of two or more transitions occurring during this interval is negligible. Then the probability of being in the operating state after this time interval *(t+dt)* is

[Probability of being operative at time t, AND not failing in time dt]
+ *[probability of being in one of the failed states at time t AND of being repaired in time dt]*

This is expressed as

$$P_0(t+dt) = P_0(t)\left(1-\sum_{i=1}^{10}\lambda_i dt\right) + P_1(t)(\mu_1 dt) + P_2(t)(\mu_2 dt)\ldots + P_{10}(t)(\mu_{10} dt) \quad \ldots(3.22)$$

Rearranging and simplifying yields

$$\left.\frac{P_0(t+dt)-P_0(t)}{dt}\right|_{dt\to 0} = P_0'(t) = \sum_{i=1}^{10}\mu_i P_i(t) - P_0(t)\sum_{i=1}^{10}\lambda_i \quad \ldots\ldots(3.23)$$

Similarly the probability of being in any one of the different failed states after this time interval *(t+dt)* is

[Probability of being in any one of the failed states at time t, AND not being repaired in time dt]+ [probability of being operative at time t AND of failing in time dt]

This is expressed as

$$P_i\left(t+dt\right)=P_i\left(t\right)\left(1-\mu_i dt\right)+P_0\left(t\right)\lambda_i dt \quad \ldots\ldots\ldots \qquad \ldots\ldots\ldots\ldots(3.24)$$

Rearranging and simplifying gives

$$\frac{P_i\left(t+dt\right)-P_i\left(t\right)}{dt}\Big|_{dt\to 0}=P_i'\left(t\right)=P_0\left(t\right)\lambda_i-\mu_i P_i\left(t\right) \quad 1\le i\le 10 \ldots.(3.25)$$

Together Eq's 3.2 and 3.5 form a set of linear differential equations with constant coefficients that may be presented in matrix format as

$$\left[P_0'\left(t\right) \quad P_1'\left(t\right) \quad \ldots \quad P_{10}'\left(t\right)\right]=$$

$$\left[P_0\left(t\right) \quad P_1\left(t\right) \quad \ldots \quad P_{10}\left(t\right)\right]\cdot\begin{bmatrix} -\lambda_1-\lambda_2\ldots-\lambda_{10} & \lambda_1 & \ldots & \lambda_{10} \\ \mu_1 & -\mu_1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{10} & 0 & \ldots & -\mu_{10} \end{bmatrix} \ldots..(3.26)$$

Where $\left[P_0\left(t\right) \quad P_1\left(t\right) \quad \ldots \quad P_{10}\left(t\right)\right]$ is the state probability vector.

Computational complexity does not allow the derivation of an explicit expression for the time dependent or transient behaviour of the system. However, the expressions for steady-state behaviour is obtained by solving Eq 3.26 (see Appendix 2 for full derivation) as

$$P_1 = \frac{\lambda_1}{\mu_1} P_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.27a)}$$

$$P_2 = \frac{\lambda_2}{\mu_2} P_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.27b)}$$

$$\vdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \vdots$$

$$P_{10} = \frac{\lambda_{10}}{\mu_{10}} P_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.27j)}$$

According to the law of probabilities

$$P_0 + P_1 + P_2 + P_3 \cdots + P_{10} = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.28)}$$

Substituting Eq 3.27 into Eq 3.28

$$P_0 = \left[\frac{\prod_{i=1}^{10} \mu_i}{\prod_{i=1}^{10} \mu_i + \sum_{\substack{i=1 \\ j \neq i}}^{10} \left(\lambda_i \cdot \prod \mu_j \right)} \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.29)}$$

Values of $P_1, P_2, P_3, \cdots P_{10}$ are then determined by back substation of Eq 3.29 into Eq 3.28 which is the steady state probabilities of the system. From this it follows that

Unit process reliability $R_i = e^{-\lambda_i t}$ ……………………….………..…….(3.30)

Unit process maintainability $M_i = 1 - e^{-\mu_i t}$ …………………………………..(3.31)

Unit process Mean time to failure $MTTF_i = {}^{1}\!/\!_{\lambda_i}$ …………………………..…(3.32)

Unit Process Mean time to repair $MTTR_i = {}^{1}\!/\!_{\mu_i}$ ………………………..…(3.33)

Frequency of encountering a particular failed state $f_i = P_i \mu_i$ ……………..(3.34)

3.2.3. Evaluating a set of primary mills in parallel as a partially redundant system

The combination of the models described in sections 3.2.1 and 3.2.2 above allows the reliability of a single primary mill, regardless of whether it is part of a larger parallel set of mills or a single stream plant, to be fully evaluated. It remains to describe how the overall system reliability of a set of primary mills in parallel can be evaluated.

As explained in section 3.1.2 a typical multi-stream Platinum concentrator will always have a certain degree of partial redundancy i.e. stopping a limited number of primary mills will not result overall system failure. Using this characteristic then permits the parallel configuration to be considered as a 3-state Markov process where State 0 is the fully operational state (all the mills operational, State 1 is the partially redundant state (limited number of mills off-line) and state 2 is the fully failed state i.e. all the mills are down. It is also almost always the case that the mills are identical, or can be grouped into sets of identical mills i.e. it may be assumed that their failure rates and repair rates are identical. Adopting this methodology helps to overcome the computational complexity normally encountered with Markov analysis when evaluating a large number of states.

Appendix 3 describes the detail derivation by informal induction of a set of general expressions for evaluating a 3-state, m-out-of-n parallel configuration of primary mills where n is the total number of mills in parallel and m is the limiting number of mills that must be operational to enable the overall system to sustain design throughput i.e. system success. The general state-space diagram is shown in figure 3.8 below.

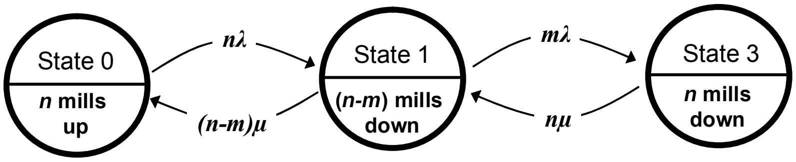


Figure 3.8 State-space diagram for 3-state, m-out-of-n parallel System

Therefore in general

$$\therefore \quad P_0 = \frac{(n-m)\mu^2}{[m\lambda+(n-m)\mu]\cdot[\lambda+\mu]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(3.35)}$$

and

$$\therefore \quad P_1 = \frac{n\lambda\mu}{[m\lambda+(n-m)\mu]\cdot[\lambda+\mu]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(3.36)}$$

and

$$\therefore \quad P_2 = \frac{m\lambda^2}{[m\lambda+(n-m)\mu]\cdot[\lambda+\mu]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(3.37)}$$

Where

λ = failure rate

μ =repair rate

n = total number of mills configured in parallel

m = minimum number of mills that must be operational to prevent all the mills from having to be stopped

P_0 = Probability of all the mills operating

P_1 = Probability of $m\text{-}out\text{-}of\text{-}n$ mills being operational i.e. derated state

P_2 = Probability of all the mills being failed or stopped.

Furthermore in general for the 3-state system, assuming that states 0 and 1 are considered for system success, then the mean time to failure MTTF is

$$= \frac{n\lambda+(n-m)\mu}{nm\lambda^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(3.38)}$$

and hence the effective failure rate is

$$= \frac{nm\lambda^2}{n\lambda + (n-m)\mu} \quad \text{……………………………………………..…….(3.39)}$$

State	Rate of departure	Rate of return
0	$n\lambda$	$(n-m)\mu$
1	$m\lambda + (n-m)\mu$	$n\lambda + n\mu$
2	$n\mu$	$m\lambda$

Table 3.2: Departure and return rates

"*The frequency of encountering a state = the probability of being in the state multiplied by the rate of departure from the state.*"

$$f_0 = P_0 \times n\lambda = \frac{n(n-m)\lambda\mu^2}{[m\lambda + (n-m)\mu][\lambda + \mu]} \quad \text{……………………………...(3.40a)}$$

$$f_1 = P_1 \times [m\lambda + (n-m)\mu] = \frac{n\lambda\mu}{(\lambda + \mu)} \quad \text{………………………………….(3.40b)}$$

$$f_2 = P_2 \times n\mu = \frac{nm\lambda^2\mu}{[m\lambda + (n-m)\mu][\lambda + \mu]} \quad \text{………………………..…….(3.40c)}$$

State 2 is considered the fully failed state and therefore the mean time to repair is

$$MTTR = 1/n\mu \qquad \text{…………………………………………………….…..(3.41)}$$

Mean time between failures is the sum of mean time to fail and mean time to repair

$$MTBF = MTTF + MTTR \qquad \text{…...(3.42)}$$

3.3. Primary Mill Reliability Evaluation Methodology

The crux of the proposed primary mill reliability evaluation methodology rests on firstly analysing the reliability of the individual mills using the two Markov models described in sections 3.2.1 and 3.2.2 reliability block diagrams and then finally, in the case of multiple milling streams, applying the Markov model described in section 3.2.3 for evaluating the overall system performance of a set of primary mills in parallel. The different reliability block diagrams are summarised in figure 3.9 below. I

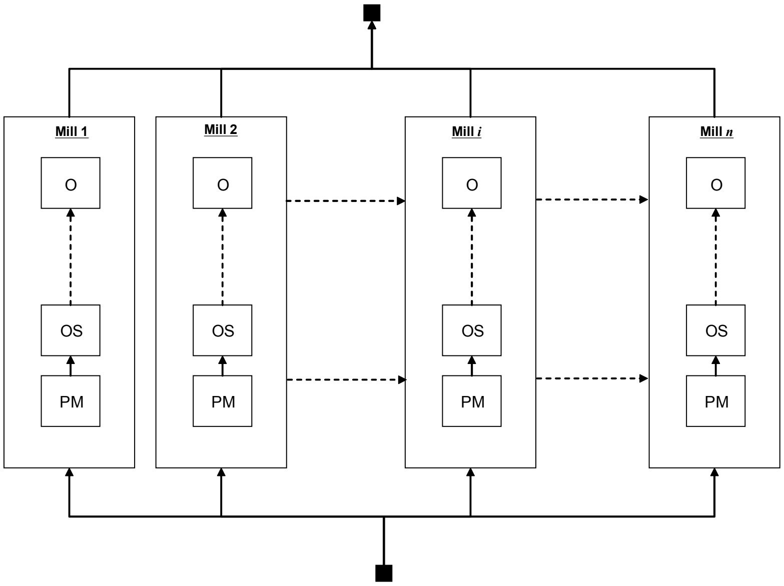


Figure 3.9 Combined Reliability Block Diagram

It is important to note that each individual mill is considered firstly as a single component 2-state systems, and secondly as a multi-component system in series. If a large single stream milling circuit is being evaluated, then only the first two Markov models are applicable. If the concentrator contains more than one primary milling circuit, then the third Markov model also becomes relevant.

The overall process is summarised in as a flowchart shown in figure 3.10 below. The first step is obviously to gather the basic failure data. Important information that must be recorded for each individual primary mill is:

i. Exact date and time when the mill was stopped.

ii. The primary reason why the mill was stopped. The categories described in table 3.1 have been formulated specifically for the purposes of this study, but is by no means comprehensive and can be adopted to suite any individual concentrator.

iii. The exact date and time when the mill was restarted.

Appendix 4 contains the Visual Basic code for setting up a spreadsheet in Microsoft Excel® for recording and sorting primary downtime data.

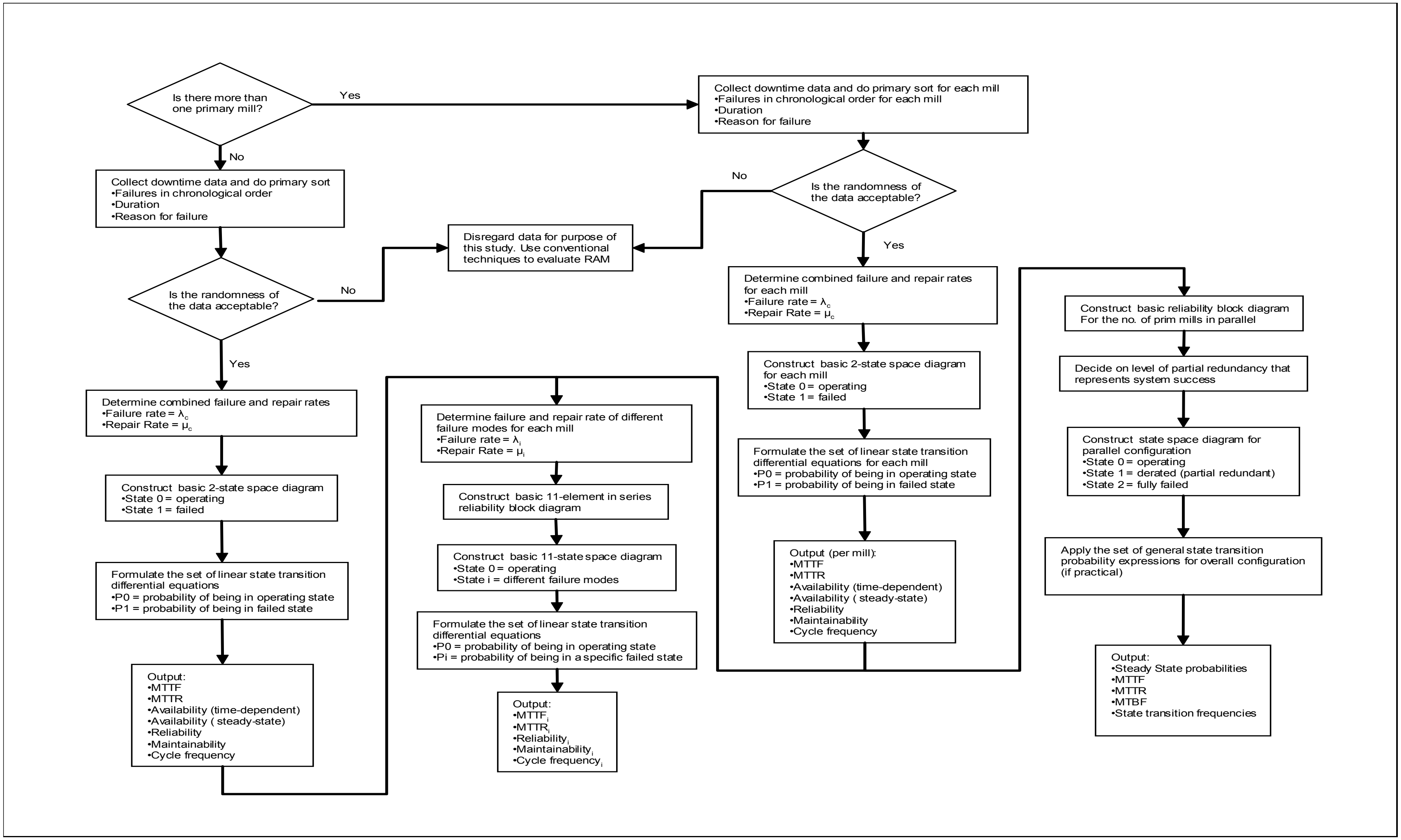


Figure 3.10 **Primary Mill Reliability, Availability, and Maintainability (RAM) evaluation flowchart**

4. MODEL VALIDATION

The main aim of this chapter is to evaluate and demonstrate the methodology developed in the preceding chapters. This will be achieved by performing case studies of two Platinum concentrators using empirically derived data.

The chapter is divided into three main sections. The first section covers a case study of a Platinum concentrator with a large single stream primary mill. Being a single stream primary mill, this case study will be subjected to the first two Markov analyses namely 2-state and 11-state systems.

The next section covers the evaluation of a conventional multiple stream Platinum concentrator. Here the data set is subjected all three Markov analysis models i.e. including the 3-state, m-out-of-n system evaluation.

The final section of this chapter provides a comparison of the key reliability parameters of the two plants.

The two data sets were obtained The different plants have been designated Plant A and Plant B for the purposes of this study in order to protect the confidentially requirements of relevant mining companies.

4.1. Case Study 1: Plant A; Large Single Stream Primary Mill

4.1.1. General Information

The general information of Plant A primary mill is summarised in table 4.1 below.

Designated Name	Plant A
Region/Location	South Africa
Primary mineral being recovered	Platinum
Size Category	Large
Configuration Category	Single Stream MF2
Nominal plant throughput capacity	400,000 tons per month
Mill Details:	
Diameter (inside shell)	7.32m
Mill Length (EGL)	8.54m
Type of Milling mode	ROM Ball Mill
Type of drive	Gear & pinion
Installed Power	2x 5.2MW

Table 4.1 General information of Plant A primary mill

The basic configuration of Plant is shown in Figure 4.1 below. Plant A is a modern Platinum concentrator based on a large, single stream MF2 configuration. The single primary mill is fed by a conveyor from a storage silo.

The primary mill product is then pumped to the primary flotation section. The primary flotation tailings then passes onto the single secondary regrind mill. The secondary mill product is then sent to the secondary flotation stage.

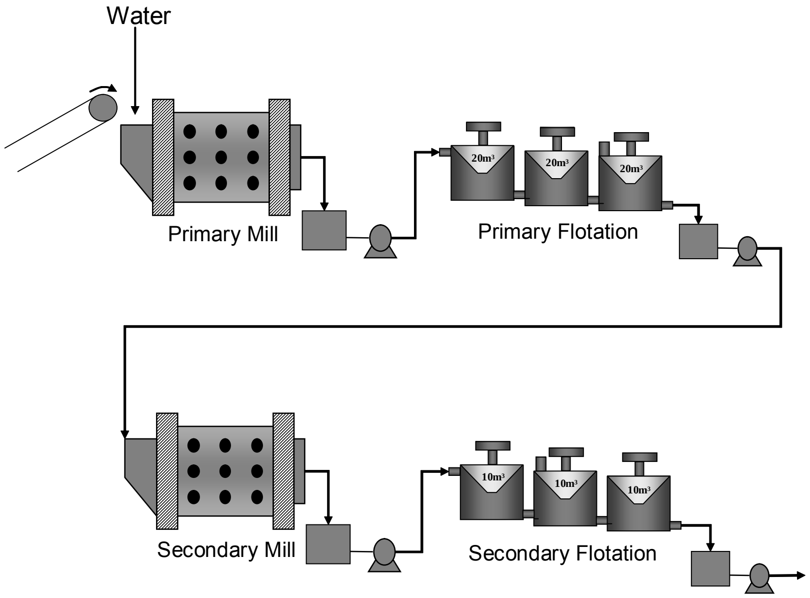


Figure 4.1 Basic configuration of Plant A

All the different main stream pump and pipeline sets have been provided with standby redundancy. Each mill has its own dedicated oil lubrication system consisting of reservoir, high pressure oil pumps and cooling systems. The overall plant is highly automated.

4.1.2. Original Data Set

The detailed schedule of failures for Plant A is shown in appendix 6. and is summarised in table 4.2 below

From	1 April 2002	
To	30 June 2004	
No. of Failures	1035	
Total repair time	3321.97	hrs
Repair rate	0.31	per hr
MTTR	3.21	hrs
Total operating time	16,389.97	hrs
Failure rate	0.06	per hr
MTTF	15.85	hrs
Laplace statistic	-4.25	
H_0: zero trend	Rejected on 95% level of confidence	

Table 3.2: Summary of original data set.

From the summary of the original data set shown in table 4.2 above the Laplace statistic is -4.25 and hence the null hypothesis of zero trend is rejected on the 95% confidence limit. The negative sign of the Laplace statistic indicates that ROCOF is decreasing over the time period under consideration. This is confirmed by a visual inspection of the plot of overall cumulative failures against overall cumulative operating time are shown in figure 4.2 below.

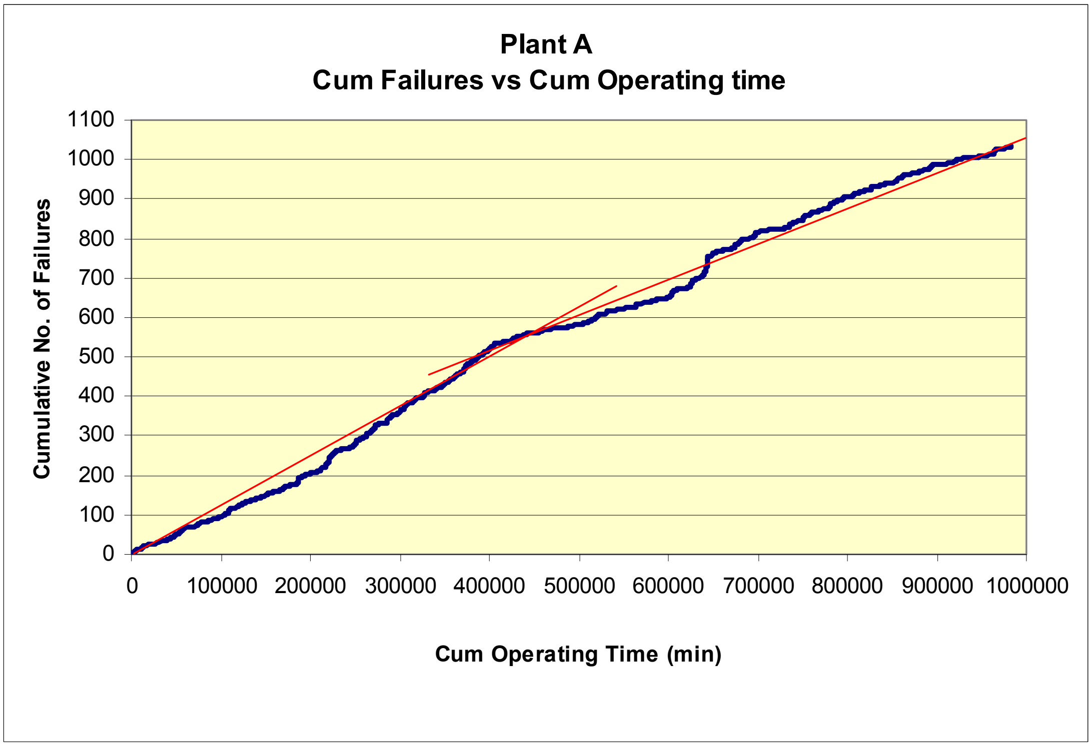


Figure 4.2: **Cumulative failures vs. cumulative operating time.**

The plot clearly indicates an inflection point at about the 500 failure mark which corresponds to a cumulative operating time of approximately 400,000 minutes.

Plant A is relatively new and was only commissioned end of February 2002. Although much longer than usual, the period up to approximately March 2003 may therefore be considered part of the burn-in period and must be rejected for the purposes of the reliability evaluation as part of this study.

The summary of the censored data set is shown in table 4.3 below.

From	5 March 2003	
To	30 June 2004	
No. of Failures	514	
Total repair time	1,869.5	hrs
Repair rate	0.27	per hr
MTTR	3.64	hrs
Total operating time	9,723.9	hrs
Failure rate	0.0528	per hr
MTTF	18.95	hrs
Laplace statistic	-0.43	
H_0: zero trend	Accepted on 95% level of confidence	

Table 4.3: Summary of censored data set.

The Laplace test static for the censored data set is –0.43 which allows the Null hypothesis of zero trend to be accepted at the 95% confidence limit. This revised data set is therefore considered suitable for further reliability evaluation.

4.1.3. 2-State; Single component Markov Analysis

The reliability block diagram and the associated state space diagram for the 2-state, single component Markov analysis of the primary mill of Plant A is shown in figure 4.2 below.

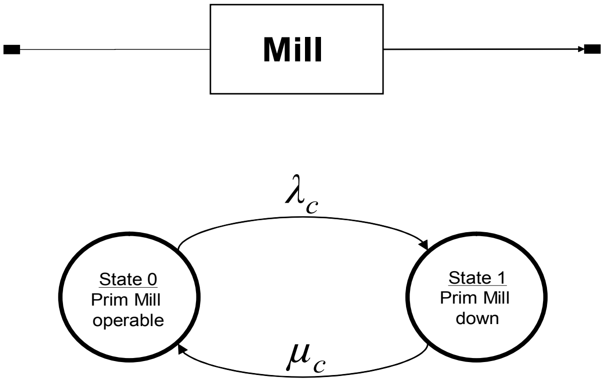


Figure 4.3: **RBD and State-space diagram for Plant A**

The estimated failure rate and repair rate for the primary mill is indicated in table 4.3 above and the transient behaviour of the 2-state system is shown graphically in figure 4.3 below.

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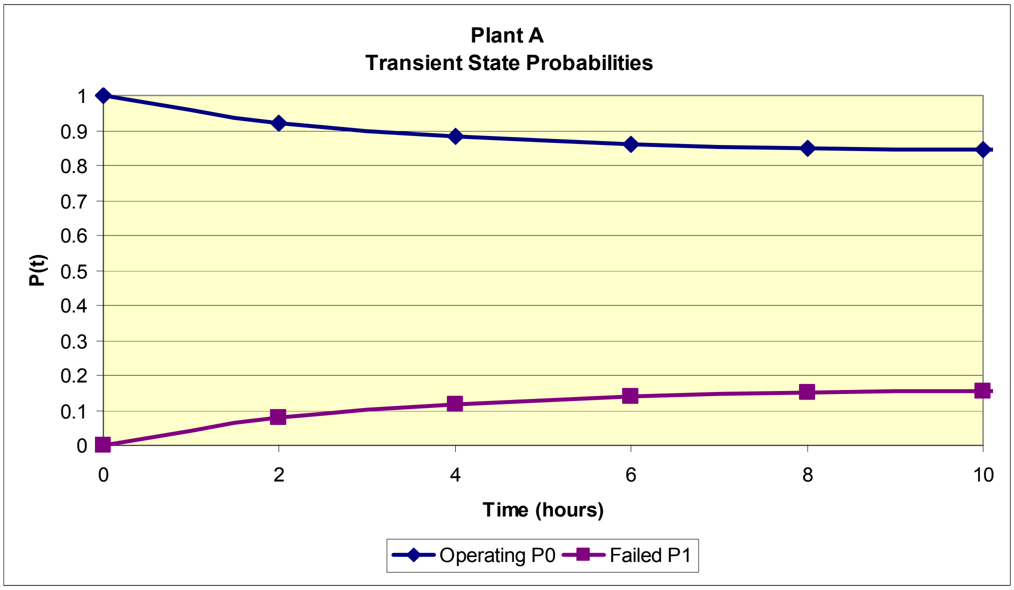

Figure 4.4: Transient behaviour of Plant A primary mill

The steady-state condition is reached after approximately 24hrs with steady state plant availability being equal to 0.839.

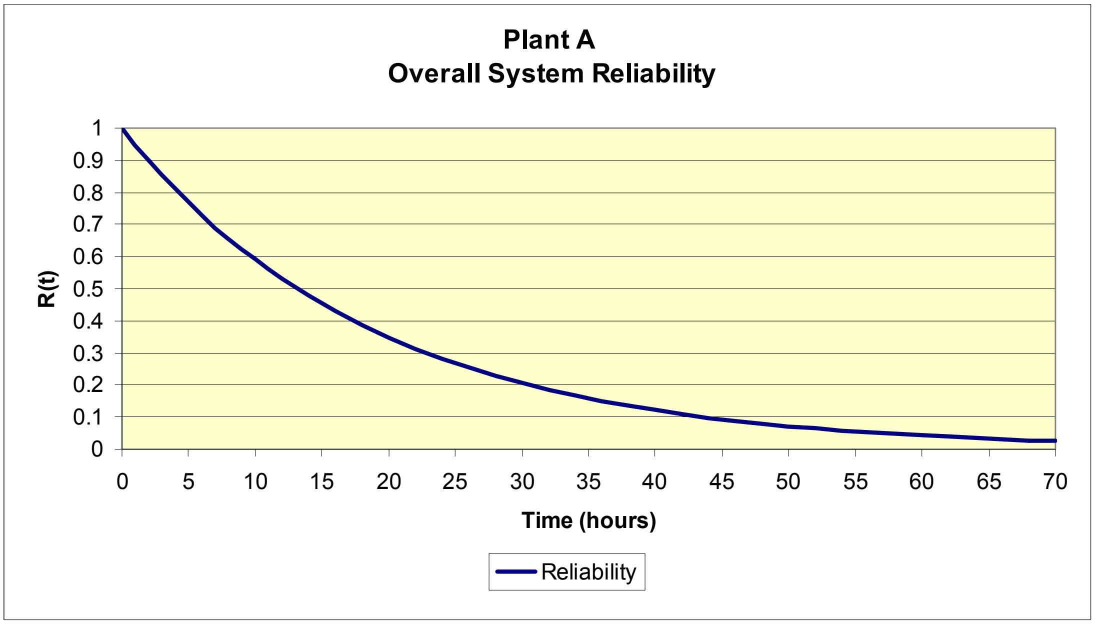

Figure 4.5: Overall system reliability of Plant A

Figure 4.4 shows the overall reliability profile of Plant A. According to the definition of reliability this graph shows the probability of remaining operational as a function of lapsed time. This Platinum concentrator has routine planned maintenance stoppages on a weekly basis. In reliability engineering terms this would be equivalent to a mission time of 168 hours. As can be seen from figure 4.4 the reliability function for Plant A approaches the asymptotic value after only approximately 70 hours. This is significantly low and indicates that Plant A has a very low probability of operating without unplanned stoppages between the weekly planned inspection stops.

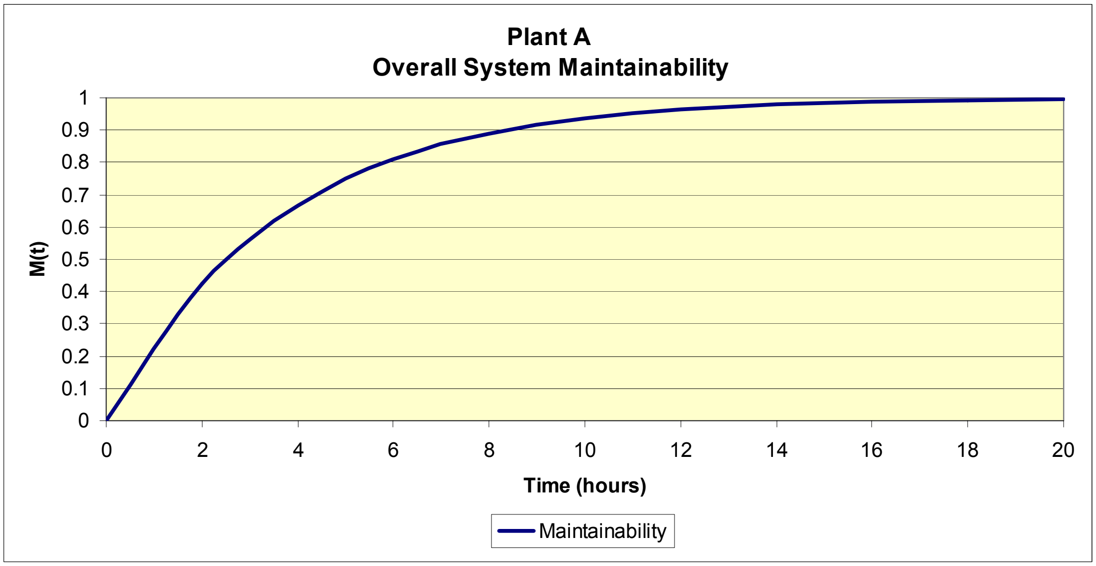

Figure 4.6: System Maintainability of Plant A

Figure 4.4 shows the maintainability profile of Plant A. According to the definition of maintainability this graph shows the probability of the primary mill being restored to an operational state as a function of elapsed time since the failure first occurred. As can be seen from figure 4.5 the maintainability function for Plant A approaches the asymptotic value after approximately 15 hours.

4.1.4. 11-State, Single Component Markov Analysis

The reliability block diagram and the associated 11-state space diagram for the primary mill of Plant A is shown figures 4.6 and 4.7 respectively.

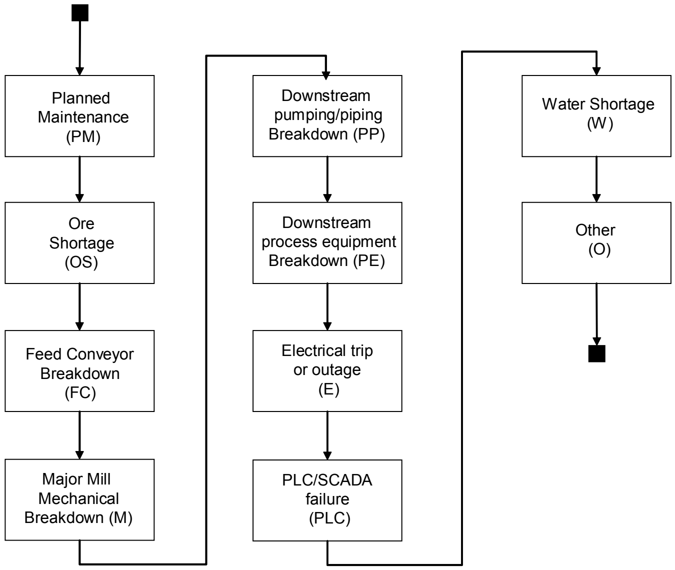

Figure 4.7: RBD of Plant A primary mill

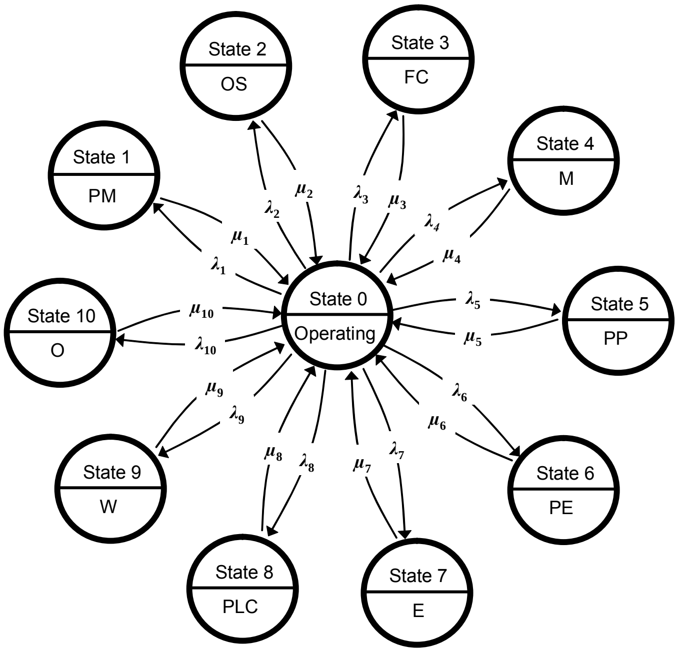

Figure 4.8: 11- State Space diagram of Plant A primary mill.

The pertinent results of the 11-state Markov analysis for the primary mill of Plant A is summarised in table 4.4 below.

State	Λ /hr	MTTF hrs	µ /hr	MTTR hrs	Prob	Rel. Freq.
PM	0.00289	345.867	0.03637	27.495	0.0680	197.8
OS	0.00112	893.279	0.07166	13.954	0.0134	15.0
FC	0.00420	237.92	6.63594	0.151	0.0005	2.3
M	0.00125	801.818	0.12722	7.860	0.0084	10.5
L	0.00213	469.249	0.58884	1.698	0.0031	6.6
PP	0.00571	175.245	0.23287	4.294	0.0209	120.3
PE	0.00944	105.907	0.41104	2.433	0.0196	186.6
E	0.00309	323.311	0.79532	1.257	0.0033	10.4
PLC	0.00199	503.356	0.55527	1.801	0.0031	6.1
W	0.00057	1755.925	0.27907	3.583	0.0017	1.0
O	0.00213	469.249	0.58884	1.698	0.0031	6.6
Steady State					0.8549	

Table 4.4: **Summary of 11-state Markov analysis for Plant A primary mill**

The results indicate that the steady state probability of being operational is 0.8549, or 85.49% of total time based on the 11-state Markov analysis. The three failure modes with the highest probabilities of occurrence are; planned maintenance at 6.80%, followed by downstream pumping and pipeline failures at 2.09%, and downstream process equipment failures at 1.96%. The results shown in the relative frequency column are obtained by selecting the failure mode with the lowest frequency of occurrence and then expressing the frequencies of the remaining failure modes relative to it. In this case stoppages due to water shortage are the least frequent failures while stoppages due to downstream process equipment failures are the most frequent failures.

The reliability and maintainability profiles of the individual failure modes are shown graphically in figures 4.8 and 4.9 respectively.

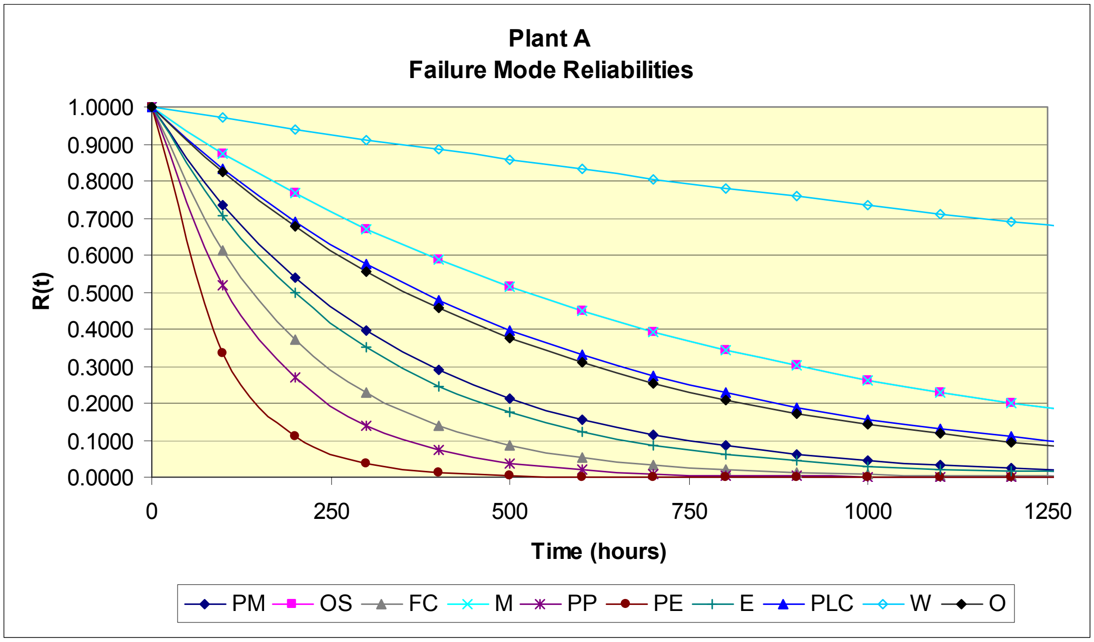

Figure 4.9: Failure mode reliabilities of Plant A primary mill

Figure 4.8 shows the reliability profiles of the different failure modes of Plant A. According to the definition of reliability this graph shows the probability of a specific unit process remaining operational as a function of elapsed time. From the graph it is clear that the downstream process equipment is the most likely to cause the system to fail while water shortages is the least likely to happen.

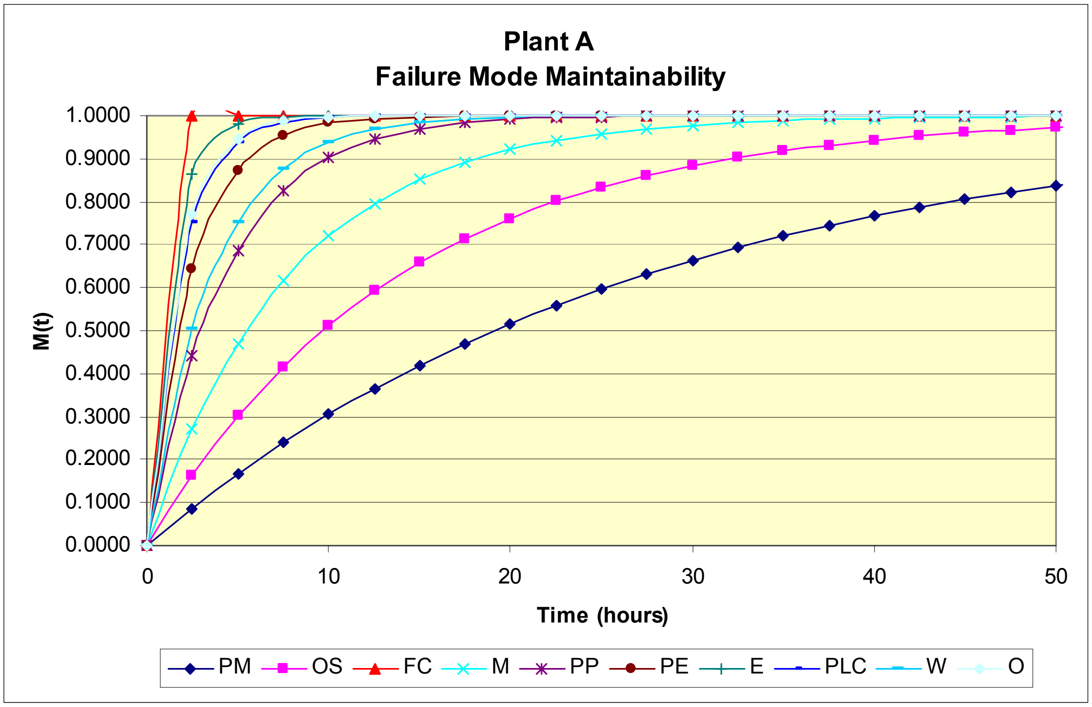

Figure 4.10: **Failure mode maintainabilities for Plant A primary mill.**

Figure 4.9 shows the maintainability profiles of the different failure modes of Plant A. According to the definition of maintainability this graph shows the probability of the specific unit process, or failure mode being restored to an operational state as a function of elapsed time since the start of the failure. As can be seen from figure 4.9 the feed conveyor breakdowns will be repaired the quickest while planned maintenance will take the longest to restore.

4.2. Case Study 2: Plant B; Multiple Stream Primary Mills

4.2.1. General Information

The general information of the primary mill of Plant B is summarised in table 4.5 below.

Designated Name	Plant B
Region/Location	South Africa
Primary mineral being recovered	Platinum
Size Category	Conventional
Configuration Category	Multiple Stream MF1 2x Sections of 7 mills/section
Nominal plant throughput capacity	700,000 tons per month
Mill Details:	
Diameter (inside shell)	4.27m
Mill Length (EGL)	5.03m
Type of Milling mode	SAG Mill
Type of drive	Gear & pinion
Installed Power	1340kW/mill

Table 4.5: General information of Plant B primary mill

The basic configuration of Plant B is shown in Figure 4.10 below. Plant B is an old conventional Platinum concentrator based on a large, multiple stream

MF1 configuration. It has a total of fourteen primary mills that are divided into two sections of seven mills each. Each primary mill is fed by a conveyor from a dedicated set of storage silos. The primary mill product from all seven mills is then combined and pumped to the primary flotation section that consists of a single bank of large flotation cells. The primary flotation tailings then gets pumped to the tailings dams for final deposal.

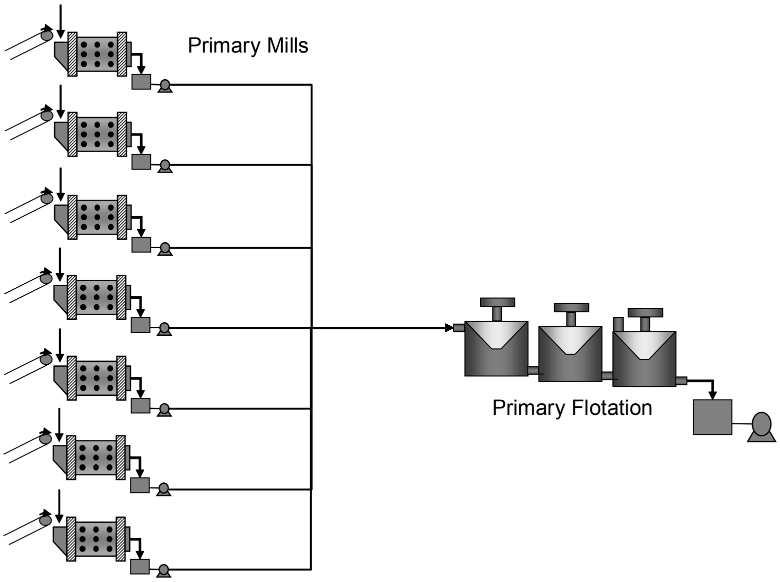

Figure 4.11: Basic configuration each section of Plant B

All the different main stream pump and pipeline sets have been provided with standby redundancy. Each mill has its own dedicated oil lubrication system consisting of reservoir, high pressure oil pumps and cooling systems. The overall plant has a limited amount of automation.

4.2.2. Original Data Set

The detailed schedule of failures for mills 1-14 of Plant B is shown in appendix 7 and is summarised in table 4.6a and 4.6b below. From the summary of the original data set the value Laplace statistic for the individual mills never exceeds ±1.96 and hence the null hypothesis of zero trend is accepted on the 95% confidence limit for all mills. This is to be expected as Plant B is relatively mature and failure and repair rates should therefore be stable. The entire data set for all the mills is therefore considered suitable for further reliability evaluation.

4.2.3. 2-State; Single component Markov Analysis

The reliability block diagram and the associated state space diagram for the 2-state, single component Markov analysis of each of the primary mills of Plant B is shown in figure 4.12 below.

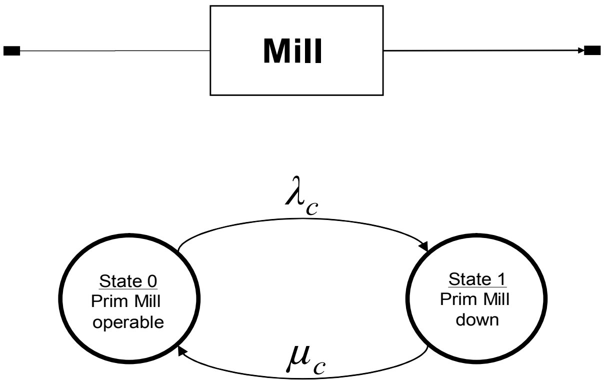

Figure 4.12: RBD and State-space diagram for each primary mills of Plant B

	Mill 1	Mill 2	Mill 3	Mill 4	Mill 5	Mill 6	Mill 7	
From	29 June 2003	29 June 2003	29 June 2003	29 June 2003	29 June 2003	29 June 2003	29 June 2003	
To	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	
Total No. of Failures	52	42	34	58	66	52	63	
Total repair time	340.52	332.12	341.25	337.87	362.18	490.62	221.72	hrs
Repair rate	0.15	0.13	0.10	0.17	0.18	0.11	0.28	per hr
MTTR	6.55	7.91	10.04	5.83	5.49	9.43	3.52	hrs
Total operating time	2029.3	2030.7	2021.6	2026.2	2000.7	1909.4	2142.9	hrs
Failure rate	0.03	0.02	0.02	0.03	0.03	0.03	0.03	per hr
MTTF	39.79	49.53	61.26	35.55	30.78	37.44	34.56	hrs
Laplace statistic	-0.02	-0.06	-0.01	-0.31	-0.32	0.04	-0.47	
H_0: zero trend	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	

Table 4.6: Summary of original data set for Mills 1-7.

	Mill 8	Mill 9	Mill 10	Mill 11	Mill 12	Mill 13	Mill 14	
From	29 June 2003	29 June 2003	29 June 2003	29 June 2003	29 June 2003	29 June 2003	29 June 2003	
To	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	30 Sept 2003	
Total No. of Failures	37	71	49	92	45	48	26	
Total repair time	117.7	132.37	478.33	137.75	79.30	102.98	66.42	hrs
Repair rate	0.31	0.54	0.10	0.67	0.57	0.47	0.39	per hr
MTTR	3.18	1.86	9.76	1.50	1.76	2.15	2.55	hrs
Total operating time	2251.1	2260.95	1878.15	2221.7	2277.3	2187.3	2147.3	hrs
Failure rate	0.02	0.03	0.03	0.04	0.02	0.02	0.01	per hr
MTTF	62.53	32.3	39.13	24.41	51.76	46.54	85.89	hrs
Laplace statistic	0.07	-0.75	-0.18	-1.04	0.02	-0.07	-0.17	
H_0: zero trend	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	Accepted on 95% level of confidence	

Table 4.7: Summary of original data set for Mills 8-14.

The failure rates and repair rates for the individual mills have already been indicated in table 4.6 above. The average transient behaviour of the 2-state system for all fourteen mills is shown graphically in figure 4.12 below.

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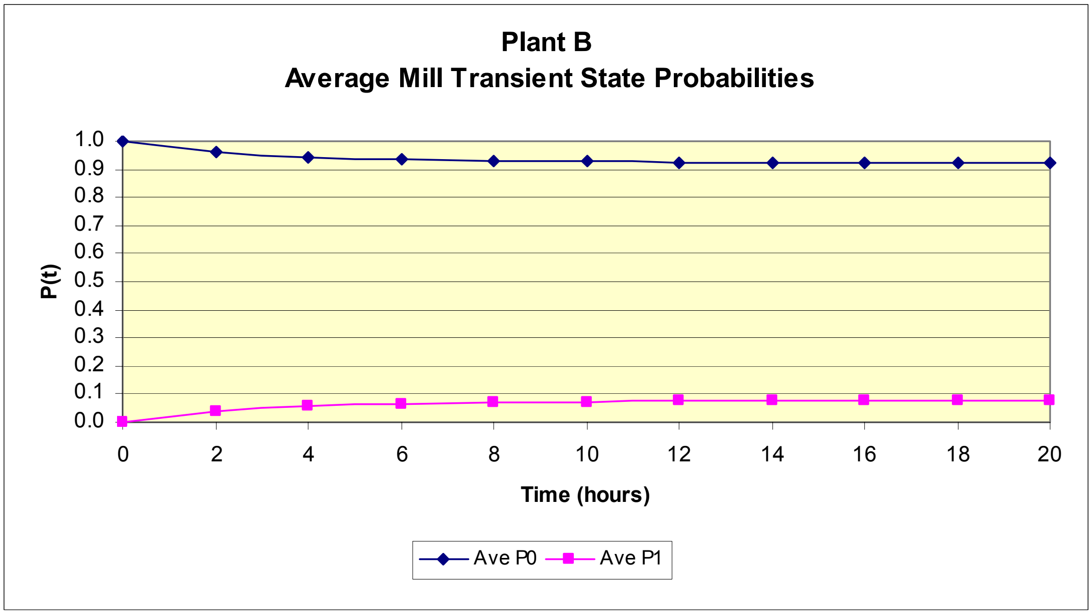

Figure 4.13: Average transient behaviour of Plant B primary mills

The average steady-state condition is reached after approximately 12hrs with average steady state plant availability being equal to 0.924 based on the average failure and repair rates i.e. 2-state Markov analysis.

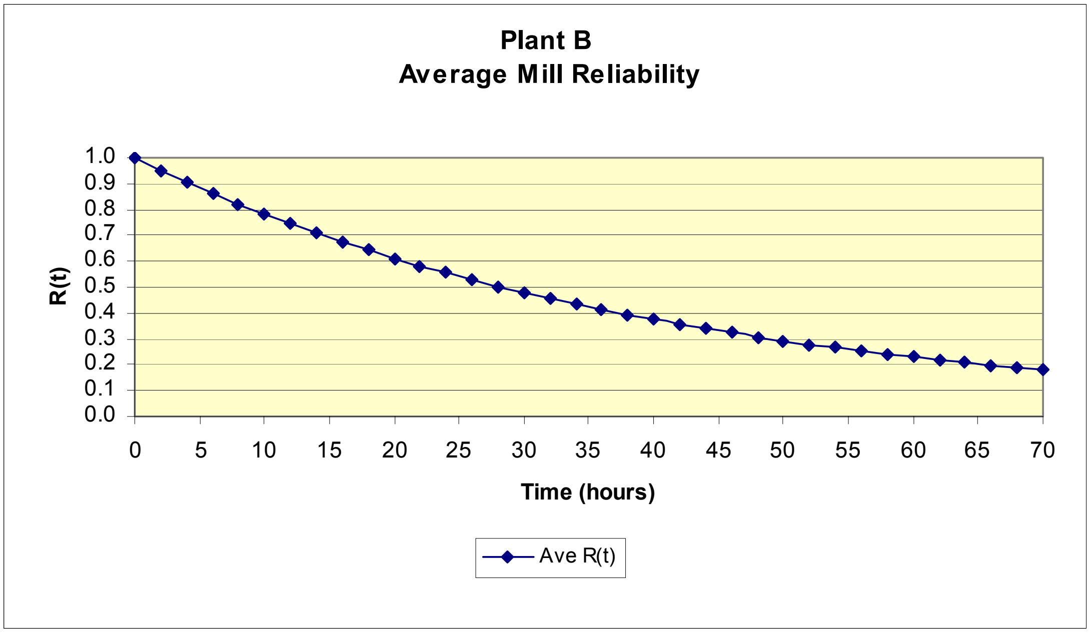

Figure 4.14 Average primary mill reliability of Plant B

Figure 4.14 shows the average reliability profile of Plant B primary mills without distinguishing between the different causes of failures. According to the definition of reliability this graph shows the average probability of a primary mill remaining operational as a function of time. The management at Plant B indicated that they follow a highly disciplined routine of planned inspections and repairs. Each mill is scheduled to be stopped once a month for planned maintenance. In reliability engineering terms this would be equivalent to a mission time of approximately 720 hours. As can be seen from figure 4.14 the average reliability function for the primary mills of Plant B approaches the asymptotic value after only approximately 185 hours. This is significantly low and indicates that the mills of Plant B have a very low probability of operating without unplanned stoppages between the monthly planned inspection stops.

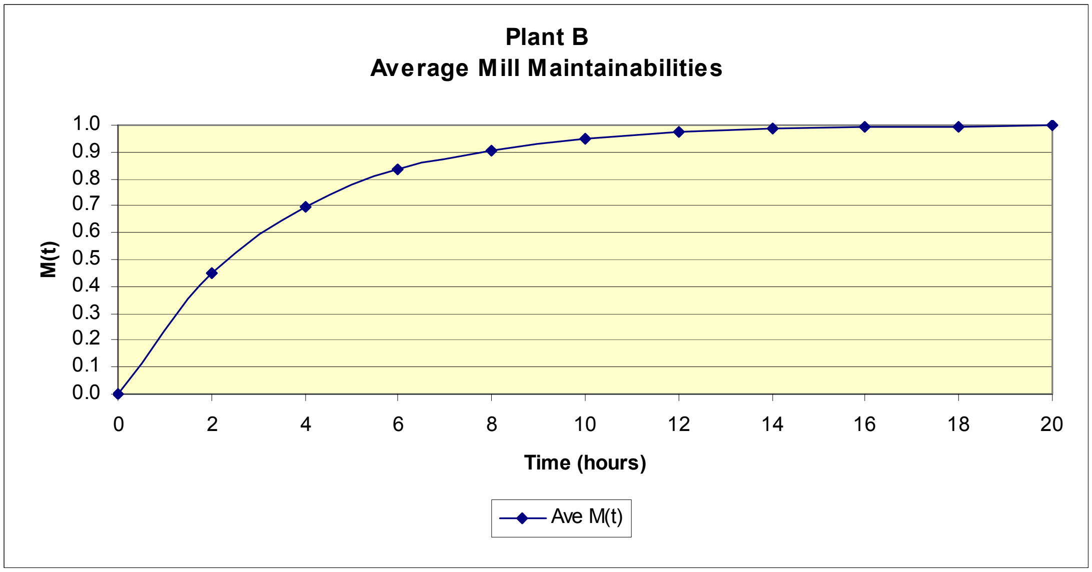

Figure 4.15: System Maintainability of Plant A

Figure 4.15 shows the average maintainability profile of the primary mills of Plant B without distinguishing between different types of failures. According to the definition of maintainability this graph shows the probability of a primary mill being restored to an operational state as a function of elapsed time since the failure first occurred. As can be seen from figure 4.15 the maintainability function for Plant B primary mills approaches the asymptotic value after approximately 12-15 hours.

4.2.4. 11-State, Single Component Markov Analysis

The reliability block diagram and the associated 11-state space diagram for each of the primary mills of Plant B is shown figures 4.16 and 4.17 respectively.

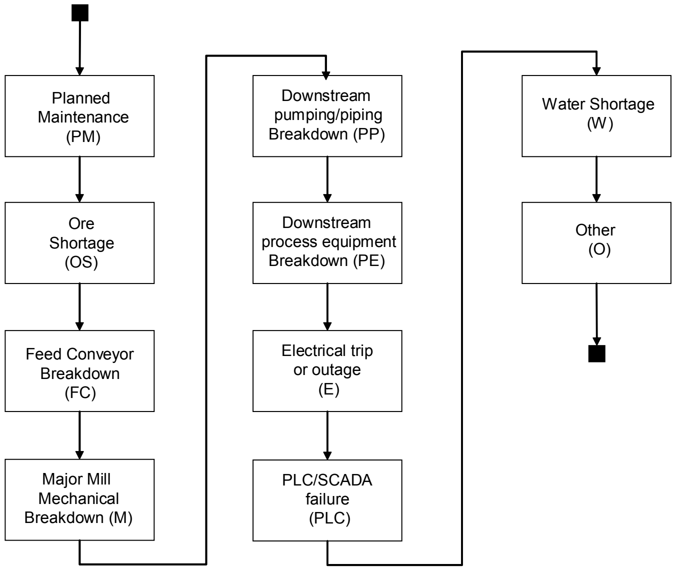

Figure 4.16: RBD of Plant B primary mills

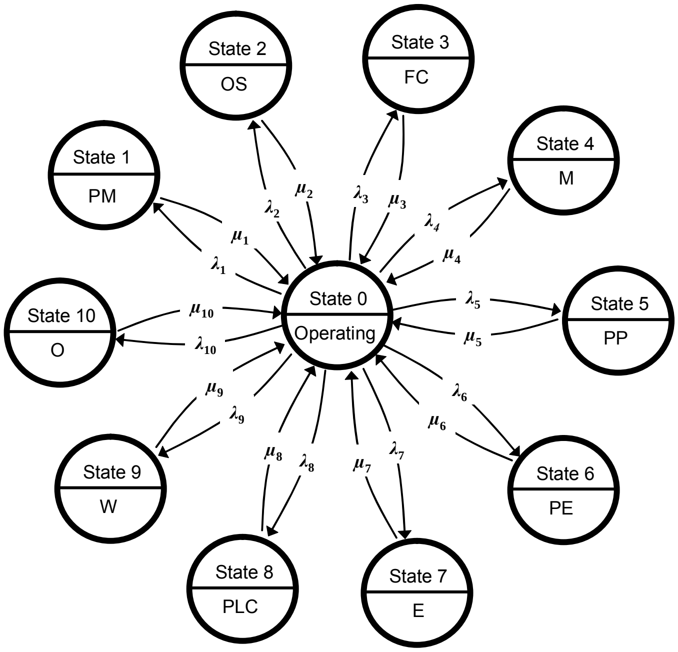

Figure 4.17: 11- State Space diagram of Plant B primary mills.

The averages results of the 11-state Markov analysis for all fourteen of the primary mills of Plant B is summarised in table 4.8 below. The results of the 11-state Markov analysis for the individual mills is included in Appendix 7.

These results indicate that the steady state probability of being operational is 0.9292, or 92.92% of total time. The three failure modes with the highest probabilities of occurrence are; ore shortages at 3.94%, planned maintenance stoppages at 1.50%, and feed conveyor breakdowns at 0.67%. The results shown in the relative frequency column are obtained by selecting the failure mode with the lowest frequency of occurrence and then expressing the frequencies of the remaining failure modes relative to it. In this case stoppage due to other undefined causes is the failure mode that occurs the least frequently. Stoppages due to ore shortages are the most frequent failure modes.

These results indicate that the steady state probability of being operational is 0.928, or 92.82% of total time based on the average 11-state Markov analysis. The three failure modes with the highest probabilities of occurrence are; ore shortages at 3.94%, planned maintenance stoppages at 1.50%, and feed conveyor breakdowns at 0.67%. The results shown in the relative frequency column are obtained by selecting the failure mode with the lowest frequency of occurrence and then expressing the frequencies of the remaining failure modes relative to it. In this case stoppage due to other undefined causes is the failure mode that occurs the least frequently. Stoppages due to ore shortages are the most frequent.

State	Λ /hr	MTTF hrs	µ /hr	MTTR hrs	Prob	Rel. Freq.
PM	0.00161	621.1	0.10000	9.996	0.015	351.4
OS	0.00390	256.4	0.09182	10.891	0.0394	2233.3
FC	0.00355	281.7	0.49326	2.027	0.0067	344.9
M	0.00363	275.4	1.37731	0.726	0.0024	129.3
L	0.00790	126.6	6.61614	0.1511	0.0011	192.2
PP	0.00732	136.6	3.76400	0.266	.0018	192.2
PE	0.00129	774.3	1.00462	0.995	0.0012	22.4
E	0.00183	547.5	0.86819	1.151	0.0020	51.9
PLC	0.00269	372.2	1.15215	0.868	0.0022	84.6
W	-	-	-	-	-	-
O	0.00051	1975.8	3.460	0.289	0.0001	1.0
Steady State	-	-	-	-	0.9282	

Table 4.8: **Summary of average 11-state Markov analysis for Plant B primary mills**

The average reliability and maintainability profiles of the individual failure modes are shown graphically in figures 4.18 and 4.19 respectively.

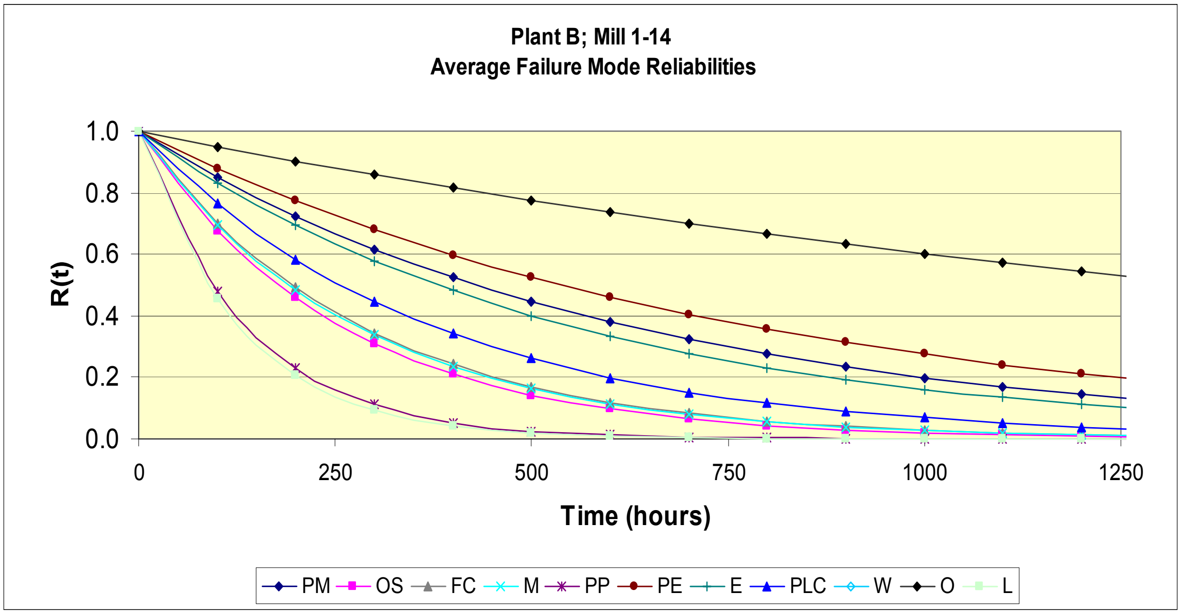

Figure 4.18: Average Failure mode reliabilities of Plant B primary mills

Figure 4.18 shows the average reliability profiles of the different failure modes of Plant B primary mills. According to the definition of reliability this graph shows the probability of a specific unit process remaining operational as a function of time. From the graph it is clear that lubrication failures and downstream pumping and piping breakdowns are the most likely to cause the individual mill to fail while water shortages is the least likely to happen.

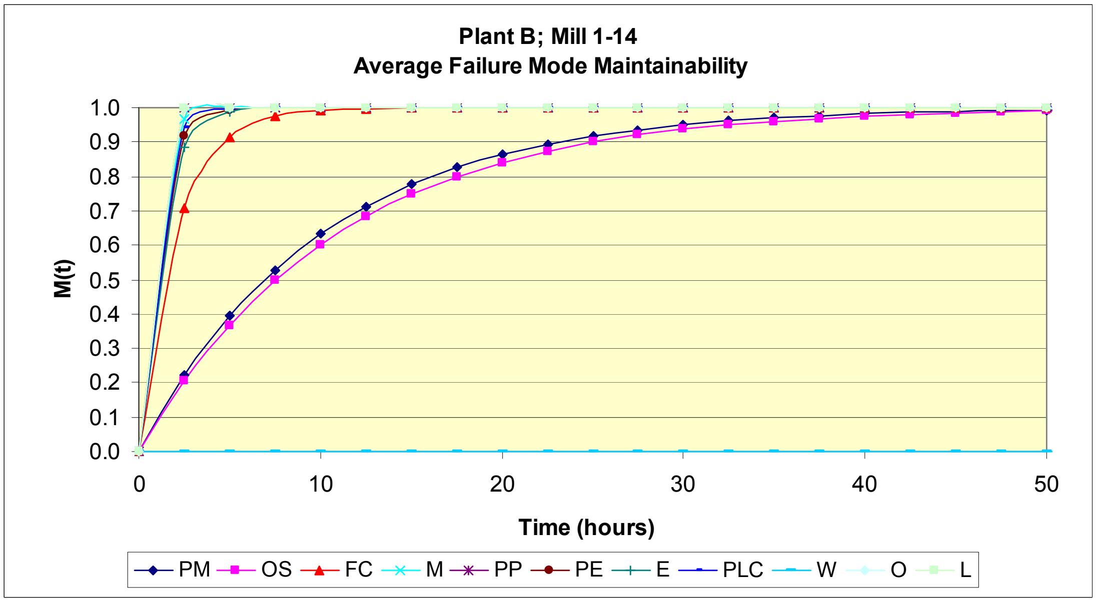

Figure 4.19: Average failure mode maintainabilities for Plant B primary mills.

Figure 4.19 shows the average maintainability profiles of the different failure modes of Plant B primary mills. According to the definition of maintainability this graph shows the probability of the specific unit process, or failure mode being restored to an operational state after a certain period of time has elapsed since the failure first occurred. As can be seen from figure 4.19 the majority of the failure modes will be restored to the operational state in a relatively short period of time while stops due to planned maintenance and ore shortages will take the longest.

4.2.5. 3-State; m-out-of-n Markov Analysis

As mentioned in section 4.2.1 above Plant B has a total of fourteen primary mills that are divided into two sections of seven mills each. Plant management have indicated that a minimum of four mills per section must be online in order for the section to continue operating. In reliability engineering terms this is defined as a 4-out-of-7 system. The 3-state space diagram for each section of Plant B is shown in figure 4.20 below.

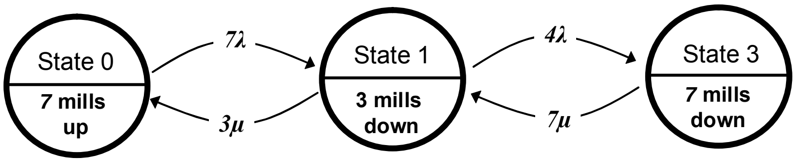

Figure 4.20: 3-State space diagram for a section of Plant B

The reliability analysis of the 4-out-of-7 system is based on the average failure and repair rates of all fourteen primary mills. The determination of the effective failure and repair rates for the 4-out-of-7 system is summarised in Table 4.9 below.

Total number of mills per section (n)	7	
Minimum no. of mills required for system to operate (m)	4	
Average failure rate of individual mills	0.0246	Per hour
Average MTTF of individual mills	40.65	hrs
Effective system failure rate	0.0159	Per hour
System MTTF	63.0763	hours
Average repair rate of individual mills	0.2978	Per hour
Average MTTR of individual mills	3.36	hours
Effective system repair rate	2.0845	Per hour
System MTTR	0.4797	hours
System MTBF	63.5560	hours

Table 4.9: Summary of 4-out-of-7 system reliability

The results shown in table 4.9 indicate that the average failure rate of the individual mills of 0.0246/hr, or MTTF of 40.65 hours, translates to an effective failure rate of only 0.0145/hr, or MTTF of 63.08 hours, for the 4-out-of-7 system configuration. This implies that the failure rate, or MTTF, of this partially redundant system is significantly better than the average failure rate of the individual mills that make up the system.

Similarly the average repair rate of the individual mills of 0.2978/hr translates to an effective repair rate of 2.0845/hr for the system. Stated differently, this means that the average time taken to repair an individual mill is 3.36 hours, while the overall system will only require an average of 0.4797 hours to repair.

The results of the 3-state Markov process as shown in figure 4.20 above is summarised in table 4.10 below.

State	Probability	Departure rate /hr	Return rate /hr	Frequency /hr	Cycle time hrs	Mean duration hrs
0	0.8323	0.1719	0.8933	0.1431	6.9890	5.8168
1	0.1602	0.9916	2.2564	0.1588	6.2966	1.0085
2	0.0075	2.0845	0.0982	0.0157	63.5560	0.4797

Table 4.10: Summary of 3-state Markov analysis

The probability of all seven mills being online is 83.23% and the probability of the derated state when only four mills are online is 16.02%. In this case states 0 and 1 are considered system up states and therefore the probability of the system being in the up state is $P_0 + P = 0.8323 + 0.1602 = 0.9925$ or 99.25%.

The cycle time of a specific state is defined as the mean time from entering the state to the next time that the same state is entered again while the mean duration time is the mean time of residing in a state once it has been entered. The fully failed state will thus be entered on average every 63.556 hours, which is the same as the MTBF, and it will remain in the fully failed state for an average duration of only 0.4797 hours. Similarly state 0, with all seven mills will be entered on average every 6.989 hours and will reside in this state for an average duration of 5.8168 before making a transition to the derated state.

4.3. Comparison of Plant A and Plant B

4.3.1. Primary Mill Reliability and Maintainability

	Plant A	Plant B	
Repair rate	0.2749	0.2978	per hr
MTTR	3.64	3.36	hrs
Failure rate	0.0528	0.0246	per hr
MTTF	18.95	40.72	hrs

Table 4.11: Failure and repair rates of Plant A & B primary mills

The average failure and repair rates, and the associated MTTF and MTTR, for Plant A and Plant B primary mills are shown in table 4.11 above. It is important to note that, with it being a single stream circuit, the parameters for Plant A are the same for both the primary mill and the overall plant while those for Plant B relate to the individual primary mills only and not the overall circuit.

It is interesting to note that the mean time to failure of 40.72hrs for the smaller conventional mills of Plant B is twice as long as that for the large modern mill of Plant A at 18.95hrs. In contrast to this the mean time to repair of the two types of mills is almost the same. This is shown graphically as the reliability and maintainability profiles of the two types of primary mills in figures 4.21 and 4.22 below.

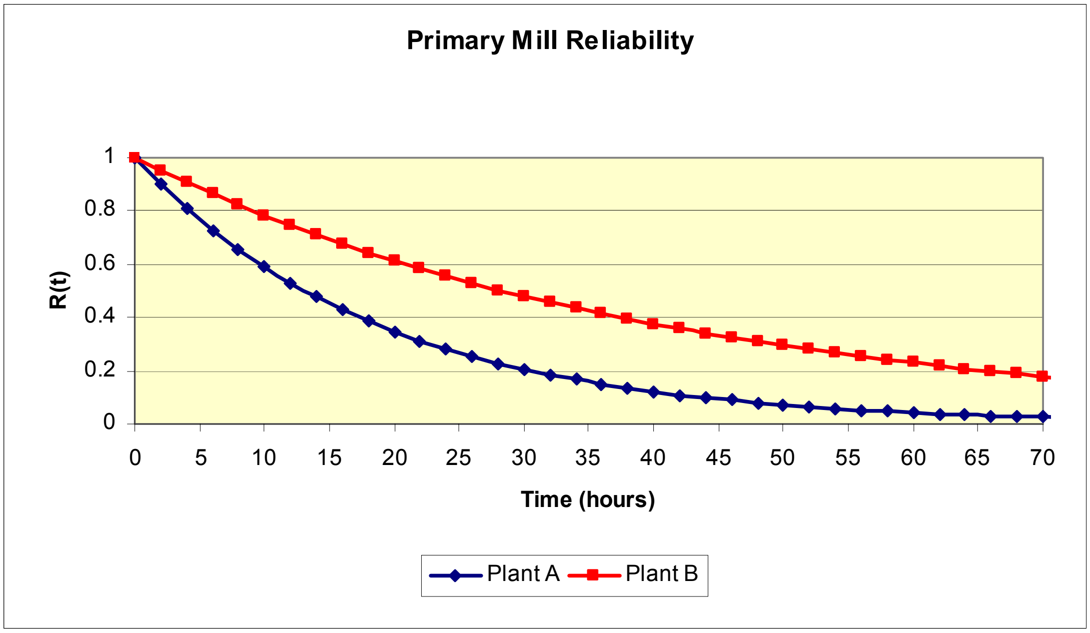

Figure 4.21: Primary Mill reliability profiles

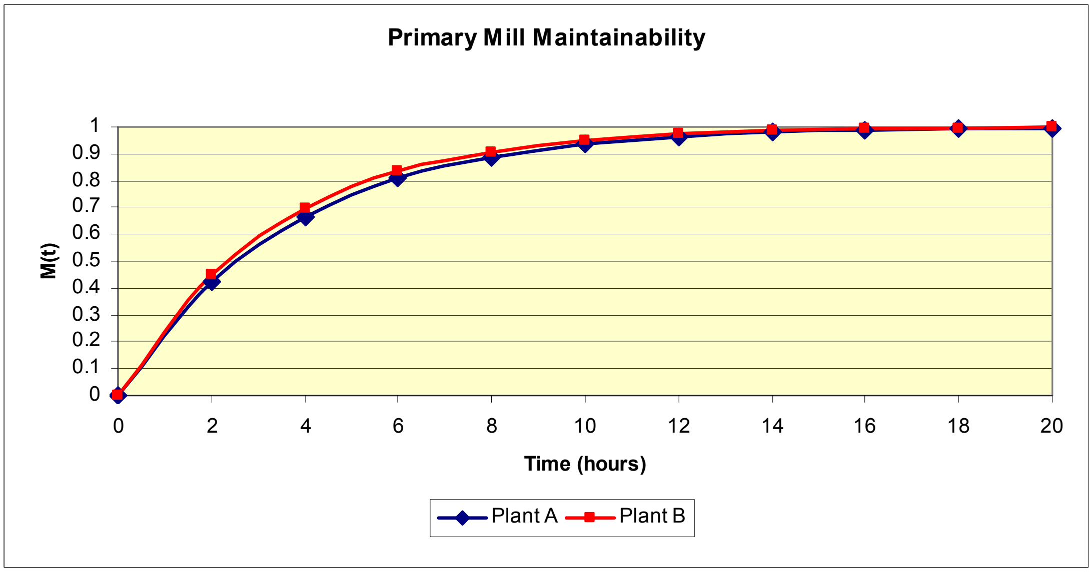

Figure 4.22: Primary mill maintainability profiles

4.3.2. Transient Behaviour

The comparison of the transient behaviour of the two types of primary mills is important for two reasons. Firstly it serves as an indication of how rapidly steady state conditions are achieved, and secondly it is the most accurate indication of steady state availability.

The transient state probability profiles of Plant A and Plant B primary mills is shown in figure 4.23 below

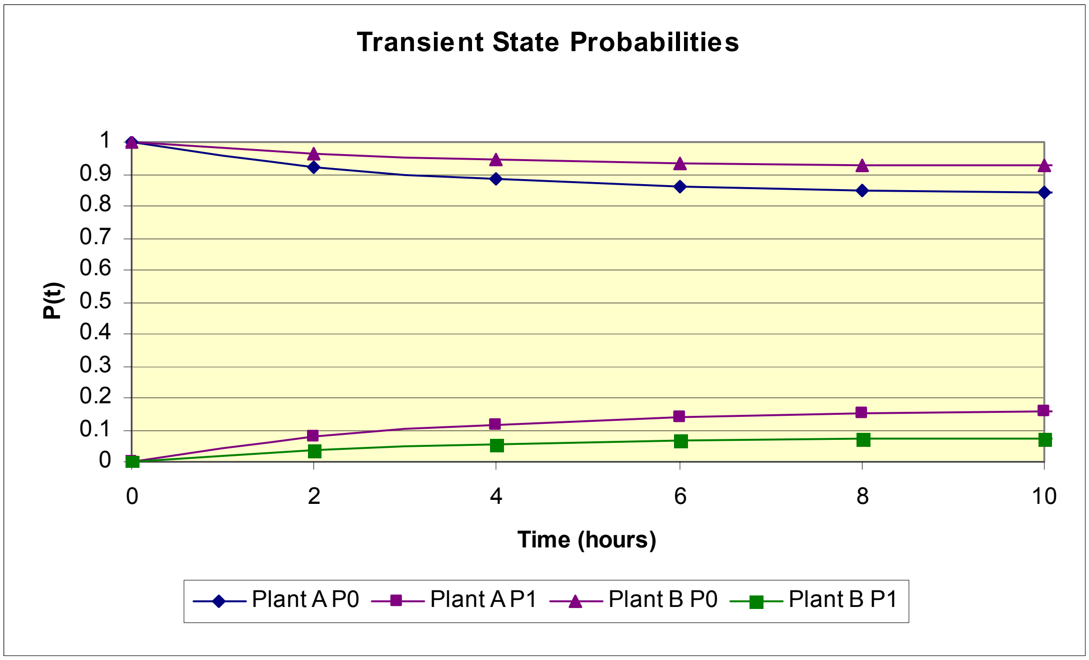

Figure 4.23: Transient state probability profiles for Plant A and Plant B

From figure 4.23 is very obvious that the conventional primary mills of plant B reach steady state conditions much quicker than the primary mill of Plant A. The steady state availability of Plant B primary mills at 92.4% is also significantly higher than that of Plant A primary mill at 83.9%.

4.3.3. Failure Modes

The results of the 11-state Markov analysis can be used to identify the most probable causes of unavailabilities for the two respective types of primary mills i.e. how the mechanical reliabilities of the two mills compare and also what the configuration implications on their reliabilities are.

The inherent mechanical reliability of the primary mills may be evaluated as a stand alone unit process by extracting the relevant information of stoppages due to major mill mechanical repairs (M) and lubrication breakdowns (L) from the 11-state Markov analysis results. These results are summarised in table 4.12 below for the two respective types of mills.

	Plant A		**Plant B**	
	Lubrication	**Mechanical**	**Lubrication**	**Mechanical**
Failure rate	0.00213	0.00125	0.0079	0.00363
MTTF	469.2	801.8	126.6	275.4
Repair rate	0.589	0.127	6.616	1.377
MTTR	1.698	7.860	0.151	0.726

Table 4.12: Primary Mill mechanical reliabilities

The mean time to failure for both the lubrication and mechanical failure modes of the conventional primary mills of Plant B is substantially shorter than those of the large modern mill of Plant A, thereby indicating that the smaller mills will fail more frequently. However, in contrast to this the mean time to repair for these two failure modes of Plant A are significantly longer than those of the conventional mills of Plant B.

The impact of the size of the mill on the reliabilities of the downstream equipment can be evaluated in a in a similar manner by combining the results due to downstream pumping and piping breakdowns (PP) and downstream process equipment failures (PE). These results are summarised in table 4.13 below for the two respective types of mills.

	Plant A		**Plant B**	
	Pumping & Piping	**Process Equipment**	**Pumping & Piping**	**Process Equipment**
Failure rate	0.00571	0.00944	0.00732	0.00129
MTTF	175.2	105.9	136.6	774.3
Repair rate	0.232	0.411	3.764	1.005
MTTR	4.294	2.433	0.266	0.995

Table 4.13: Downstream Reliabilities

These results indicate that the stoppages due to downstream pumping and piping failures are approximately the same for both types of primary mills but that these breakdowns are repaired much quicker for Plant B. This can possibly be explained by considering the size of the pumps in Plant A and the logistics involved in effecting emergency repairs on such large pumps.

Plant B primary mills are also less prone to be stopped due to downstream process equipment failures.

4.3.4. Overall System Performance

Finally the system performance of the multiple stream configuration can be compared to that of the single stream circuit. The relevant information is summarised in table 4.14 below.

	Plant A			**Plant B**		
	Probability	**Cycle Time**	**Duration**	**Probability**	**Cycle Time**	**Duration**
Operational	0.839	22.59	18.95	0.9925	63.55	63.08
Failed	0.161	22.59	3.64		63.55	0.48

Table 4.14: Summary of system performance

Table 4.14 is arguably the most important way of indicating the differences in expected system reliabilities between a single stream configuration and a multiple parallel configuration with partial redundancy.

In the case of the single stream circuit the probability of the primary mill being operational is exactly equal to the probability of the overall circuit being operational.

For Plant B the operational state is defined as the combination of the probability of all seven mills being on line and the probability of any number of mills up to a maximum of three being down.

5. CONCLUDING REMARKS

The primary objective of this study was to develop a methodology for evaluating how the reliability profile of the typical South African Platinum concentrator plant is affected by firstly the size of the primary milling units incorporated into the circuit and secondly by the way that the primary milling units are configured. The South African Platinum mining industry has been experiencing a major expansion phase resulting in the design and construction of several new concentrators. It is recognised that the trend during this expansion is towards incorporating the single, largest primary mills available for the specific duty. The size of these large primary mills then plays a pivotal role in determining the size and configuration of all the other associated process equipment and plant infrastructure. Furthermore these mills require highly sophisticated and automated monitoring devices and systems to function. It is the premise of this study that this new trend towards large single stream plants may be imposing severe limitations on the ultimate reliability profile and performance of these new concentrators.

It is therefore considered critical to develop a simple, yet effective methodology for measuring and evaluating the influence of the different factors that determine the reliability profile of the new concentrators as a function of the size and number of primary mills included in the circuit configuration. For this reason it was necessary to study the fundamental principles of reliability engineering. This study then progressed to developing an understanding of the different methods and models described in the available literature for evaluating the reliability, availability and maintainability (RAM) of the typical Platinum concentrator.

Ultimately a methodology, together with a set of general expressions was developed which considers the Platinum concentrator as a stochastic process where the behaviour of the primary mill is a direct measure of the failure pattern of the overall concentrator. The reliability, availability and maintainability (RAM) of the primary mill, and hence the overall concentrator, is then determined by a combination of three different Markov models where each Markov model is used to evaluate and measure a separate set of reliability parameters. This approach allows one to effectively overcome the computational complexity associated with complex Markov models and still provide a very good "big picture" understanding of the reliability profile of the plant under consideration.

The first step is to assess whether the behaviour of the primary mill conforms to the requirements of a stochastic process. This is achieved by a simple plot of the cumulative number of failures against the cumulative operating time. Any changes, and hence tends, in the rate of occurrence of failures (ROCOF) will easily be detected by visual inspection. The data set is further subjected to the Laplace trend test where the test statistic is used to test the Null hypotheses of zero trends against a selected level of confidence. The value of the Laplace statistics also serves as a measure of the both the magnitude and direction (increasing or decreasing) in the ROCOF. The general expression used to test the null hypothesis H_0 of zero trend i.e. $\alpha = 1$ in $A\alpha t^{\alpha-1}$ against either increasing or decreasing ROCOF is

$$U = \frac{\sum_{i=1}^{n-1} \frac{T_i}{n-1} - \frac{T_n}{2}}{T \sqrt{\frac{1}{12(n-1)}}} \quad \ldots\ldots(5.1)$$

The first Markov model considers an individual primary mill, regardless of whether it is part of a single stream circuit or a multiple stream configuration, as a single component reliability block diagram and is used to determine the frequency and average duration that the mill resides in either the operational state or the failed state. This Markov model is used primarily to determine the key reliability parameters such as the overall failure and repair rates, the overall reliability profile, the maintainability profile, and finally the steady state availability of the primary mill under consideration. This Markov model does not allow any analysis of the different causes of failures recorded for the primary mill nor does it give any understanding of configuration implications on reliability performance. The general expressions relevant to this Markov model are

$$P_0(t) = \frac{\mu_c}{\lambda_c + \mu_c} + \frac{\lambda_c}{\lambda_c + \mu_c} \cdot e^{-(\lambda_c + \mu_c)t} \text{ ....(5.2)}$$

$$P_1(t) = \frac{\lambda_c}{\lambda_c + \mu_c} - \frac{\lambda_c}{\lambda_c + \mu_c} \cdot e^{-(\lambda_c + \mu_c)t} \text{ ....(5.3)}$$

where Eq’s 5.2 and 5.3 can now be used to evaluate the transient behaviour of the individual primary milling circuit given that it started in the operating state. The steady state behaviour is obtained by reducing Eq’s 5.2 and 5.3 when $t \to \infty$.

The second Markov model describes the individual primary mill as a single component that switches discretely between the operational state and several other states where the other states represent the different modes, or causes of failures. The primary purpose of this model is to evaluate the different causes of system failures of the primary mill. The different causes of failures are seen as unit processes for which the reliability and maintainability profile of each failure mode is measured. These failure modes can also be further classified as upstream, downstream, or inherent to the mill itself, thereby allowing a further indirect measure of the RAM profile of the circuit configuration.

The set of general expression derived for the different state probabilities as defined by this specific Markov model is

$$P_0 = \left[\frac{\prod_{i=1}^{10} \mu_i}{\prod_{i=1}^{10} \mu_i + \sum_{\substack{i=1 \\ j \neq i}}^{10} \left(\lambda_i \cdot \prod \mu_j \right)} \right] \text{...(5.4)}$$

and

$$P_i = \frac{\lambda_i}{\mu_i} P_0 \qquad i \geq 0 \text{ ....(5.5)}$$

The values of P_i are then determined by back substation of Eq 5.4 into Eq 5.5 which is used to describe the steady state probabilities of the system.

These first two Markov models are used to fully describe the RAM of both an individual primary mill in a multiple stream configuration and also of the overall system of a large single stream Platinum concentrator. However, an additional Markov model is necessary to fully evaluate the system RAM of a multiple stream primary milling configuration. The third Markov model views the overall set of primary mills as an m-out-of-n system i.e. the principle of partial redundancy is applied. Here the relevant set of expressions that was derived are

$$\therefore \quad P_0 = \frac{(n-m)\mu^2}{[m\lambda + (n-m)\mu]\cdot[\lambda + \mu]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.6)$$

and

$$\therefore \quad P_1 = \frac{n\lambda\mu}{[m\lambda + (n-m)\mu]\cdot[\lambda + \mu]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.7)$$

and

$$\therefore \quad P_2 = \frac{m\lambda^2}{[m\lambda + (n-m)\mu]\cdot[\lambda + \mu]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.8)$$

The methodology was then successfully evaluated by applying it to two case studies using actual plant downtime data. One data set was of a large, modern single stream concentrator while the other was of an older, conventional multiple stream concentrators. Even though the two case studies were used for validation purposes only, the results clearly indicated that the methodology is effective in characterising the RAM profile of a Platinum concentrator. A further comparison of the RAM results of the two plants clearly identified the specific areas where firstly the unit RAM profile of the large modern primary mill differs from that of the smaller conventional mills, and also where the system RAM profile of the a large single stream concentrator differs from that of the conventional multi stream configuration.

5.1. Final Conclusions & Recommendations

The primary contribution of this study is the development of a methodology, together with a set of general expressions for evaluating the reliability, availability and maintainability of South African Platinum concentrator plants. The methodology is based on considering a typical Platinum concentrator as a stochastic process where the failure pattern of the overall concentrator and the reliability behaviour of the primary mill are directly interrelated. The reliability, availability and maintainability (RAM) profiles of the primary mill, and hence of the overall concentrator, is then measured by means of a combination of three different Markov models where each Markov model is used to evaluate and measure a separate set of reliability parameters.

Even though the proposed methodology was successfully applied to two case studies certain areas of were identified during the course of this study that merits further investigation.

The most important question that still needs to be answered is whether there are, in general, fundamental differences in the RAM profiles of large, modern, single stream Platinum concentrators and conventional multiple stream configurations based on smaller primary mills, and also what the reason for any differences are. This question can only be answered by conducting a full RAM survey of a representative sample of South African Platinum concentrators. An observation made during the course of this study was the lack of consistency in the format that historical downtime data is recorded by the different Platinum concentrators. This lack of consistency will not allow such a comprehensive survey from being conducted using historical data only. It is therefore envisaged that the most challenging part of such a survey will be to persuade the management of the participating concentrator plants to record downtime data in a generic format and to run the survey over a statistically acceptable period of time.

The simple data recording format developed for the purposes of evaluating the two cases as part of this study (see appendix 4) could easily serve as the framework for developing a more comprehensive downtime data recording format. It is a fact that all the new Platinum concentrators are installed with sophisticated supervisory control and data acquisition systems (SCADA) and the majority of the older plants are being retrofitted with such SCADA systems. These systems allow all the relevant data of any stoppage of either an individual piece of equipment or of the overall system, to be recorded very accurately in an electronic format. The possibility therefore exists to link an on-line downtime data acquisition and analysis system, which is based on the 3-Markov methodology developed during the course of this study, to these SCADA systems. Not only will such a system reduce the effort associated with the proposed downtime survey, but it could also be used to produce routine reports for use by the management of the specific plant. The predictive power of this methodology will certainly make a valuable contribution to the ongoing maintenance strategy of any Platinum concentrator.

The second area of possible future investigation relates to the multiple state Markov model presented in section 3.2.2 of this study. This Markov model describes the individual primary mill as a single component that switches discretely between the operational state and several other states where the other states represent the different modes, or causes of failures. Eq’s 5.4 and 5.5 describe the steady-state behaviour of the primary mill.

An unsuccessful attempt was made during this study to derive a general expression that could be used to explicitly describe the transient behaviour, as opposed to only the steady-state behaviour, of the individual primary mill. Unfortunately the explicit transient analysis of this Markov model is not possible due to the computational complexity normally associated with complex Markov models. However, the ability to evaluate the transient behaviour of the primary mill will make a significant contribution to the overall power of the 3-Markov model methodology presented here. More specifically it will permit the short term prediction of system behaviour as the primary mill switches between the operational state and the various failure modes with obvious benefits to the plant operator and maintenance engineer. It is assumed that such analysis of the transient behaviour will only be possible by means of customised algorithm based on numerical methods.

A further observation made during this study was that if the combined failure pattern of a Platinum concentrator conformed to the definition of a stochastic process, it could not be assumed that the failure patterns of the individual failure modes described by the second Markov model would also automatically conform to these requirements. In short it means that the rate of occurrence of failures (ROCOF) of the individual failure modes would not necessarily by without any trends or structures. The result of this is that the P_0 as measured by Equation 5.2 will not necessarily be equal to the P_0 as calculated by Equation 5.4. The direct implication of this to the methodology presented here needs to be investigated and quantified.

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8. APPENDIX 1 Derivation of the probability expressions for a 2-state, single unit, primary milling circuit

Consider a primary milling circuit as a single component, 2-state Markov process i.e. it is either operational (state 0), or failed (state 1). The specific reason for being in the failed state is ignored for the purpose of this analysis.

The system failure and repair rates are defined as

$$\lambda_c = \frac{no.\ of\ all\ failures\ in\ a\ given\ time\ period}{total\ period\ of\ time\ spent\ in\ the\ operating\ state} \quad \text{……………...……(8.1)}$$

and

$$\mu_c = \frac{no.\ of\ all\ repairs\ in\ a\ given\ time\ period}{total\ period\ of\ time\ in\ the\ failed\ state} \quad \text{……………..…………...(8.2)}$$

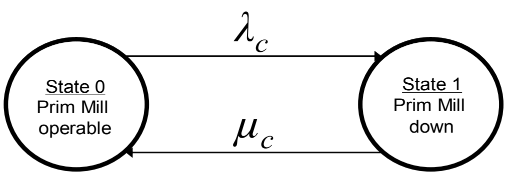

Figure 8.1: Single Primary mill state-space diagram

Define

$P_0(t)$ = probability that the primary mill is operable at time t

$P_1(t)$ = probability that the primary mill is down at time t

λ_c = failure rate

μ_c = repair rate

Therefore

$\lambda_c dt$ = Probability of failing in $(t+dt)$

$1-\lambda_c dt$ = Probability of not failing in $(t+dt)$

$\mu_c dt$ = Probability of being repaired in $(t+dt)$

$1-\mu_c dt$ = Probability of not being repaired in $(t+dt)$

Consider the system shown in figure 8.1 above and allowing for an incremental time interval dt that is sufficiently small so that the probability of two or more transitions occurring during this interval is negligible. Then the probability of being in the operating state after this time interval $(t+dt)$ is

[Probability of being operative at time t, AND not failing in time dt]
\+ *[probability of being failed at time t AND of being repaired in time dt]*

This is expressed as

$$P_0(t+dt) = P_0(t)(1-\lambda_c dt) + P_1(t)(\mu_c dt) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(8.3)}$$

$$P_0(t+dt) = P_0(t) - P_0(t)\lambda_c dt + P_1(t)\mu_c dt$$

Rearranging

$$\frac{P_0(t+dt) - P_0(t)}{dt} = \mu_c P_1(t) - \lambda_c P_0(t)$$

Letting $dt \to 0$ yields

$$\left.\frac{P_0(t+dt) - P_0(t)}{dt}\right|_{dt\to 0} = P_0'(t) = \mu_c P_1(t) - \lambda_c P_0(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8.4)$$

Similarly the probability of being in the failed state after this time interval *(t+dt)* is

[Probability of being failed at time t, AND not being repaired in time dt]

+ *[probability of being operative at time t AND of failing in time dt]*

$$= P_1(t+dt) = P_1(t)(1 - \mu_c dt) + P_0(t)(\lambda_c dt) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8.5)$$

$$P_1(t+dt) = P_1(t) - P_1(t)\mu_c dt + P_0(t)\lambda_c dt$$

Rearranging

$$\frac{P_1(t+dt) - P_1(t)}{dt} = \lambda_c P_0(t) - \mu_c P_1(t)$$

Letting $dt \to 0$ yields

$$\left.\frac{P_1(t+dt) - P_1(t)}{dt}\right|_{dt\to 0} = P_1'(t) = \lambda_c P_0(t) - \mu_c P_1(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8.6)$$

Together Eq's 9.4 and 9.6 form a set of linear differential equations with constant coefficients that may be presented in matrix format as

$$\left[P_0'(t) \quad P_1'(t)\right] = \left[P_0(t) \quad P_1(t)\right] \cdot \begin{bmatrix} -\lambda & \lambda \\ \mu & -\mu \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots(8.7)$$

where $\left[P_0(t) \quad P_1(t)\right]$ is known as the state-probability vector.

Eq's 9.4 and 9.6 are now solved by means of the Laplace transform method.

The Laplace transform of Eq. 9.4 is

$$sP_0(s) - P_0(0) = \mu_c P_1(s) - \lambda_c P_0(s) \ldots\ldots\ldots\ldots\ldots\ldots(8.8)$$

$$P_0(s)\left(s + \lambda_c\right) = \mu_c P_1(s) - P_0(0)$$

$$P_0(s) = \frac{\mu_c}{s + \lambda_c} P_1(s) + \frac{1}{s + \lambda_c} P_0(0) \ldots\ldots\ldots\ldots\ldots\ldots(8.9)$$

Similarly the Laplace transform of Eq. 8.6 is

$$sP_1(s) - P_1(0) = \lambda_c P_0(s) - \mu_c P_1(s) \ldots\ldots\ldots\ldots\ldots\ldots(8.10)$$

$$P_1(s)\left(s + \mu_c\right) = \lambda_c P_1(s) - P_1(0)$$

$$P_1(s) = \frac{\lambda_c}{s + \mu_c} P_0(s) + \frac{1}{s + \mu_c} P_1(0) \ldots\ldots\ldots\ldots\ldots\ldots(8.11)$$

Now by substituting Eq 8.11 into Eq. 8.9 yields

$$P_0(s)=\frac{\mu_c}{s+\lambda_c}\left[\frac{\lambda_c}{s+\mu_c}P_0(s)+\frac{1}{s+\mu_c}P_1(0)\right]+\frac{1}{s+\lambda_c}P_0(0)$$

$$P_0(s)=\frac{\mu_c\lambda_c}{(s+\lambda_c)\cdot(s+\mu_c)}P_0(s)+\frac{\mu_c}{(s+\lambda_c)\cdot(s+\mu_c)}P_1(0)+\frac{1}{s+\lambda_c}P_0(0)$$

$$P_0(s)\left[\frac{(s+\lambda_c)\cdot(s+\mu_c)-\mu_c\lambda_c}{(s+\lambda_c)\cdot(s+\mu_c)}\right]=\frac{\mu_cP_1(0)+(s+\mu_c)P_0(0)}{(s+\lambda_c)\cdot(s+\mu_c)}$$

Multiplying both sides by $(s+\lambda_c)\cdot(s+\mu_c)$ and re-arranging

$$P_0(s)=\frac{\mu_cP_1(0)+(s+\mu_c)P_0(0)}{s(s+\lambda_c+\mu_c)}$$

Using the property of partial fractions

$$\frac{\mu_cP_1(0)+(s+\mu_c)P_0(0)}{s(s+\lambda_c+\mu_c)}=\frac{A}{s}+\frac{B}{(s+\lambda_c+\mu_c)}\quad\text{……………………(8.12)}$$

Multiply both sides by $s(s+\lambda_c+\mu_c)$

$$\mu_c P_1(0) + (s + \mu_c) P_0(0) = A(s + \lambda_c + \mu_c) + Bs$$

Let $s = 0$

$$\mu_c P_1(0) + \mu_c P_0(0) = A(\lambda_c + \mu_c)$$

$$\therefore \qquad A = \frac{\mu_c}{\lambda_c + \mu_c} \cdot \left[P_1(0) + P_0(0) \right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.13)$$

Let $s = (-\lambda_c - \mu_c)$

$$\mu_c P_1(0) + \lambda_c P_0(0) = B(-\lambda_c - \mu_c)$$

$$\mu_c P_1(0) - \mu_c P_1(0) = B(\lambda_c + \mu_c)$$

$$\therefore \qquad B = \frac{\lambda_c P_0(0) - \mu_c P_1(0)}{\lambda_c + \mu_c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.14)$$

Substituting Eq's 8.13 and 8.14 into Eq. 8.12 yields

$$P_0(s) = \frac{1}{s} \cdot \frac{\mu_c}{\lambda_c + \mu_c} \cdot \left[P_1(0) + P_0(0) \right] + \frac{1}{(s + \lambda_c + \mu_c)} \cdot \frac{1}{\lambda_c + \mu_c} \cdot \left[\lambda_c P_0(0) - \mu_c P_1(0) \right]$$

$$\ldots\ldots\ldots\ldots (8.15)$$

Converting Eq 8.15 from s-domain back into the time domain

$$P_0(t) = \frac{\mu_c}{\lambda_c + \mu_c} \cdot \left[P_1(0) + P_0(0)\right] + \frac{e^{-(\lambda_c + \mu_c)t}}{\lambda_c + \mu_c} \cdot \left[\lambda_c P_0(0) - \mu_c P_1(0)\right] \ldots (8.16)$$

Similarly by substituting Eq 8.9 into Eq 8.11

$$P_1(s) = \frac{\lambda_c}{s + \lambda_c} \cdot \left[\frac{\mu_c}{s + \lambda_c} P_1(s) + \frac{1}{s + \lambda_c} P_0(0) \right] + \frac{1}{s + \lambda_c} \cdot P_1(0)$$

$$P_1(s) = \frac{\mu_c \lambda_c}{(s + \lambda_c) \cdot (s + \mu_c)} \cdot P_1(s) + \frac{\lambda_c P_0(0) +}{(s + \lambda_c) \cdot (s + \mu_c)} + \frac{1}{s + \mu_c} P_1(0)$$

$$P_1(s) \left[\frac{(s + \lambda_c) \cdot (s + \mu_c) - \mu_c \lambda_c}{(s + \lambda_c) \cdot (s + \mu_c)} \right] = \frac{\lambda_c P_0(0) + (s + \lambda_c) P_1(0)}{(s + \lambda_c) \cdot (s + \mu_c)}$$

Multiplying both sides by $(s + \lambda_c)(s + \mu_c)$ and re-arranging

$$P_1(s) = \frac{\lambda_c P_1(0) + (s + \lambda_c) P_1(0)}{s(s + \lambda_c + \mu_c)}$$

Using the property of partial fractions

$$\frac{\lambda_c P_0(0) + (s + \lambda_c) P_1(0)}{s(s + \lambda_c + \mu_c)} = \frac{A}{s} + \frac{B}{(s + \lambda_c + \mu_c)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.17)$$

Multiply both sides by $s(s + \lambda_c + \mu_c)$

$$\lambda_c P_0(0) + (s + \mu_c) P_1(0) = A(s + \lambda_c + \mu_c) + Bs$$

Let $s = 0$

$$\lambda_c P_0(0) + \lambda_c P_1(0) = A(\lambda_c + \mu_c)$$

$$\therefore \qquad A = \frac{\lambda_c}{\lambda_c + \mu_c} \cdot [P_0(0) + P_1(0)] \text{……………………………..…….(8.18)}$$

Let $s = (-\lambda_c - \mu_c)$

$$\lambda_c P_0(0) - \mu_c P_1(0) = -B(\lambda_c + \mu_c)$$

$$\mu_c P_1(0) - \lambda_c P_0(0) = B(\lambda_c + \mu_c)$$

$$\therefore \qquad B = \frac{\mu_c P_1(0) - \lambda_c P_0(0)}{\lambda_c + \mu_c} \text{ ……………………………………….….. (8.19)}$$

Substituting Eq's 8.18 and 8.19 into Eq. 8.17 yields

$$P_1(s) = \frac{1}{s} \cdot \frac{\lambda_c}{\lambda_c + \mu_c} \cdot [P_1(0) + P_0(0)] + \frac{1}{(s + \lambda_c + \mu_c)} \cdot \frac{1}{\lambda_c + \mu_c} \cdot [\mu_c P_1(0) - \lambda_c P_0(0)]$$

$$\text{………………... (8.20)}$$

Converting Eq 8.20 from s-domain back into the time domain

$$P_1(t) = \frac{\lambda_c}{\lambda_c + \mu_c} \cdot [P_1(0) + P_0(0)] + \frac{e^{-(\lambda_c + \mu_c)t}}{\lambda_c + \mu_c} \cdot [\mu_c P_1(0) - \lambda_c P_0(0)] \text{… (8.21)}$$

According to the Laws of probability

$$P_0(t)+P_1(t)=1$$

Assuming the system starts in the operating state at $t=0$ then

$$P_0(0)=1$$

and

$$P_1(0)=0$$

Then Eq's 8.16 and 8.21 reduce to

$$P_0(t)=\frac{\mu_c}{\lambda_c+\mu_c}+\frac{\lambda_c}{\lambda_c+\mu_c}\cdot e^{-(\lambda_c+\mu_c)t} \quad \text{..(8.22)}$$

$$P_1(t)=\frac{\lambda_c}{\lambda_c+\mu_c}-\frac{\lambda_c}{\lambda_c+\mu_c}\cdot e^{-(\lambda_c+\mu_c)t} \quad \text{..(8.23)}$$

respectively. Eq's 8.22 and 8.23 can now be used to evaluate the transient behaviour of the system given that it started in the operating state.

Letting $t\to\infty$ reduces Eq 8.22 to

$$P_0(\infty)=\frac{\mu_c}{\lambda_c+\mu_c} \quad \text{..(8.24)}$$

which is the steady state availability of the system. From this it follows that

System reliability $R_c = e^{-\lambda_c t}$ ……………………………………………...……(8.25)

System Maintainability $M_c = 1 - e^{-\mu_c t}$ ……………………………………..……..(8.26)

Mean time to failure $MTTF_c = {}^{1}\!/_{\lambda_c}$ …………………………………………..…(8.27)

Mean time to repair $MTTR_c = {}^{1}\!/_{\mu_c}$ …………………………………………..…(8.28)

Mean time between failure $MTBF_c = MTTR_c + MTTF_c$

$$= {}^{1}\!/_{\lambda_c} + {}^{1}\!/_{\mu_c} = \frac{\lambda_c + \mu_c}{\lambda_c \mu}$$ ………………(8.29)

Frequency of encountering the failed state $f_c = P_1 \mu_c$ ……………

$$= \frac{\lambda_c}{\lambda_c + \mu_c} \cdot \frac{\mu_c}{1} = \frac{\lambda_c \mu_c}{\lambda_c + \mu_c}$$ ……………...(8.30)

9. APPENDIX 2 Derivation of the probability expressions for an 11-state, single unit, primary milling circuit

Consider a single primary milling circuit as a single component, 11-state Markov process i.e. it is either in the operational (state 0), or in any one of the different failed sates (state i). The specific reason for being in the failed state is categorised generically as shown in Table 9.1 below.

State no.	Description	Code
0	Normal operating	
1	Planned maintenance	PM
2	Ore shortage	OS
3	Feed conveyor breakdown	FC
4	Major mill mechanical breakdown	M
5	Downstream pumping/piping breakdown	PP
6	Downstream process equipment breakdown	PE
7	Electrical failure or outage	E
8	PLC/SCADA failure	PLC
9	Water shortage	W
10	Other	O

Table 9.1: State categories and description

The primary mill and its associated failed states are considered to be in a series configuration i.e. failure of any one of the different components (failure modes) will cause system failure. The reliability diagram of this configuration is shown in Figure 9.1 below.

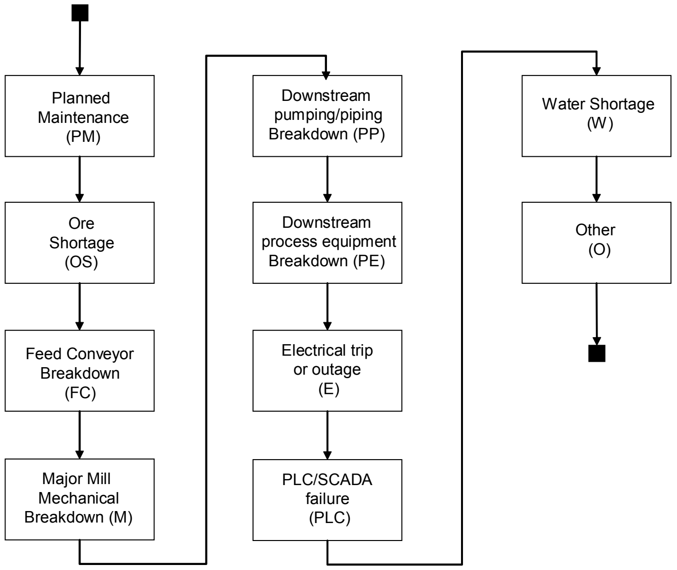

Figure 9.1: RBD of single unit primary milling circuit

The system failure rates and repair rates are defined as follows for the different failure modes as described in Table 9.1 above.

$$\lambda_i = \frac{no.\,of\ \ failures\ due\ to\ a\ specific\ reason\ in\ a\ given\ time\ period}{total\ \ period\ \ of\ \ time\ spent\ in\ the\ operating\ state} \ldots\ldots (9.1)$$

and

$$\mu_i = \frac{no.\,of\ \ repairs\ in\ a\ specific\ \ failure\ mode\ in\ a\ given\ time\ period}{total\ \ period\ \ of\ \ time\ in\ the\ \ failed\ state} \ldots\ldots (9.2)$$

The state-space diagram associated with the RBD in Figure 9.1 is shown in Figure 9.2 below.

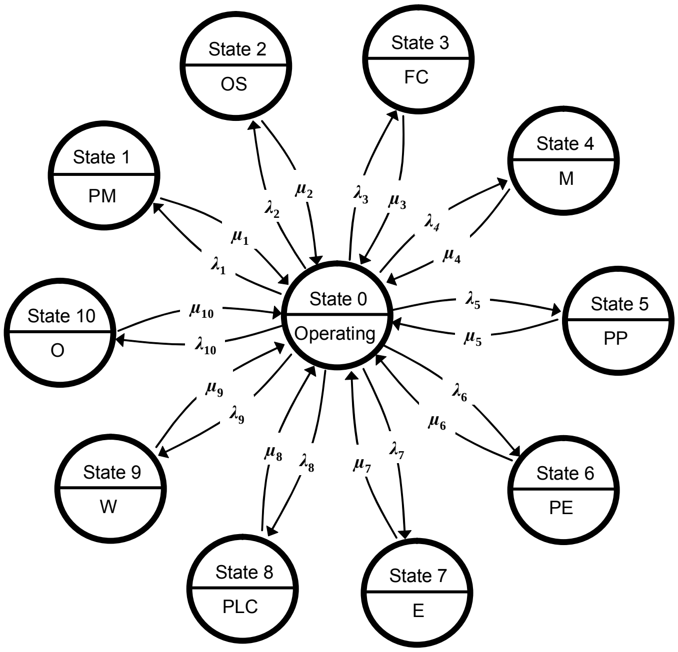

Figure 9.2: State-space diagram of an 11-state primary mill

Define

$P_0(t)$ = probability that the primary mill is operable at time t

$P_i(t)$ = probability that the primary mill is down at time t due to any one of the defined failure modes

λ_i = failure rate due to a specific failure mode

μ_i = repair rate in a specific failure mode

Therefore

$\lambda_i dt$ = Probability of failing due to a specific failure mode in $(t+dt)$ $1 \le i \le 10$

$1-\sum_{i=1}^{10} \lambda_i dt$ = Probability of not failing in $(t+dt)$ $1 \le i \le 10$

$\mu_i dt$ = Probability of being repaired in $(t+dt)$ $1 \le i \le 10$

$1-\mu_i dt$ = Probability of not being repaired in $(t+dt)$ $1 \le i \le 10$

Consider the system shown in figure 9.2 above and allowing for an incremental time interval dt that is sufficiently small so that the probability of two or more transitions occurring during this interval is negligible. Then the probability of being in the operating state after this time interval *(t+dt)* is

[Probability of being operative at time t, AND not failing in time dt]
+ [probability of being in one of the failed states at time t AND of being repaired in time dt]

This is expressed as

$$P_0(t+dt) = P_0(t)(1-\sum_{i=1}^{10}\lambda_i dt) + P_1(t)(\mu_1 dt) + P_2(t)(\mu_2 dt)\ldots + P_{10}(t)(\mu_{10} dt)\ldots \text{ (9.3)}$$

$$P_0(t+dt) = P_0(t) - P_0(t)\sum_{i=1}^{10}\lambda_i dt + \sum_{i=1}^{10} P_i(t)\mu_i dt$$

Rearranging

$$\frac{P_0(t+dt)-P_0(t)}{dt} = \sum_{i=1}^{10}\mu_i P_i(t) - P_0(t)\sum_{i=1}^{10}\lambda_i$$

Letting $dt \to 0$ yields

$$\frac{P_0(t+dt)-P_0(t)}{dt}\Big|_{dt\to 0} = P_0'(t) = \sum_{i=1}^{10}\mu_i P_i(t) - P_0(t)\sum_{i=1}^{10}\lambda_i \ldots\ldots\ldots\ldots \quad \ldots\text{.(9.4)}$$

Similarly the probability of being in any one of the different failed states after this time interval *(t+dt)* is

[Probability of being in any one of the failed states at time t, AND not being repaired in time dt]+ [probability of being operative at time t AND of failing in time dt]

This is expressed as

$$P_i(t+dt) = P_i(t)(1-\mu_i dt) + P_0(t)\lambda_i dt \qquad 1 \le i \le 10 \text{ ……………………….(9.5)}$$

Rearranging

$$\frac{P_i(t+dt) - P_i(t)}{dt} = P_0(t)\lambda_i - \mu_i P_i(t) \qquad 1 \le i \le 10 \text{ ………………..…….(9.6)}$$

Letting $dt \to 0$ yields

$$\frac{P_i(t+dt) - P_i(t)}{dt}\Big|_{dt \to 0} = P_i^{'}(t) = P_0(t)\lambda_i - \mu_i P_i(t) \qquad 1 \le i \le 10 \text{ ……..….(9.7)}$$

Together Eq's 9.4 and 9.7 form a set of linear differential equations with constant coefficients that may be presented in matrix format as

$$\left[P_0^{'}(t) \quad P_1^{'}(t) \quad \ldots \quad P_{10}^{'}(t)\right] =$$

$$\left[P_0\ (t) \quad P_1\ (t) \quad \ldots \quad P_{10}\ (t)\right] \cdot \begin{bmatrix} -\lambda_1 - \lambda_2 \ldots - \lambda_{10} & \lambda_1 & \ldots & \lambda_{10} \\ \mu_1 & -\mu_1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{10} & 0 & \ldots & -\mu_{10} \end{bmatrix} \text{…..(9.8)}$$

Where $\left[P_0\,(t)\quad P_1\,(t)\quad \ldots\quad P_{10}\,(t)\right]$ is the state probability vector.

Computational complexity does not allow the derivation of an explicit expression for the time dependent or transient behaviour of the system. However, the expressions for steady-state behaviour is obtained by letting $t \to \infty$

Eq 9.4 then becomes

$$P_0'(\infty) = \sum_{i=1}^{10} \mu_i P_i - P_0 \sum_{i=1}^{10} \lambda_i = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9.9)$$

and Eq 9.7 becomes

$$P_1'(\infty) = P_0\lambda_1 - \mu_1 P_1 = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9.10a)$$

$$P_2'(\infty) = P_0\lambda_2 - \mu_2 P_2 = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9.10b)$$

$$\vdots \qquad \vdots \qquad \vdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad \vdots$$

$$P_{10}'(\infty) = P_0\lambda_{10} - \mu_{10} P_{10} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9.10j)$$

From Eq 9,9

$$P_1 = \frac{\lambda_1}{\mu_1} P_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9.11a)$$

$$P_2 = \frac{\lambda_2}{\mu_2} P_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9.11b)$$

$$\vdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \vdots$$

$$P_{10} = \frac{\lambda_{10}}{\mu_{10}} P_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9.11j)$$

According to the law of probabilities

$$P_0 + P_1 + P_2 + P_3 \cdots + P_{10} = 1 \qquad (9.12)$$

Substituting Eq 9.11 into Eq 9.12

$$P_0 + \frac{\lambda_1}{\mu_1} P_0 + \frac{\lambda_2}{\mu_2} P_0 \cdots + \frac{\lambda_{10}}{\mu_{10}} P_0 = 1 \qquad (9.13)$$

$$P_0 \left[\frac{\mu_1 \mu_2 \cdots \mu_{10} + \lambda_1 \mu_2 \mu_3 \mu_4 \cdots \mu_{10} + \lambda_2 \mu_1 \mu_3 \mu_4 \cdots \mu_{10} + \cdots + \lambda_{10} \mu_1 \mu_2 \mu_3 \cdots \mu_9}{\mu_1 \mu_2 \cdots \mu_{10}} \right] = 1$$

$$P_0 = \left[\frac{\prod_{i=1}^{10} \mu_i}{\prod_{i=1}^{10} \mu_i + \sum_{\substack{i=1 \\ j \neq i}}^{10} \left(\lambda_i \cdot \prod \mu_j \right)} \right] \qquad (9.14)$$

Values of $P_1, P_2, P_3, \cdots P_{10}$ are then determined by back substation of Eq 9.14 into Eq 9.11 which is the steady state probabilities of the system. From this it follows that

Unit process reliability $R_i = e^{-\lambda_i t}$ ……………………………..…………...……(9.15)

Unit process maintainability $M_i = 1 - e^{-\mu_i t}$ …………………………………..(9.16)

Unit process Mean time to failure $MTTF_i = 1/\lambda_i$ ………………………...…(9.17)

Unit Process Mean time to repair $MTTR_i = 1/\mu_i$ ………………………...…(9.18)

Frequency of encountering a particular failed state $f_i = P_i \mu_i$ ……………..(9.19)

10. APPENDIX 3 Derivation of the probability expressions for a 3-state, m-out-of-n parallel configuration of primary mills.

10.1. 2x Primary mills in parallel – 4-state Markov process

Consider 2 identical primary mills configured in parallel. These mills can adopt a maximum of four different states as shown in figure 10.1 below.

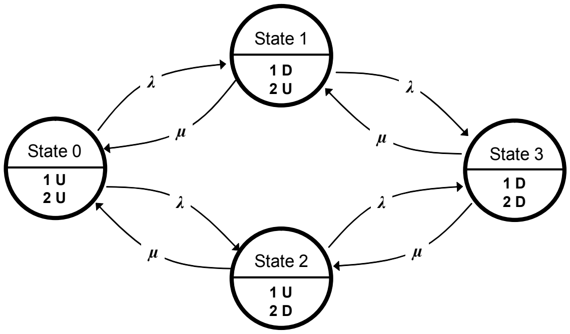

Figure 10.1: 4x State-space diagram for two mills in parallel.

State 0 is the fully operational state where both mills are operational, states 1 and 2 are the derated states where either one of the mills is down i.e. the order in which the mills go down is important, and state 3 is the fully failed state with both mills down. The failure and repair rates are identical for both mills.

The stochastic transitional probability matrix for the system shown in figure 10.1 is

$$P = \begin{bmatrix} (1-\lambda-\lambda) & \lambda & \lambda & 0 \\ \mu & (1-\lambda-\mu) & 0 & \lambda \\ \mu & 0 & (1-\lambda-\mu) & \lambda \\ 0 & \mu & \mu & (1-\mu-\mu) \end{bmatrix} \text{..................(10.1)}$$

If $\begin{bmatrix} P_0 & P_1 & P_2 & P_3 \end{bmatrix}$ is the limiting state probability vector then Eq 10.1 gives

$$\begin{bmatrix} P_0 & P_1 & P_2 & P_3 \end{bmatrix} = \begin{bmatrix} P_0 & P_1 & P_2 & P_3 \end{bmatrix} \cdot \begin{bmatrix} (1-2\lambda) & \lambda & \lambda & 0 \\ \mu & (1-\lambda-\mu) & 0 & \lambda \\ \mu & 0 & (1-\lambda-\mu) & \lambda \\ 0 & \mu & \mu & (1-2\mu) \end{bmatrix}$$

$$\text{.. (10.2)}$$

which in explicit form is

$$P_0 = (1-2\lambda)P_0 + \mu P_1 + \mu P_2 \text{..(10.3a)}$$

$$P_1 = \lambda P_0 - (1+\lambda+\mu)P_1 + \mu P_3 \text{..(10.3b)}$$

$$P_2 = \lambda P_0 - (1+\lambda+\mu)P_2 + \mu P_3 \text{..(10.3c)}$$

$$P_3 = \lambda P_1 + \lambda P_2 - (1+2\mu)P_3 \text{..(10.3d)}$$

Also from the laws of probability

$$P_0 + P_1 + P_2 + P_3 = 1 \qquad (10.4)$$

Simplifying Eq's 10.3 and replacing Eq 10.3c with Eq 10.4 gives

$$-2\lambda P_0 + \mu P_1 + \mu P_2 = 0 \qquad (10.5a)$$

$$\lambda P_0 - (\lambda + \mu) P_1 + \mu P_3 = 0 \qquad (10.5b)$$

$$\lambda P_1 + \lambda P_2 - 2\mu P_3 = 0 \qquad (10.5c)$$

$$P_0 + P_1 + P_2 + P_3 = 1 \qquad (10.5d)$$

Solving Eq's 10.5 as simultaneous equations gives

$$P_0 = \frac{\mu^2}{(\lambda + \mu) \cdot (\lambda + \mu)} \qquad (10.6a)$$

$$P_1 = \frac{\mu\lambda}{(\lambda + \mu) \cdot (\lambda + \mu)} \qquad (10.6b)$$

$$P_2 = \frac{\mu\lambda}{(\lambda + \mu) \cdot (\lambda + \mu)} \qquad (10.6c)$$

$$P_3 = \frac{\lambda^2}{(\lambda + \mu) \cdot (\lambda + \mu)} \qquad (10.6d)$$

Following from Eq's 10.6 the probability of the system being in a derated state i.e. any one of the two mills being down in no specific order is

$$= P_1 + P_2 = \frac{\mu\lambda}{(\lambda+\mu)\cdot(\lambda+\mu)} + \frac{\mu\lambda}{(\lambda+\mu)\cdot(\lambda+\mu)} = \frac{2\mu\lambda}{(\lambda+\mu)\cdot(\lambda+\mu)} \text{.........(10.7)}$$

Consider State 3 as the absorbing state. Then by deleting the 4th row and the 4th column, the new truncated matrix Q is

$$Q = \begin{bmatrix} (1-2\lambda) & \lambda & \lambda \\ \mu & (1-\lambda-\mu) & 0 \\ \mu & 0 & (1-\lambda-\mu) \end{bmatrix} \text{..................................(10.8)}$$

Define a new matrix $M = [I - Q]^{-1}$..................................(10.9)

$$M = \left[\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} (1-2\lambda) & \lambda & \lambda \\ \mu & (1-\lambda-\mu) & 0 \\ \mu & 0 & (1-\lambda-\mu) \end{bmatrix} \right]^{-1}$$

$$M = \begin{bmatrix} 2\lambda & -\lambda & -\lambda \\ -\mu & (\lambda+\mu) & 0 \\ -\mu & 0 & (\lambda+\mu) \end{bmatrix}^{-1}$$

Now $|I - Q| = 2\lambda^2 (\lambda+\mu)$

And

$$a_{11} = \begin{vmatrix} (\lambda+\mu) & 0 \\ 0 & (\lambda+\mu) \end{vmatrix} = (\lambda+\mu)^2$$

$$a_{12} = \begin{vmatrix} -\lambda & -\lambda \\ 0 & (\lambda+\mu) \end{vmatrix} = \lambda(\lambda+\mu)$$

$$a_{13} = \begin{vmatrix} -\lambda & -\lambda \\ (\lambda+\mu) & 0 \end{vmatrix} = \lambda(\lambda+\mu)$$

$$a_{21} = \begin{vmatrix} -\mu & 0 \\ -\mu & (\lambda+\mu) \end{vmatrix} = \mu(\lambda+\mu)$$

$$a_{22} = \begin{vmatrix} 2\lambda & -\lambda \\ -\mu & (\lambda+\mu) \end{vmatrix} = \lambda(2\lambda+\mu)$$

$$a_{23} = \begin{vmatrix} 2\lambda & -\lambda \\ -\mu & 0 \end{vmatrix} = \lambda\mu$$

$$a_{31} = \begin{vmatrix} -\mu & (\lambda+\mu) \\ -\mu & 0 \end{vmatrix} = \mu(\lambda+\mu)$$

$$a_{32} = \begin{vmatrix} 2\lambda & -\lambda \\ -\mu & 0 \end{vmatrix} = \lambda\mu$$

$$a_{33} = \begin{vmatrix} 2\lambda & -\lambda \\ -\mu & (\lambda+\mu) \end{vmatrix} = \lambda(2\lambda+\mu)$$

Therefore

$$M = \frac{1}{2\lambda^2(\lambda+\mu)}\begin{bmatrix} (\lambda+\mu) & \lambda(\lambda+\mu) & \lambda(\lambda+\mu) \\ \mu(\lambda+\mu) & \lambda(2\lambda+\mu) & \lambda\mu \\ \mu(\lambda+\mu) & \lambda\mu & \lambda(2\lambda+\mu) \end{bmatrix} \quad \text{…………….(10.10)}$$

where m_{ij} is the average time spent in state j given that the system started in state i. Therefore the average combined time spent in the fully operating and derated states is

$$= \frac{2\lambda+\mu}{2\lambda^2} \quad \text{…………………………………………………………..….(10.11)}$$

and therefore the effective failure rate of the system is

$$= \frac{2\lambda^2}{2\lambda+\mu} \quad \text{…………………………………………………………..…….(10.12)}$$

State	Rate of departure	Rate of return
0	2λ	2μ
1	$\lambda+\mu$	$\lambda+\mu$
2	$\lambda+\mu$	$\lambda+\mu$
3	2μ	2λ

Table 10.1: Departure and return rates

“The frequency of encountering a state = the probability of being in the state multiplied by the rate of departure from the state.”

$$f_0 = P_0 \times 2\lambda = \frac{2\lambda\mu^2}{(\lambda+\mu)^2} \quad \text{………………………………………...(10.13a)}$$

$$f_1 = P_1 \times (\lambda+\mu) = \frac{\lambda\mu}{(\lambda+\mu)} \quad \text{…………………………………………(10.13c)}$$

$$f_2 = P_2 \times (\lambda+\mu) = \frac{\lambda\mu}{(\lambda+\mu)} \quad \text{……………………………..……(10.13c)}$$

$$f_3 = P_3 \times 2\lambda = \frac{2\lambda^2\mu}{(\lambda+\mu)^2} \quad \text{……………………………..……(10.13d)}$$

State 3 is considered the fully failed state and therefore the mean time to repair is

$$MTTR = {}^{1}\!/_{2\mu} \quad \text{……………………………………………….…..(10.14)}$$

Mean time between failures is the sum of mean time to fail and mean time to repair

$$MTBF = MTTF + MTTR \quad \text{…………………………………..…...(10.15)}$$

10.2. 2x Primary mills in parallel – 3-state Markov process

Consider two identical primary mills configured in parallel. If the order of the mills failing is ignored then the derated state where any one of the two mills being failed can be represented as a single state and the 4x state-space diagram shown in figure 6.1 above reduces to a 3x state-space diagram as shown in figure 10.2 below.

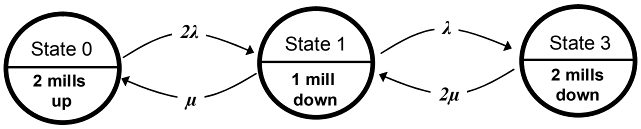

Figure 10.2: 3x State-space diagram for two mills in parallel.

The 2λ and 2μ terms indicate that two mills are available for failure and repair respectively but that only one can fail or be repaired in the next increment of time.

State 0 is the fully operational state where both mills are operational, states 1 is the derated state where any one of the two mills is down i.e. the order in which the mills go down is ignored, and state 2 is the fully failed state with both mills down. The failure and repair rates are identical for both mills.

The stochastic transitional probability matrix for the system shown in figure 10.2 is

$$P = \begin{bmatrix} (1-2\lambda) & 2\lambda & 0 \\ \mu & (1-\lambda-\mu) & \lambda \\ 0 & 2\mu & (1-2\mu) \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{.....(10.16)}$$

If $\begin{bmatrix} P_0 & P_1 & P_2 \end{bmatrix}$ is the limiting state probability vector then Eq 10.16 gives

$$\begin{bmatrix} P_0 & P_1 & P_2 \end{bmatrix} = \begin{bmatrix} P_0 & P_1 & P_2 \end{bmatrix} \cdot \begin{bmatrix} (1-2\lambda) & 2\lambda & 0 \\ \mu & (1-\lambda-\mu) & \lambda \\ 0 & 2\mu & (1-2\mu) \end{bmatrix} \ldots\ldots\ldots\text{...(10.17)}$$

which in explicit form is

$$P_0 = (1-2\lambda)P_0 + \mu P_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{.....(10.18a)}$$

$$P_1 = 2\lambda P_0 - (1+\lambda+\mu)P_1 + 2\mu P_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{..(10.18b)}$$

$$P_2 = \lambda P_1 - (1+2\mu)P_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(10.18c)}$$

Also from the laws of probability

$$P_0 + P_1 + P_2 = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(10.19)}$$

Simplifying Eq's 10.18 gives

$$-2\lambda P_0 + \mu P_1 = 0 \tag{10.20a}$$

$$2\lambda P_0 - (\lambda + \mu)P_1 + 2\mu P_2 = 0 \tag{10.20b}$$

$$\lambda P_1 - 2\mu P_2 = 0 \tag{10.20c}$$

Solving Eq's 10.20 and substituting values into Eq 10.19 gives

$$P_0 = \frac{\mu}{2\lambda} P_1 \tag{10.21a}$$

$$P_2 = \frac{\lambda}{2\mu} P_1 \tag{10.21b}$$

$$\therefore \quad \frac{\mu}{2\lambda} P_1 + P_1 + \frac{\lambda}{2\mu} P_1 = 1 \tag{10.21c}$$

$$\therefore \quad P_1 = \frac{2\lambda\ \mu}{(\lambda + \mu)\cdot(\lambda + \mu)} \tag{10.22}$$

and

$$\therefore \quad P_0 = \frac{\mu^2}{(\lambda + \mu)\cdot(\lambda + \mu)} \tag{10.23}$$

and

$$\therefore \quad P_2 = \frac{\lambda^2}{(\lambda + \mu)\cdot(\lambda + \mu)} \tag{10.24}$$

It is therefore evident that the probability of the fully operational states P_0 and the fully failed state P_2 *and* P_3 is the same for the three-state and four-state systems respectively. The probability of the derated state P_1 in the three-state system is equal to the sum of P_1 *and* P_2 of the four-state system as shown in Eq. 10.7 above.

Consider State 2 as the absorbing state. Then by deleting the 3rd row and the 3rd column, the new truncated matrix Q is

$$Q = \begin{bmatrix} (1-2\lambda) & 2\lambda \\ \mu & (1-\lambda-\mu) \end{bmatrix} \text{……………………………..………….……(10.25)}$$

Define a new matrix $M = [I-Q]^{-1}$ ………………………………..………..(10.26)

$$M = \left[\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} (1-2\lambda) & 2\lambda \\ \mu & (1-\lambda-\mu) \end{bmatrix} \right]^{-1}$$

$$M = \begin{bmatrix} 2\lambda & -2\lambda \\ -\mu & (\lambda+\mu) \end{bmatrix}^{-1}$$

Now $|I-Q| = 2\lambda^2$

And

$$a_{11} = (\lambda+\mu)$$

$$a_{12} = 2\lambda$$

$$a_{21} = \mu$$

$$a_{22} = 2\lambda$$

Therefore

$$M = \frac{1}{2\lambda^2}\begin{bmatrix} (\lambda+\mu) & 2\lambda \\ \mu & 2\lambda \end{bmatrix} \text{……………………………………………..….}(10.27)$$

where m_{ij} is the average time spent in state j given that the system started in state i. Therefore the average time spent in the fully operating and derated states is

$$= m_{12} + m_{21}$$

$$= \frac{2\lambda+\mu}{2\lambda^2} \text{……………………………………………………….…..}(10.28)$$

which is exactly the same as Eq 10.11. The effective failure rate of the system is

$$= \frac{2\lambda^2}{2\lambda+\mu} \text{………………………………………………………..…….}(10.29)$$

State	Rate of departure	Rate of return
0	2λ	μ
1	$\lambda+\mu$	$2\lambda+2\mu$
2	2μ	2μ

Table 10.2: Departure and return rates

“The frequency of encountering a state = the probability of being in the state multiplied by the rate of departure from the state.”

$$f_0 = P_0 \times 2\lambda = \frac{2\lambda\mu^2}{(\lambda+\mu)^2} \text{ ....(10.30a)}$$

$$f_1 = P_1 \times (\lambda+\mu) = \frac{2\lambda\mu}{(\lambda+\mu)} \text{ ....(10.30b)}$$

$$f_3 = P_3 \times 2\mu = \frac{2\lambda^2\mu}{(\lambda+\mu)^2} \text{ ....(10.30c)}$$

State 2 is considered the fully failed state and therefore the mean time to repair is

$$MTTR = 1/2\mu \text{ ....(10.31)}$$

Mean time between failures is the sum of mean time to fail and mean time to repair

$$MTBF = MTTF + MTTR = \frac{3\lambda+\mu}{2\lambda^2} + 1/2\mu = \frac{\lambda^2 + 3\lambda\mu + \mu^2}{2\lambda^2\mu} \text{ ....(10.32)}$$

10.3. 5x Primary mills in parallel; 4-out-of-5, 3-state Markov process

Consider five identical primary mills configured in parallel. Assume that the system is able to continue functioning if any one of the five mills is down for repairs, but that all the mills have to be stopped if more than one mill is down for repairs, then the system can be represented as a 3x state-space diagram shown in figure 10.3 below.

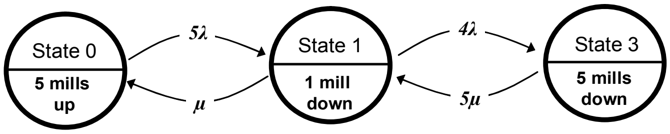

Figure 10.3: 3x State-space diagram for 4-out-of-5 mills in parallel.

The 5λ and 5μ terms indicate that five mills are available for failure and repair from states 0 and 3 respectively but that only four are available fro failure and only one can be repaired from state 1 in the next increment of time.

State 0 is the fully operational state where all five mills are operational, state 1 is the derated state where any one of the five mills is down for repairs i.e. the order in which the mills go down is ignored, and state 2 is the fully failed state with all five mills down. The failure and repair rates are identical for all mills The stochastic transitional probability matrix for the system shown in figure 10.3 is

$$P = \begin{bmatrix} (1-5\lambda) & 5\lambda & 0 \\ \mu & (1-4\lambda-\mu) & 4\lambda \\ 0 & 5\mu & (1-5\mu) \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10.33)$$

If $\begin{bmatrix} P_0 & P_1 & P_2 \end{bmatrix}$ is the limiting state probability vector then Eq 10.33 gives

$$\begin{bmatrix} P_0 & P_1 & P_2 \end{bmatrix} = \begin{bmatrix} P_0 & P_1 & P_2 \end{bmatrix} \cdot \begin{bmatrix} (1-5\lambda) & 5\lambda & 0 \\ \mu & (1-4\lambda-\mu) & 4\lambda \\ 0 & 5\mu & (1-5\mu) \end{bmatrix} \ldots\ldots\ldots(10.34)$$

which in explicit form is

$$P_0 = (1-5\lambda)P_0 + \mu P_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10.35a)$$

$$P_1 = 5\lambda P_0 - (1+4\lambda+\mu)P_1 + 5\mu P_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10.35b)$$

$$P_2 = 4\lambda P_1 - (1+5\mu)P_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10.35c)$$

Also from the laws of probability

$$P_0 + P_1 + P_2 = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10.36)$$

Simplifying Eq's 10.35 gives

$$-5\lambda P_0 + \mu P_1 = 0 \quad \text{..........(10.37a)}$$

$$5\lambda P_0 - (4\lambda + \mu)P_1 + 5\mu P_2 = 0 \quad \text{..........(10.37b)}$$

$$4\lambda P_1 - 5\mu P_2 = 0 \quad \text{..........(10.37c)}$$

Solving Eq's 10.37 and substituting values into Eq 10.36 gives

$$P_0 = \frac{\mu}{5\lambda} P_1 \quad \text{..........(10.38a)}$$

$$P_2 = \frac{4\lambda}{5\mu} P_1 \quad \text{..........(10.38b)}$$

$$\therefore \quad \frac{\mu}{5\lambda} P_1 + P_1 + \frac{\lambda}{5\mu} P_1 = 1 \quad \text{..........(10.39)}$$

$$\therefore \quad P_1 = \frac{5\lambda\mu}{(4\lambda + \mu)\cdot(\lambda + \mu)} \quad \text{..........(10.40)}$$

and

$$\therefore \quad P_0 = \frac{\mu^2}{(4\lambda + \mu)\cdot(\lambda + \mu)} \quad \text{..........(10.41)}$$

and

$$\therefore \quad P_2 = \frac{4\lambda^2}{(4\lambda + \mu)\cdot(\lambda + \mu)} \quad \text{..........(10.42)}$$

Consider State 2 as the absorbing state. Then by deleting the 3rd row and the 3rd column, the new truncated matrix Q is

$$Q = \begin{bmatrix} (1-5\lambda) & 5\lambda \\ \mu & (1-4\lambda-\mu) \end{bmatrix} \qquad \text{……………………………...…………..….(10.43)}$$

Define a new matrix $M = [I - Q]^{-1}$ …………………………………...……..(10.44)

$$M = \left[\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} (1-5\lambda) & 5\lambda \\ \mu & (1-4\lambda-\mu) \end{bmatrix} \right]^{-1}$$

$$M = \begin{bmatrix} 5\lambda & -5\lambda \\ -\mu & (4\lambda+\mu) \end{bmatrix}^{-1}$$

Now $|I - Q| = 20\lambda^2$

And

$$a_{11} = (4\lambda + \mu)$$

$$a_{12} = 5\lambda$$

$$a_{21} = \mu$$

$$a_{22} = 5\lambda$$

Therefore

$$M = \frac{1}{20\lambda^2} \begin{bmatrix} (4\lambda+\mu) & 5\lambda \\ \mu & 5\lambda \end{bmatrix} \qquad \text{……………………………….……………...….(10.45)}$$

where m_{ij} is the average time spent in state j given that the system started in state i. Therefore the average combined time spent in the fully operating and derated states is

$$= m_{12} + m_{21}$$

$$= \frac{5\lambda + \mu}{20\lambda^2} \quad \text{...(10.46)}$$

$$= \frac{20\lambda^2}{5\lambda + \mu} \quad \text{...(10.47)}$$

State	Rate of departure	Rate of return
0	5λ	μ
1	$4\lambda + \mu$	$5\lambda + 5\mu$
2	5μ	4μ

Table 10.3: Departure and return rates

“The frequency of encountering a state = the probability of being in the state multiplied by the rate of departure from the state.”

$$f_0 = P_0 \times 5\lambda = \frac{5\lambda\mu^2}{(4\lambda + \mu)(\lambda + \mu)} \quad \text{...(10.48a)}$$

$$f_1 = P_1 \times (4\lambda + \mu) = \frac{5\lambda\mu}{(\lambda+\mu)} \quad \text{……………………………………….(10.48b)}$$

$$f_2 = P_2 \times 5\mu = \frac{20\lambda^2\mu}{(4\lambda+\mu)(\lambda+\mu)} \quad \text{……………………………..….(10.48c)}$$

State 2 is considered the fully failed state and therefore the mean time to repair is

$$MTTR = {1}/{5\mu} \quad \text{……………………………………………….…..(10.49)}$$

Mean time between failures is the sum of mean time to fail and mean time to repair

$$MTBF = MTTF + MTTR = \frac{9\lambda+\mu}{20\lambda^2} + {1}/{5\mu} = \frac{4\lambda^2 + 9\lambda\mu + \mu^2}{20\lambda^2\mu} \quad \text{……..(10.50)}$$

10.4. 5x Primary mills in parallel; 3-out-of-5, 3-state Markov process

Consider five identical primary mills configured in parallel. Assume that the system is able to continue functioning if any two of the five mills are down for repairs, but that all the mills have to be stopped if more than two mills are down for repairs, then the system can be represented as a 3x state-space diagram shown in figure 10.4 below.

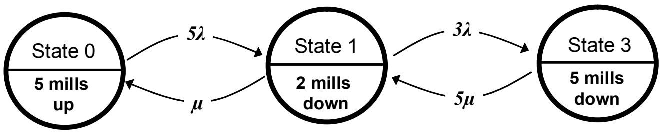

Figure 10.4: 3x State-space diagram for 3-out-of-5 mills in parallel.

The 5λ and 5μ terms indicate that five mills are available for failure and repair from states 0 and 3 respectively but that only three are available for failure and only one can fail or be repaired from state 1 in the next increment of time.

State 0 is the fully operational state where all five mills are operational, state 1 is the derated state where any two of the five mills are down for repairs i.e. the order in which the mills go down is ignored, and state 2 is the fully failed state with all five mills down. The failure and repair rates are identical for all mills

The stochastic transitional probability matrix for the system shown in figure 10.4 is

$$P = \begin{bmatrix} (1-5\lambda) & 5\lambda & 0 \\ 2\mu & (1-3\lambda-2\mu) & 3\lambda \\ 0 & 5\mu & (1-5\mu) \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots(10.51)$$

If $\lfloor P_0 \quad P_1 \quad P_2 \rfloor$ is the limiting state probability vector then Eq 10.51 gives

$$[P_0 \quad P_1 \quad P_2] = [P_0 \quad P_1 \quad P_2] \cdot \begin{bmatrix} (1-5\lambda) & 5\lambda & 0 \\ 2\mu & (1-3\lambda-2\mu) & 3\lambda \\ 0 & 5\mu & (1-5\mu) \end{bmatrix} \ldots\ldots(10.52)$$

which in explicit form is

$$P_0 = (1-5\lambda)P_0 + 2\mu P_1 \ldots\ldots\ldots\ldots\ldots\ldots(10.53a)$$

$$P_1 = 5\lambda P_0 - (1+3\lambda+2\mu)P_1 + 5\mu P_2 \ldots\ldots\ldots\ldots\ldots\ldots(10.53b)$$

$$P_2 = 3\lambda P_1 - (1+5\mu)P_2 \ldots\ldots\ldots\ldots\ldots\ldots(10.53c)$$

Also from the laws of probability

$$P_0 + P_1 + P_2 = 1 \ldots\ldots\ldots\ldots\ldots\ldots(10.54)$$

Simplifying Eq's 10.53 gives

$$-5\lambda P_0 + 2\mu P_1 = 0 \quad \text{....(10.55a)}$$

$$5\lambda P_0 - (3\lambda + 2\mu)P_1 + 5\mu P_2 = 0 \quad \text{....(10.55b)}$$

$$3\lambda P_1 - 5\mu P_2 = 0 \quad \text{....(10.55c)}$$

Solving Eq's 10.55 and substituting values into Eq 10.54 gives

$$P_0 = \frac{2\mu}{5\lambda} P_1 \quad \text{....(10.56a)}$$

$$P_2 = \frac{3\lambda}{5\mu} P_1 \quad \text{....(10.56b)}$$

$$\therefore \quad \frac{2\mu}{5\lambda} P_1 + P_1 + \frac{3\lambda}{5\mu} P_1 = 1 \quad \text{....(10.57)}$$

$$\therefore \quad P_1 = \frac{5\lambda\mu}{(3\lambda + 2\mu)\cdot(\lambda + \mu)} \quad \text{....(10.58)}$$

and

$$\therefore \quad P_0 = \frac{2\mu^2}{(3\lambda + 2\mu)\cdot(\lambda + \mu)} \quad \text{....(10.59)}$$

and

$$\therefore \quad P_2 = \frac{3\lambda^2}{(3\lambda + 2\mu)\cdot(\lambda + \mu)} \quad \text{....(10.60)}$$

Consider State 2 as the absorbing state. Then by deleting the 3rd row and the 3rd column, the new truncated matrix Q is

$$Q = \begin{bmatrix} (1-5\lambda) & 5\lambda \\ 2\mu & (1-3\lambda-2\mu) \end{bmatrix} \qquad (10.61)$$

Define a new matrix $M = [I - Q]^{-1}$ ……………………………..……..(10.62)

$$M = \left[\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} (1-5\lambda) & 5\lambda \\ 2\mu & (1-3\lambda-2\mu) \end{bmatrix} \right]^{-1}$$

$$M = \begin{bmatrix} 5\lambda & -5\lambda \\ -2\mu & (3\lambda+2\mu) \end{bmatrix}^{-1}$$

Now $|I - Q| = 15\lambda^2$

And

$$a_{11} = (3\lambda + 2\mu)$$

$$a_{12} = 5\lambda$$

$$a_{21} = 2\mu$$

$$a_{22} = 5\lambda$$

Therefore

$$M = \frac{1}{15\lambda^2} \begin{bmatrix} (3\lambda+2\mu) & 5\lambda \\ 2\mu & 5\lambda \end{bmatrix} \qquad (10.63)$$

where m_{ij} is the average time spent in state j given that the system started in state i. Therefore the average combined time spent in the fully operating and derated states is

$$= m_{12} + m_{21} = MTTF$$

$$= \frac{5\lambda + 2\mu}{15\lambda^2} \qquad \text{(10.64)}$$

and hence the effective failure rate is

$$= \frac{15\lambda^2}{5\lambda + 2\mu} \qquad \text{(10.65)}$$

State	Rate of departure	Rate of return
0	5λ	2μ
1	$3\lambda + 2\mu$	$5\lambda + 5\mu$
2	5μ	3λ

Table 10.4: Departure and return rates

“The frequency of encountering a state = the probability of being in the state multiplied by the rate of departure from the state.”

$$f_0 = P_0 \times 5\lambda = \frac{10\lambda\mu^2}{(3\lambda + 2\mu)(\lambda + \mu)} \quad \text{..(10.66a)}$$

$$f_1 = P_1 \times (3\lambda + 2\mu) = \frac{5\lambda\mu}{(\lambda + \mu)} \quad \text{..(10.66b)}$$

$$f_2 = P_2 \times 5\mu = \frac{15\lambda^2\mu}{(3\lambda + 2\mu)(\lambda + \mu)} \quad \text{.......................................(10.67)}$$

State 2 is considered the fully failed state and therefore the mean time to repair is

$$MTTR = {}^{1}\!/_{5\mu} \quad \text{..(10.68)}$$

Mean time between failures is the sum of mean time to fail and mean time to repair

$$MTBF = MTTF + MTTR \quad \text{..(10.69)}$$

Considering the form of the 3-state probability expressions derived for the different numbers of mills with different partial redundancy states above it is now possible to derive a general expression for 3-state m-out-of-n primary mill installations by means of informal induction.

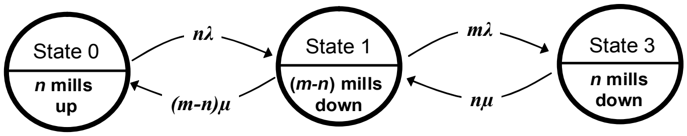

Figure 10.5: State-space diagram for 3-state, m-out-of-n parallel System

Therefore, by means of informal induction, in general

$$\therefore\ P_0 = \frac{(n-m)\mu^2}{[m\lambda+(n-m)\mu]\cdot[\lambda+\mu]} \quad \ldots\ldots(10.70)$$

and

$$\therefore\ P_1 = \frac{n\lambda\mu}{[m\lambda+(n-m)\mu]\cdot[\lambda+\mu]} \quad \ldots\ldots(10.71)$$

and

$$\therefore \quad P_2 = \frac{m\lambda^2}{\left[m\lambda + (n-m)\mu\right] \cdot \left[\lambda + \mu\right]} \qquad \text{……………………………..………..(10.72)}$$

Where

λ = failure rate

μ =repair rate

n = total number of mills configured in parallel

m = minimum number of mills that must be operational to prevent all the mills from having to be stopped

P_0 = Probability of all the mills operating

P_1 = Probability of $m\text{-}out\text{-}of\text{-}n$ mills being operational i.e. derated state

P_2 = Probability of all the mills being failed or stopped.

Furthermore in general for the 3-state system, assuming that states 0 and 1 are considered for system success, then the mean time to failure is

$$MTTF = \frac{n\lambda + (n-m)\mu}{nm\lambda^2} \qquad \text{……………………………………..….(10.73)}$$

and hence the effective failure rate is

$$= \frac{nm\lambda^2}{n\lambda + (n-m)\mu} \qquad \text{…………………………………………..…….(10.74)}$$

State	Rate of departure	Rate of return
0	$n\lambda$	$(n-m)\mu$
1	$m\lambda+(n-m)\mu$	$n\lambda+n\mu$
2	$n\mu$	$m\lambda$

Table 10.5: General expressions for departure and return rates

"*The frequency of encountering a state = the probability of being in the state multiplied by the rate of departure from the state.*"

$$f_0 = P_0 \times n\lambda = \frac{n(n-m)\lambda\mu^2}{[m\lambda+(n-m)\mu][\lambda+\mu]} \quad \text{.................................(10.75a)}$$

$$f_1 = P_1 \times [m\lambda+(n-m)\mu] = \frac{n\lambda\mu}{(\lambda+\mu)} \quad \text{....................................(10.75b)}$$

$$f_2 = P_2 \times n\mu = \frac{nm\lambda^2\mu}{[m\lambda+(n-m)\mu][\lambda+\mu]} \quad \text{...................................(10.75c)}$$

State 2 is considered the fully failed state and therefore the mean time to repair is

$$MTTR = {}^{1}\!/_{n\mu} \quad \text{..(10.76)}$$

Mean time between failures is the sum of mean time to fail and mean time to repair

$$MTBF = MTTF + MTTR \qquad (10.77)$$

11. APPENDIX 4 Visual Basic® code for recording mill downtime data in Microsoft Excel®

```
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'
'Program to insert mill downtime information into matrix format
'Created and Developed by Mark Greyling and Duane Muller
'14 March 2004
'
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

Private Sub CommandButton2_Click()
'Make Entry


Dim Response As Variant
 Response = MsgBox("Are you sure this entry does not already exist? Have you correctly completed the duration times, mill no. selection, and Stoppage category selection?", vbYesNo)
 If Response = vbYes Then


If CheckBox1.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 1")
 Call Populate_Matrix
End If
If CheckBox2.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 2")
 Call Populate_Matrix
End If
If CheckBox3.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 3")
 Call Populate_Matrix
End If
If CheckBox4.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 4")
 Call Populate_Matrix
End If
If CheckBox5.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 5")
 Call Populate_Matrix
End If
If CheckBox6.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 6")
 Call Populate_Matrix
End If
If CheckBox7.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 7")
 Call Populate_Matrix
End If
If CheckBox8.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 8")
 Call Populate_Matrix
End If
If CheckBox9.Value = True Then
 Get_Position_To_Start_Populate ("Primary Mill No. 9")
 Call Populate_Matrix
End If
```

```
If CheckBox10.Value = True Then
  Get_Position_To_Start_Populate ("Primary Mill No. 10")
  Call Populate_Matrix
End If
If CheckBox11.Value = True Then
  Get_Position_To_Start_Populate ("Primary Mill No. 11")
  Call Populate_Matrix
End If
If CheckBox12.Value = True Then
  Get_Position_To_Start_Populate ("Primary Mill No. 12")
  Call Populate_Matrix
End If
If CheckBox13.Value = True Then
  Get_Position_To_Start_Populate ("Primary Mill No. 13")
  Call Populate_Matrix
End If
If CheckBox14.Value = True Then
  Get_Position_To_Start_Populate ("Primary Mill No. 14")
  Call Populate_Matrix
End If
If CheckBox15.Value = True Then
  Get_Position_To_Start_Populate ("Primary Mill No. 15")
  Call Populate_Matrix
End If
End If
End Sub

Private Sub CommandButton3_Click()
Dim Response As Variant
  Response = MsgBox("Are You Sure You Want To Exit?", vbYesNo)
  If Response = vbYes Then
   MillDowntimeInput.Hide

  End If
End Sub

Private Sub Label1_Click()

End Sub

Private Sub TextBox1_Change()

End Sub

Private Sub UserForm_Initialize()
'Fill the date & time input boxes with the last entries when re-opening the file
With Worksheets("Mill Downtime Matrix")
.Range("ha1").Value = TextBox2.Value
.Range("hb1").Value = TextBox3.Value
.Range("hc1").Value = TextBox4.Value
.Range("hd1").Value = TextBox5.Value
.Range("he1").Value = TextBox6.Value
.Range("hf1").Value = TextBox7.Value
.Range("hg1").Value = TextBox8.Value
.Range("hh1").Value = TextBox9.Value
```

```
.Range("hi1").Value = TextBox10.Value
.Range("hj1").Value = TextBox11.Value
End With

'Initialize the combobox
If ComboBox1.ListCount <> 0 Then
 ComboBox1.Clear
End If

  ComboBox1.AddItem "Planned Maintenance Shutdown(incl relining)" 'ListIndex = 0
  ComboBox1.AddItem "Ore Shortage"                     'ListIndex = 1
  ComboBox1.AddItem "Mill feed conveyor breakdown"          'ListIndex = 2
  ComboBox1.AddItem "Mill lubrication breakdown"          'ListIndex = 3
  ComboBox1.AddItem "Major mill mechanical breakdown"         'ListIndex = 4
  ComboBox1.AddItem "Downstream pumping/piping breakdown"         'ListIndex = 5
  ComboBox1.AddItem "Downstream process equipment breakdown"       'ListIndex = 6
  ComboBox1.AddItem "Electrical trip or outage"         'ListIndex = 7
  ComboBox1.AddItem "PLC/Scada network failure"            'ListIndex = 8
  ComboBox1.AddItem "Water shortage"                   'ListIndex = 9
  ComboBox1.AddItem "Other"                        'List Index = 10
  'Use drop-down list
  ComboBox1.Style = fmStyleDropDownList
  'Combo box values are ListIndex values
  ComboBox1.BoundColumn = 0



End Sub

Private Sub ComboBox1_Click()
  Select Case ComboBox1.Value
  Case 0  'Planned Maintenance Shutdown(incl relining)
    CommandButton1.Caption = "PM"


  Case 1  'Ore Shortage
    CommandButton1.Caption = "OS"

  Case 2  'Mill feed conveyor breakdown
    CommandButton1.Caption = "FC"


  Case 3  'Mill lubrication breakdown
    CommandButton1.Caption = "L"


  Case 4  'Major mill mechanical breakdown
    CommandButton1.Caption = "M"


  Case 5  'Downstream pumping/piping breakdown
    CommandButton1.Caption = "PP"


  Case 6  'Downstream process equipment breakdown
```

```
        CommandButton1.Caption = "PE"


    Case 7  'Electrical trip or outage
        CommandButton1.Caption = "E"


    Case 8  'PLC/Scada network failure
        CommandButton1.Caption = "PLC"


    Case 9  'Water shortage
        CommandButton1.Caption = "W"


    Case 10 'Other
        CommandButton1.Caption = "O"


    End Select



End Sub




Sub Get_Position_To_Start_Populate(LookupString As Variant)

Worksheets("Mill Downtime Matrix").Activate
Sheets("Mill Downtime Matrix").Select
Sheets("Mill Downtime Matrix").Range("A1").Select

    Set c = Sheets("Mill Downtime Matrix").Cells.Find(What:=LookupString, _
            After:=ActiveCell, LookIn:=xlFormulas, LookAt:=xlPart, _
            SearchOrder:=xlByColumns, SearchDirection:=xlNext, MatchCase:=True)
      If c = 0 Or c Is Nothing Then
       MsgBox ("This Mill Has Not Been Included In The Matrix")
      Else
       Sheets("Mill Downtime Matrix").Cells.Find(What:=LookupString, _
       After:=ActiveCell, LookIn:=xlValues, LookAt:=xlWhole, SearchOrder:=xlByColumns, _
       SearchDirection:=xlNext, MatchCase:=True).Activate
      End If

End Sub




Sub Populate_Matrix()

Do
  ActiveCell.Offset(1, 0).Select
  i = i + 1
```

```
Loop Until ActiveCell.Text = ""

ActiveCell.Value = MillDowntimeInput.TextBox2.Value
ActiveCell.Offset(0, 1).Value = MillDowntimeInput.TextBox3.Value
ActiveCell.Offset(0, 2).Value = MillDowntimeInput.TextBox4.Value
ActiveCell.Offset(0, 3).Value = MillDowntimeInput.TextBox5.Value
ActiveCell.Offset(0, 4).Value = MillDowntimeInput.TextBox6.Value
ActiveCell.Offset(0, 5).Value = MillDowntimeInput.TextBox7.Value
ActiveCell.Offset(0, 6).Value = MillDowntimeInput.TextBox8.Value
ActiveCell.Offset(0, 7).Value = MillDowntimeInput.TextBox9.Value
ActiveCell.Offset(0, 8).Value = MillDowntimeInput.TextBox10.Value
ActiveCell.Offset(0, 9).Value = MillDowntimeInput.TextBox11.Value

ActiveCell.Offset(0, 10).Value = DateDiff("n", ActiveCell.Value & "/" _
& ActiveCell.Offset(0, 1).Value & "/" & ActiveCell.Offset(0, 2).Value & " " _
& ActiveCell.Offset(0, 3).Value & ":" & ActiveCell.Offset(0, 4).Value, _
ActiveCell.Offset(0, 5).Value & "/" & ActiveCell.Offset(0, 6).Value & _
"/" & ActiveCell.Offset(0, 7).Value & " " & ActiveCell.Offset(0, 8).Value & _
":" & ActiveCell.Offset(0, 9).Value)

ActiveCell.Offset(0, 11).Value = MillDowntimeInput.CommandButton1.Caption
End Sub



Sub SortPM()
'
' SortPM Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

  If Range("M526").Cells(i) = "PM" Then

    temp1 = Range("M526").Cells(i).Offset(0, -12).Value
    temp2 = Range("M526").Cells(i).Offset(0, -11).Value
    temp3 = Range("M526").Cells(i).Offset(0, -10).Value
    temp4 = Range("M526").Cells(i).Offset(0, -9).Value
    temp5 = Range("M526").Cells(i).Offset(0, -8).Value
    temp6 = Range("M526").Cells(i).Offset(0, -7).Value
    temp7 = Range("M526").Cells(i).Offset(0, -6).Value
    temp8 = Range("M526").Cells(i).Offset(0, -5).Value
    temp9 = Range("M526").Cells(i).Offset(0, -4).Value
    temp10 = Range("M526").Cells(i).Offset(0, -3).Value
    temp11 = Range("M526").Cells(i).Offset(0, -2).Value
    temp12 = Range("M526").Cells(i).Offset(0, -1).Value
    temp13 = Range("M526").Cells(i).Offset(0, 0).Value
```

```
     Sheets("Mill 1 Analysis").Range("T4").Select

        X = X + 1

        ActiveCell.Offset(X, 0).Select

        ActiveCell.Value = temp1
        ActiveCell.Offset(0, 1).Value = temp2
        ActiveCell.Offset(0, 2).Value = temp3
        ActiveCell.Offset(0, 3).Value = temp4
        ActiveCell.Offset(0, 4).Value = temp5
        ActiveCell.Offset(0, 5).Value = temp6
        ActiveCell.Offset(0, 6).Value = temp7
        ActiveCell.Offset(0, 7).Value = temp8
        ActiveCell.Offset(0, 8).Value = temp9
        ActiveCell.Offset(0, 9).Value = temp10
        ActiveCell.Offset(0, 10).Value = temp11
        ActiveCell.Offset(0, 11).Value = temp12
        ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i

End Sub




Public Sub SortOS()
'
' SortOS Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

    If Range("M526").Cells(i) = "OS" Then

      temp1 = Range("M526").Cells(i).Offset(0, -12).Value
      temp2 = Range("M526").Cells(i).Offset(0, -11).Value
      temp3 = Range("M526").Cells(i).Offset(0, -10).Value
      temp4 = Range("M526").Cells(i).Offset(0, -9).Value
      temp5 = Range("M526").Cells(i).Offset(0, -8).Value
      temp6 = Range("M526").Cells(i).Offset(0, -7).Value
      temp7 = Range("M526").Cells(i).Offset(0, -6).Value
      temp8 = Range("M526").Cells(i).Offset(0, -5).Value
      temp9 = Range("M526").Cells(i).Offset(0, -4).Value
      temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
      temp11 = Range("M526").Cells(i).Offset(0, -2).Value
      temp12 = Range("M526").Cells(i).Offset(0, -1).Value
      temp13 = Range("M526").Cells(i).Offset(0, 0).Value

     Sheets("Mill 1 Analysis").Range("AH4").Select

       X = X + 1

       ActiveCell.Offset(X, 0).Select

       ActiveCell.Value = temp1
       ActiveCell.Offset(0, 1).Value = temp2
       ActiveCell.Offset(0, 2).Value = temp3
       ActiveCell.Offset(0, 3).Value = temp4
       ActiveCell.Offset(0, 4).Value = temp5
       ActiveCell.Offset(0, 5).Value = temp6
       ActiveCell.Offset(0, 6).Value = temp7
       ActiveCell.Offset(0, 7).Value = temp8
       ActiveCell.Offset(0, 8).Value = temp9
       ActiveCell.Offset(0, 9).Value = temp10
       ActiveCell.Offset(0, 10).Value = temp11
       ActiveCell.Offset(0, 11).Value = temp12
       ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i
End Sub

Public Sub SortFC()
'
' SortFC Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

    If Range("M526").Cells(i) = "FC" Then

      temp1 = Range("M526").Cells(i).Offset(0, -12).Value
      temp2 = Range("M526").Cells(i).Offset(0, -11).Value
      temp3 = Range("M526").Cells(i).Offset(0, -10).Value
      temp4 = Range("M526").Cells(i).Offset(0, -9).Value
      temp5 = Range("M526").Cells(i).Offset(0, -8).Value
      temp6 = Range("M526").Cells(i).Offset(0, -7).Value
      temp7 = Range("M526").Cells(i).Offset(0, -6).Value
      temp8 = Range("M526").Cells(i).Offset(0, -5).Value
      temp9 = Range("M526").Cells(i).Offset(0, -4).Value
      temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
   temp11 = Range("M5").Cells(i).Offset(0, -2).Value
   temp12 = Range("M526").Cells(i).Offset(0, -1).Value
   temp13 = Range("M526").Cells(i).Offset(0, 0).Value

  Sheets("Mill 1 Analysis").Range("AV4").Select

    X = X + 1

    ActiveCell.Offset(X, 0).Select

    ActiveCell.Value = temp1
    ActiveCell.Offset(0, 1).Value = temp2
    ActiveCell.Offset(0, 2).Value = temp3
    ActiveCell.Offset(0, 3).Value = temp4
    ActiveCell.Offset(0, 4).Value = temp5
    ActiveCell.Offset(0, 5).Value = temp6
    ActiveCell.Offset(0, 6).Value = temp7
    ActiveCell.Offset(0, 7).Value = temp8
    ActiveCell.Offset(0, 8).Value = temp9
    ActiveCell.Offset(0, 9).Value = temp10
    ActiveCell.Offset(0, 10).Value = temp11
    ActiveCell.Offset(0, 11).Value = temp12
    ActiveCell.Offset(0, 12).Value = temp13

  End If

Next i
End Sub

Public Sub SortM()
'
' SortM Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

  If Range("M526").Cells(i) = "M" Then

   temp1 = Range("M526").Cells(i).Offset(0, -12).Value
   temp2 = Range("M526").Cells(i).Offset(0, -11).Value
   temp3 = Range("M526").Cells(i).Offset(0, -10).Value
   temp4 = Range("M526").Cells(i).Offset(0, -9).Value
   temp5 = Range("M526").Cells(i).Offset(0, -8).Value
   temp6 = Range("M526").Cells(i).Offset(0, -7).Value
   temp7 = Range("M526").Cells(i).Offset(0, -6).Value
   temp8 = Range("M526").Cells(i).Offset(0, -5).Value
   temp9 = Range("M526").Cells(i).Offset(0, -4).Value
   temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
      temp11 = Range("M526").Cells(i).Offset(0, -2).Value
      temp12 = Range("M526").Cells(i).Offset(0, -1).Value
      temp13 = Range("M526").Cells(i).Offset(0, 0).Value

     Sheets("Mill 1 Analysis").Range("BJ4").Select

       X = X + 1

       ActiveCell.Offset(X, 0).Select

       ActiveCell.Value = temp1
       ActiveCell.Offset(0, 1).Value = temp2
       ActiveCell.Offset(0, 2).Value = temp3
       ActiveCell.Offset(0, 3).Value = temp4
       ActiveCell.Offset(0, 4).Value = temp5
       ActiveCell.Offset(0, 5).Value = temp6
       ActiveCell.Offset(0, 6).Value = temp7
       ActiveCell.Offset(0, 7).Value = temp8
       ActiveCell.Offset(0, 8).Value = temp9
       ActiveCell.Offset(0, 9).Value = temp10
       ActiveCell.Offset(0, 10).Value = temp11
       ActiveCell.Offset(0, 11).Value = temp12
       ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i
End Sub

Public Sub SortPP()
'
' SortPP Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

    If Range("M526").Cells(i) = "PP" Then

      temp1 = Range("M526").Cells(i).Offset(0, -12).Value
      temp2 = Range("M526").Cells(i).Offset(0, -11).Value
      temp3 = Range("M526").Cells(i).Offset(0, -10).Value
      temp4 = Range("M526").Cells(i).Offset(0, -9).Value
      temp5 = Range("M526").Cells(i).Offset(0, -8).Value
      temp6 = Range("M526").Cells(i).Offset(0, -7).Value
      temp7 = Range("M526").Cells(i).Offset(0, -6).Value
      temp8 = Range("M526").Cells(i).Offset(0, -5).Value
      temp9 = Range("M526").Cells(i).Offset(0, -4).Value
      temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
   temp11 = Range("M526").Cells(i).Offset(0, -2).Value
   temp12 = Range("M526").Cells(i).Offset(0, -1).Value
   temp13 = Range("M526").Cells(i).Offset(0, 0).Value

  Sheets("Mill 1 Analysis").Range("BX4").Select

    X = X + 1

    ActiveCell.Offset(X, 0).Select

    ActiveCell.Value = temp1
    ActiveCell.Offset(0, 1).Value = temp2
    ActiveCell.Offset(0, 2).Value = temp3
    ActiveCell.Offset(0, 3).Value = temp4
    ActiveCell.Offset(0, 4).Value = temp5
    ActiveCell.Offset(0, 5).Value = temp6
    ActiveCell.Offset(0, 6).Value = temp7
    ActiveCell.Offset(0, 7).Value = temp8
    ActiveCell.Offset(0, 8).Value = temp9
    ActiveCell.Offset(0, 9).Value = temp10
    ActiveCell.Offset(0, 10).Value = temp11
    ActiveCell.Offset(0, 11).Value = temp12
    ActiveCell.Offset(0, 12).Value = temp13

  End If

Next i
End Sub

Public Sub SortPE()
'
' SortPE Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

  If Range("M526").Cells(i) = "PE" Then

   temp1 = Range("M526").Cells(i).Offset(0, -12).Value
   temp2 = Range("M526").Cells(i).Offset(0, -11).Value
   temp3 = Range("M526").Cells(i).Offset(0, -10).Value
   temp4 = Range("M526").Cells(i).Offset(0, -9).Value
   temp5 = Range("M526").Cells(i).Offset(0, -8).Value
   temp6 = Range("M526").Cells(i).Offset(0, -7).Value
   temp7 = Range("M526").Cells(i).Offset(0, -6).Value
   temp8 = Range("M526").Cells(i).Offset(0, -5).Value
   temp9 = Range("M526").Cells(i).Offset(0, -4).Value
   temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
      temp11 = Range("M526").Cells(i).Offset(0, -2).Value
      temp12 = Range("M526").Cells(i).Offset(0, -1).Value
      temp13 = Range("M526").Cells(i).Offset(0, 0).Value

     Sheets("Mill 1 Analysis").Range("CL4").Select

       X = X + 1

       ActiveCell.Offset(X, 0).Select

       ActiveCell.Value = temp1
       ActiveCell.Offset(0, 1).Value = temp2
       ActiveCell.Offset(0, 2).Value = temp3
       ActiveCell.Offset(0, 3).Value = temp4
       ActiveCell.Offset(0, 4).Value = temp5
       ActiveCell.Offset(0, 5).Value = temp6
       ActiveCell.Offset(0, 6).Value = temp7
       ActiveCell.Offset(0, 7).Value = temp8
       ActiveCell.Offset(0, 8).Value = temp9
       ActiveCell.Offset(0, 9).Value = temp10
       ActiveCell.Offset(0, 10).Value = temp11
       ActiveCell.Offset(0, 11).Value = temp12
       ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i
End Sub

Public Sub SortE()
'
' SortE Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

    If Range("M526").Cells(i) = "E" Then

      temp1 = Range("M526").Cells(i).Offset(0, -12).Value
      temp2 = Range("M526").Cells(i).Offset(0, -11).Value
      temp3 = Range("M526").Cells(i).Offset(0, -10).Value
      temp4 = Range("M526").Cells(i).Offset(0, -9).Value
      temp5 = Range("M526").Cells(i).Offset(0, -8).Value
      temp6 = Range("M526").Cells(i).Offset(0, -7).Value
      temp7 = Range("M526").Cells(i).Offset(0, -6).Value
      temp8 = Range("M526").Cells(i).Offset(0, -5).Value
      temp9 = Range("M526").Cells(i).Offset(0, -4).Value
      temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
      temp11 = Range("M526").Cells(i).Offset(0, -2).Value
      temp12 = Range("M526").Cells(i).Offset(0, -1).Value
      temp13 = Range("M526").Cells(i).Offset(0, 0).Value

     Sheets("Mill 1 Analysis").Range("CZ4").Select

       X = X + 1

       ActiveCell.Offset(X, 0).Select

       ActiveCell.Value = temp1
       ActiveCell.Offset(0, 1).Value = temp2
       ActiveCell.Offset(0, 2).Value = temp3
       ActiveCell.Offset(0, 3).Value = temp4
       ActiveCell.Offset(0, 4).Value = temp5
       ActiveCell.Offset(0, 5).Value = temp6
       ActiveCell.Offset(0, 6).Value = temp7
       ActiveCell.Offset(0, 7).Value = temp8
       ActiveCell.Offset(0, 8).Value = temp9
       ActiveCell.Offset(0, 9).Value = temp10
       ActiveCell.Offset(0, 10).Value = temp11
       ActiveCell.Offset(0, 11).Value = temp12
       ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i
End Sub

Public Sub SortPLC()
'
' SortPLC Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

    If Range("M526").Cells(i) = "PLC" Then

      temp1 = Range("M526").Cells(i).Offset(0, -12).Value
      temp2 = Range("M526").Cells(i).Offset(0, -11).Value
      temp3 = Range("M526").Cells(i).Offset(0, -10).Value
      temp4 = Range("M526").Cells(i).Offset(0, -9).Value
      temp5 = Range("M526").Cells(i).Offset(0, -8).Value
      temp6 = Range("M526").Cells(i).Offset(0, -7).Value
      temp7 = Range("M526").Cells(i).Offset(0, -6).Value
      temp8 = Range("M526").Cells(i).Offset(0, -5).Value
      temp9 = Range("M526").Cells(i).Offset(0, -4).Value
      temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
      temp11 = Range("M526").Cells(i).Offset(0, -2).Value
      temp12 = Range("M526").Cells(i).Offset(0, -1).Value
      temp13 = Range("M526").Cells(i).Offset(0, 0).Value

     Sheets("Mill 1 Analysis").Range("DN4").Select

        X = X + 1

        ActiveCell.Offset(X, 0).Select

        ActiveCell.Value = temp1
        ActiveCell.Offset(0, 1).Value = temp2
        ActiveCell.Offset(0, 2).Value = temp3
        ActiveCell.Offset(0, 3).Value = temp4
        ActiveCell.Offset(0, 4).Value = temp5
        ActiveCell.Offset(0, 5).Value = temp6
        ActiveCell.Offset(0, 6).Value = temp7
        ActiveCell.Offset(0, 7).Value = temp8
        ActiveCell.Offset(0, 8).Value = temp9
        ActiveCell.Offset(0, 9).Value = temp10
        ActiveCell.Offset(0, 10).Value = temp11
        ActiveCell.Offset(0, 11).Value = temp12
        ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i
End Sub

Public Sub SortW()
'
' SortW Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

    If Range("M526").Cells(i) = "W" Then

      temp1 = Range("M526").Cells(i).Offset(0, -12).Value
      temp2 = Range("M526").Cells(i).Offset(0, -11).Value
      temp3 = Range("M526").Cells(i).Offset(0, -10).Value
      temp4 = Range("M526").Cells(i).Offset(0, -9).Value
      temp5 = Range("M526").Cells(i).Offset(0, -8).Value
      temp6 = Range("M526").Cells(i).Offset(0, -7).Value
      temp7 = Range("M526").Cells(i).Offset(0, -6).Value
      temp8 = Range("M526").Cells(i).Offset(0, -5).Value
      temp9 = Range("M526").Cells(i).Offset(0, -4).Value
      temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
      temp11 = Range("M526").Cells(i).Offset(0, -2).Value
      temp12 = Range("M526").Cells(i).Offset(0, -1).Value
      temp13 = Range("M526").Cells(i).Offset(0, 0).Value

     Sheets("Mill 1 Analysis").Range("EB4").Select

       X = X + 1

       ActiveCell.Offset(X, 0).Select

       ActiveCell.Value = temp1
       ActiveCell.Offset(0, 1).Value = temp2
       ActiveCell.Offset(0, 2).Value = temp3
       ActiveCell.Offset(0, 3).Value = temp4
       ActiveCell.Offset(0, 4).Value = temp5
       ActiveCell.Offset(0, 5).Value = temp6
       ActiveCell.Offset(0, 6).Value = temp7
       ActiveCell.Offset(0, 7).Value = temp8
       ActiveCell.Offset(0, 8).Value = temp9
       ActiveCell.Offset(0, 9).Value = temp10
       ActiveCell.Offset(0, 10).Value = temp11
       ActiveCell.Offset(0, 11).Value = temp12
       ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i
End Sub

Public Sub SortO()
'
' SortO Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

    If Range("M526").Cells(i) = "O" Then

      temp1 = Range("M526").Cells(i).Offset(0, -12).Value
      temp2 = Range("M526").Cells(i).Offset(0, -11).Value
      temp3 = Range("M526").Cells(i).Offset(0, -10).Value
      temp4 = Range("M526").Cells(i).Offset(0, -9).Value
      temp5 = Range("M526").Cells(i).Offset(0, -8).Value
      temp6 = Range("M526").Cells(i).Offset(0, -7).Value
      temp7 = Range("M526").Cells(i).Offset(0, -6).Value
      temp8 = Range("M526").Cells(i).Offset(0, -5).Value
      temp9 = Range("M526").Cells(i).Offset(0, -4).Value
      temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
   temp11 = Range("M526").Cells(i).Offset(0, -2).Value
   temp12 = Range("M526").Cells(i).Offset(0, -1).Value
   temp13 = Range("M526").Cells(i).Offset(0, 0).Value

  Sheets("Mill 1 Analysis").Range("EP4").Select

    X = X + 1

    ActiveCell.Offset(X, 0).Select

    ActiveCell.Value = temp1
    ActiveCell.Offset(0, 1).Value = temp2
    ActiveCell.Offset(0, 2).Value = temp3
    ActiveCell.Offset(0, 3).Value = temp4
    ActiveCell.Offset(0, 4).Value = temp5
    ActiveCell.Offset(0, 5).Value = temp6
    ActiveCell.Offset(0, 6).Value = temp7
    ActiveCell.Offset(0, 7).Value = temp8
    ActiveCell.Offset(0, 8).Value = temp9
    ActiveCell.Offset(0, 9).Value = temp10
    ActiveCell.Offset(0, 10).Value = temp11
    ActiveCell.Offset(0, 11).Value = temp12
    ActiveCell.Offset(0, 12).Value = temp13

  End If

Next i
End Sub

Public Sub SortL()
'
' SortL Macro
' Macro recorded 11/16/2004 by mgreyling
'
Dim temp1, temp2, temp3, temp4, temp5, temp6, temp7, temp8, _
temp9, temp10, temp11, temp12, temp13
Dim i As Integer
Dim X As Integer

Sheets("Mill 1 Analysis").Range("M526").Cells.Select

For i = 1 To 514

  If Range("M526").Cells(i) = "O" Then

   temp1 = Range("M526").Cells(i).Offset(0, -12).Value
   temp2 = Range("M526").Cells(i).Offset(0, -11).Value
   temp3 = Range("M526").Cells(i).Offset(0, -10).Value
   temp4 = Range("M526").Cells(i).Offset(0, -9).Value
   temp5 = Range("M526").Cells(i).Offset(0, -8).Value
   temp6 = Range("M526").Cells(i).Offset(0, -7).Value
   temp7 = Range("M526").Cells(i).Offset(0, -6).Value
   temp8 = Range("M526").Cells(i).Offset(0, -5).Value
   temp9 = Range("M526").Cells(i).Offset(0, -4).Value
   temp10 = Range("M526").Cells(i).Offset(0, -3).Value
```

```
      temp11 = Range("M526").Cells(i).Offset(0, -2).Value
      temp12 = Range("M526").Cells(i).Offset(0, -1).Value
      temp13 = Range("M526").Cells(i).Offset(0, 0).Value

     Sheets("Mill 1 Analysis").Range("FD4").Select

        X = X + 1

        ActiveCell.Offset(X, 0).Select

        ActiveCell.Value = temp1
        ActiveCell.Offset(0, 1).Value = temp2
        ActiveCell.Offset(0, 2).Value = temp3
        ActiveCell.Offset(0, 3).Value = temp4
        ActiveCell.Offset(0, 4).Value = temp5
        ActiveCell.Offset(0, 5).Value = temp6
        ActiveCell.Offset(0, 6).Value = temp7
        ActiveCell.Offset(0, 7).Value = temp8
        ActiveCell.Offset(0, 8).Value = temp9
        ActiveCell.Offset(0, 9).Value = temp10
        ActiveCell.Offset(0, 10).Value = temp11
        ActiveCell.Offset(0, 11).Value = temp12
        ActiveCell.Offset(0, 12).Value = temp13

    End If

Next i
End Sub


Sub Macro8()
'
' Macro8 Macro
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("N5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
    ActiveCell.Offset(1, 0).Select
    ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)
```

```
    i = i + 1
    Loop Until ActiveCell.Offset(2, -1).Value = 0




End Sub

Public Sub PMrun()
 ' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("AG5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
    ActiveCell.Offset(1, 0).Select
    ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


    i = i + 1
    Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub OSrun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("AU5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
    ActiveCell.Offset(1, 0).Select
    ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
```

```
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


   i = i + 1
   Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub FCrun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("BI5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
   ActiveCell.Offset(1, 0).Select
   ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


   i = i + 1
   Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub Mrun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("BW5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
   ActiveCell.Offset(1, 0).Select
```

```
    ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


    i = i + 1
    Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub PPrun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("CK5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
    ActiveCell.Offset(1, 0).Select
    ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


    i = i + 1
    Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub PErun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("CY5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
```

```
    ActiveCell.Offset(1, 0).Select
    ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


    i = i + 1
    Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub Erun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("DM5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
    ActiveCell.Offset(1, 0).Select
    ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


    i = i + 1
    Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub PLCrun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("EA5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)
```

```
Do
   ActiveCell.Offset(1, 0).Select
   ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


   i = i + 1
   Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub Wrun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("EO5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
   ActiveCell.Offset(1, 0).Select
   ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


   i = i + 1
   Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub Orun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
' Keyboard Shortcut: Ctrl+t
'
Sheets("Mill 1 Analysis").Range("FC5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)
```

```
Do
   ActiveCell.Offset(1, 0).Select
   ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


   i = i + 1
   Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub

Public Sub Lrun()
' Macro recorded 9/5/2004 by mgreyling to calculate the intermediate running times
'
'
Sheets("Mill 1 Analysis").Range("FQ5").Select

ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)

Do
   ActiveCell.Offset(1, 0).Select
   ActiveCell.Value = DateDiff("n", ActiveCell.Offset(0, -7).Value & "/" _
& ActiveCell.Offset(0, -6).Value & "/" & ActiveCell.Offset(0, -5).Value & _
" " & ActiveCell.Offset(0, -4).Value & ":" & ActiveCell.Offset(0, -3).Value, _
ActiveCell.Offset(1, -12).Value & "/" & ActiveCell.Offset(1, -11).Value & "/" _
& ActiveCell.Offset(1, -10).Value & " " & ActiveCell.Offset(1, -9).Value & ":" _
& ActiveCell.Offset(1, -8).Value)


   i = i + 1
   Loop Until ActiveCell.Offset(2, -1).Value = 0
End Sub
```

12. APPENDIX 5: Respondent Letter

University
of the Witwatersrand,
Johannesburg

School of Mechanical, Industrial and Aeronautical Engineering

Private Bag 3, Wits 2050, South Africa ● Telephone: +27 11 717-7308 ● Fax: +27 11 339-7997
Website: http://www.wits.ac.za/fac/engineering/mech/index.htm

2004-08-10

Dear Respondent

MASTER OF ENGINEERING, UNIVERSITY OF THE WITWATERSRAND
RELIABILITY SURVEY OF MINERAL PROCESSING INSTALLATIONS

I am currently studying towards a degree in Master of Engineering at the University of the Witwatersrand. My studies are being supervised by Dr Harold Campbell, Senior lecturer & Postgraduate Coordinator at the School of Mechanical, Industrial & Aeronautical Engineering. I have selected the reliability of Platinum mineral processing plants in South Africa as the main topic of my research. The results of this survey will be used to prepare and submit a thesis in partial fulfilment of the requirements of a Master Degree in Engineering at the above-mentioned university.

This study aims at answering the following research problem:

When considering the design of a mineral processing plant, it is important for the mineral process engineer to have a very detailed understanding of how the reliability of the rotary mills and their sub-systems will impact on the overall system reliability of the mineral processing plant. The problem faced by the modern mineral processing design engineer and operations manager may be summarised as follows:

- ➢ *To what degree is the reliability and availability of the overall mineral processing plant compromised, if at all, by selecting a single, large capacity, rotary mill compared to a multiple parallel stream configuration consisting of several smaller primary milling units?*
- ➢ *How does the mechanical reliability of large, high capacity rotary mills compare with the reliability of the older, smaller milling units?*

The demands for increased milling capacity of lower grade ores, the limited availability of capital, and the requirement for lower operating costs have resulted in the design of modern Platinum mineral processing plants being progressively based on the largest available rotary mills for the specific duty. The modern tendency is therefore to move away from multiple, low capacity rotary milling streams configured in parallel, towards single or twin stream configurations employing equipment with significantly larger unit capacities in order to achieve the same nominal plant throughput. This, in turn, has resulted in the manufacturers of modern rotary mills using heavier and more complex components and fabrications than ever before. The sheer size of the fabrications, and the enormous workload, make modern rotary mills, and the associated circuit configuration, potentially more susceptible to failures despite the use of stricter specifications and standards for design and testing procedures.

The aim of this study is aid designers and operators of modern Platinum mineral processing plants in developing a better understanding of the reliability and operational availability of their installations as a function of the size and number of primary mills employed in their circuits.

The specific objective of this survey is to obtain a detailed historical downtime record for each primary mill deployed in the relevant mineral processing plant. The data will then be statistically interrogated by Markov chain analysis. For the purpose of this study it will be necessary for the respondents to compile the requested survey data according to the following criteria:

a) The general specifications of **each primary mill** must be provided. This will include the following:
   - Type of mill (FAG, SAG, Ball or Rod mill)
   - Nominal mill dimensions (diameter & length)
   - Type of drive motor (HS induction or LS synchronous)
   - Type of drive mechanism (Gear&pinion or gearless)

b) The downtime data provided should cover a historical period of at least **12 calendar** months.

c) The downtime data should reflect the exact **date and time** when a particular primary mill was stopped and started. It is important to list **every stoppage** regardless of the duration or how trivial it may seem.

d) The reason for each stoppage must be categorised according to the following list of generic downtime reasons:
   - Planned maintenance including relining.

- No ore
- Mill feed breakdown
- Mill lubrication breakdown or interlock trip.
- Major mill mechanical breakdown e.g. drive train, bearing, mill shell failure etc.
- Downstream pumping or piping breakdown.
- Downstream process equipment breakdown.
- Electrical outage or interlock trip.
- PLC/SCADA network failure.
- Process water shortage.
- Other.

The amount of effort required to compile the requested survey data is fully appreciated. For this reason I am proposing that any one, or combination of the following strategies be followed:

i. This letter is accompanied by a Microsoft Excel spreadsheet file that has been specifically designed for recording and categorising the survey data.

ii. Alternatively, where practically possible, I am willing to visit the relevant plant and personally summarise the downtime data if plant management are willing to allow me on site and to make the necessary records and log sheets available.

iii. Lastly it may be possible to extract the downtime data in electronic format from a data acquisition and storage server. In this case it is requested that the data file be downloaded in a format that is compatible with Microsoft Excel and forwarded to me at the email address listed below.

It is important to note that I am employed by Anglo Platinum Management Services in the Concentrator process technology department when considering your participation in this survey. However, the survey data is requested in a format that should not impinge on any confidentiality issues that may exist.

Your participation is critical to the success of this study and is greatly appreciated. Please respond by end September 2004 and feel free to contact me if you have any queries regarding this survey. I look forward to your positive response.

Kind Regards

Mark Greyling
Tel. +27 11 373 6241
Fax +27 11 373 5173
Email mgreyling@angloplat.com

13. APPENDIX 6 Plant A Downtime Data

Plant A

Primary Mill No. 1 Combined Failures

Stoppage no.	Start					Stop					Stop Duration	Stop Code	Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min				
1	2002	4	1	5	4	2002	4	2	17	0	2156	PE	401	401
2	2002	4	2	23	41	2002	4	3	1	0	79	PE	409	810
3	2002	4	3	7	49	2002	4	3	8	24	35	E	186	996
4	2002	4	3	11	30	2002	4	3	11	40	10	M	55	1051
5	2002	4	3	12	35	2002	4	3	12	40	5	M	124	1175
6	2002	4	3	14	44	2002	4	3	18	32	228	M	1934	3109
7	2002	4	5	2	46	2002	4	5	4	25	99	PE	1427	4536
8	2002	4	6	4	12	2002	4	10	2	34	5662	PM	1729	6265
9	2002	4	11	7	23	2002	4	11	8	2	39	PE	72	6337
10	2002	4	11	9	14	2002	4	11	9	19	5	E	88	6425
11	2002	4	11	10	47	2002	4	11	11	20	33	PE	1457	7882
12	2002	4	12	11	37	2002	4	12	11	40	3	PP	760	8642
13	2002	4	13	0	20	2002	4	13	0	42	22	PP	3273	11915
14	2002	4	15	7	15	2002	4	15	7	43	28	PP	75	11990
15	2002	4	15	8	58	2002	4	15	9	48	50	FC	78	12068
16	2002	4	15	11	6	2002	4	15	11	14	8	PP	31	12099
17	2002	4	15	11	45	2002	4	15	13	9	84	PP	1196	13295
18	2002	4	16	9	5	2002	4	16	14	27	322	PE	0	13295
19	2002	4	16	14	27	2002	4	16	15	2	35	E	0	13295
20	2002	4	16	15	2	2002	4	16	15	34	32	PP	1057	14352
21	2002	4	17	9	11	2002	4	17	9	22	11	E	169	14521
22	2002	4	17	12	11	2002	4	17	12	20	9	FC	2015	16536
23	2002	4	18	21	55	2002	4	18	22	55	60	PP	793	17329
24	2002	4	19	12	8	2002	4	19	12	18	10	FC	3857	21186
25	2002	4	22	4	35	2002	4	22	4	40	5	L	24	21210
26	2002	4	22	5	4	2002	4	22	6	20	76	L	230	21440
27	2002	4	22	10	10	2002	4	22	19	20	550	PE	2822	24262
28	2002	4	24	18	22	2002	4	24	18	25	3	FC	1818	26080
29	2002	4	26	0	43	2002	4	26	0	45	2	FC	2156	28236
30	2002	4	27	12	41	2002	4	27	12	46	5	FC	694	28930
31	2002	4	28	0	20	2002	4	28	0	45	25	OS	1057	29987
32	2002	4	28	18	22	2002	4	28	20	24	122	PE	1161	31148
33	2002	4	29	15	45	2002	4	29	17	24	99	PE	7466	38614
34	2002	5	4	21	50	2002	5	5	15	2	1032	OS	785	39399
35	2002	5	6	4	7	2002	5	7	2	2	1315	PM	65	39464
36	2002	5	7	3	7	2002	5	7	4	25	78	PP	462	39926
37	2002	5	7	12	7	2002	5	7	12	11	4	PP	214	40140
38	2002	5	7	15	45	2002	5	7	15	55	10	FC	82	40222
39	2002	5	7	17	17	2002	5	7	17	38	21	L	753	40975
40	2002	5	8	6	11	2002	5	8	13	13	422	E	2878	43853
41	2002	5	10	13	11	2002	5	10	13	46	35	PM	42	43895
42	2002	5	10	14	28	2002	5	10	14	37	9	PE	21	43916
43	2002	5	10	14	58	2002	5	10	15	8	10	PE	1412	45328
44	2002	5	11	14	40	2002	5	11	14	55	15	PE	2447	47775
45	2002	5	13	7	42	2002	5	13	7	48	6	FC	467	48242
46	2002	5	13	15	35	2002	5	13	15	47	12	E	1445	49687
47	2002	5	14	15	52	2002	5	14	17	51	119	O	491	50178
48	2002	5	15	2	2	2002	5	15	3	44	102	L	0	50178
49	2002	5	15	3	44	2002	5	15	4	36	52	PE	189	50367
50	2002	5	15	7	45	2002	5	15	8	2	17	L	288	50655
51	2002	5	15	12	50	2002	5	15	14	31	101	OS	149	50804
52	2002	5	15	17	0	2002	5	15	18	20	80	FC	43	50847
53	2002	5	15	19	3	2002	5	15	19	23	20	FC	2602	53449
54	2002	5	17	14	45	2002	5	17	15	25	40	PE	1	53450
55	2002	5	17	15	26	2002	5	17	16	36	70	PE	104	53554
56	2002	5	17	18	20	2002	5	17	18	29	9	PE	945	54499
57	2002	5	18	10	14	2002	5	18	10	22	8	PE	53	54552
58	2002	5	18	11	15	2002	5	18	11	25	10	PE	34	54586
59	2002	5	18	11	59	2002	5	18	12	7	8	PE	1584	56170
60	2002	5	19	14	31	2002	5	19	14	43	12	PE	152	56322
61	2002	5	19	17	15	2002	5	19	17	49	34	PE	111	56433
62	2002	5	19	19	40	2002	5	19	19	58	18	PE	725	57158
63	2002	5	20	8	3	2002	5	20	23	0	897	PM	117	57275
64	2002	5	21	0	57	2002	5	21	1	2	5	FC	99	57374
65	2002	5	21	2	41	2002	5	21	2	55	14	FC	40	57414
66	2002	5	21	3	35	2002	5	21	3	40	5	FC	688	58102
67	2002	5	21	15	8	2002	5	21	15	14	6	E	2201	60303
68	2002	5	23	3	55	2002	5	23	4	2	7	FC	542	60845
69	2002	5	23	13	4	2002	5	23	13	15	11	E	1675	62520
70	2002	5	24	17	10	2002	5	24	19	40	150	PE	3766	66286
71	2002	5	27	10	26	2002	5	27	10	48	22	FC	4024	70310
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766	2003	10	3	7	44	2003	10	3	7	49	5	L	1396	654690	245	5	1396
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813	2003	11	6	19	52	2003	11	6	20	21	29	L	48	697833	292	29	48
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869	2004	1	2	15	45	2004	1	2	16	15	30	O	167	768529	348	30	167
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874	2004	1	5	0	6	2004	1	5	1	0	54	PE	4748	776080	353	54	4748
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877	2004	1	9	18	40	2004	1	9	19	5	25	O	40	778178	356	25	40
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889	2004	1	19	17	57	2004	1	19	21	16	199	L	709	784340	368	199	709
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918	2004	2	14	9	27	2004	2	14	11	37	130	PP	132	813231	397	130	132
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926	2004	2	24	14	53	2004	2	24	18	9	196	E	18	826143	405	196	18
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929	2004	2	25	4	27	2004	2	25	5	10	43	L	85	826780	408	43	85
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932	2004	2	27	1	27	2004	2	27	1	28	1	FC	4529	833755	411	1	4529
933	2004	3	1	4	57	2004	3	1	5	2	5	OS	1818	835573	412	5	1818
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936	2004	3	3	9	2	2004	3	3	9	9	7	PLC	1665	838488	415	7	1665
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941	2004	3	8	13	31	2004	3	8	13	35	4	FC	4624	848847	420	4	4624
942	2004	3	11	18	39	2004	3	11	18	42	3	FC	2747	851594	421	3	2747
943	2004	3	13	16	29	2004	3	13	19	45	196	O	1602	853196	422	196	1602
944	2004	3	14	22	27	2004	3	14	22	30	3	FC	13	853209	423	3	13
945	2004	3	14	22	43	2004	3	15	0	52	129	L	219	853428	424	129	219
946	2004	3	15	4	31	2004	3	16	21	52	2481	PM	926	854354	425	2481	926
947	2004	3	17	13	18	2004	3	17	13	27	9	PLC	78	854432	426	9	78
948	2004	3	17	14	45	2004	3	17	17	5	140	PP	616	855048	427	140	616
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951	2004	3	19	1	21	2004	3	19	1	29	8	FC	112	855757	430	8	112
952	2004	3	19	3	21	2004	3	19	3	26	5	FC	3559	859316	431	5	3559
953	2004	3	21	14	45	2004	3	21	14	50	5	FC	275	859591	432	5	275
954	2004	3	21	19	25	2004	3	21	21	40	135	PLC	482	860073	433	135	482
955	2004	3	22	5	42	2004	3	22	6	2	20	PLC	445	860518	434	20	445
956	2004	3	22	13	27	2004	3	22	13	38	11	E	345	860863	435	11	345
957	2004	3	22	19	23	2004	3	22	20	20	57	L	1020	861883	436	57	1020
958	2004	3	23	13	20	2004	3	23	15	35	135	E	1079	862962	437	135	1079
959	2004	3	24	9	34	2004	3	24	12	0	146	PE	271	863233	438	146	271
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962	2004	3	26	11	10	2004	3	26	13	40	150	W	256	866028	441	150	256
963	2004	3	26	17	56	2004	3	26	18	3	7	PLC	2392	868420	442	7	2392
964	2004	3	28	9	55	2004	3	28	13	30	215	PP	2674	871094	443	215	2674
965	2004	3	30	10	4	2004	3	30	13	42	218	PP	3583	874677	444	218	3583
966	2004	4	2	1	25	2004	4	2	4	20	175	PP	4450	879127	445	175	4450
967	2004	4	5	6	30	2004	4	5	7	10	40	L	1	879128	446	40	1
968	2004	4	5	7	11	2004	4	5	7	22	11	FC	107	879235	447	11	107
969	2004	4	5	9	9	2004	4	5	12	15	186	PP	1070	880305	448	186	1070
970	2004	4	6	6	5	2004	4	6	6	10	5	FC	1511	881816	449	5	1511
971	2004	4	7	7	21	2004	4	7	11	15	234	PP	225	882041	450	234	225
972	2004	4	7	15	0	2004	4	7	15	25	25	FC	2685	884726	451	25	2685
973	2004	4	9	12	10	2004	4	9	14	30	140	PP	2055	886781	452	140	2055
974	2004	4	11	0	45	2004	4	15	9	8	6263	PP	97	886878	453	6263	97
975	2004	4	15	10	45	2004	4	15	11	0	15	L	225	887103	454	15	225
976	2004	4	15	14	45	2004	4	15	22	0	435	PP	1020	888123	455	435	1020
977	2004	4	16	15	0	2004	4	16	15	40	40	L	2575	890698	456	40	2575
978	2004	4	18	10	35	2004	4	18	10	38	3	L	13	890711	457	3	13
979	2004	4	18	10	51	2004	4	18	11	28	37	L	399	891110	458	37	399
980	2004	4	18	18	7	2004	4	18	20	15	128	L	747	891857	459	128	747
981	2004	4	19	8	42	2004	4	19	8	44	2	PP	881	892738	460	2	881
982	2004	4	19	23	25	2004	4	20	1	20	115	PP	125	892863	461	115	125
983	2004	4	20	3	25	2004	4	20	3	42	17	PP	6	892869	462	17	6
984	2004	4	20	3	48	2004	4	20	4	0	12	FC	1555	894424	463	12	1555
985	2004	4	21	5	55	2004	4	21	9	20	205	PP	0	894424	464	205	0
986	2004	4	21	9	20	2004	4	21	18	34	554	PLC	2301	896725	465	554	2301
987	2004	4	23	8	55	2004	4	23	9	3	8	L	2715	899440	466	8	2715
988	2004	4	25	6	18	2004	4	25	6	26	8	PE	892	900332	467	8	892
989	2004	4	25	21	18	2004	4	25	22	55	97	PE	6115	906447	468	97	6115
990	2004	4	30	4	50	2004	4	30	12	45	475	PP	3919	910366	469	475	3919
991	2004	5	3	6	4	2004	5	3	21	0	896	PE	1547	911913	470	896	1547
992	2004	5	4	22	47	2004	5	4	23	28	41	PLC	2889	914802	471	41	2889
993	2004	5	6	23	37	2004	5	7	2	10	153	L	2848	917650	472	153	2848
994	2004	5	9	1	38	2004	5	9	3	15	97	PE	37	917687	473	97	37
995	2004	5	9	3	52	2004	5	9	11	40	468	PP	4390	922077	474	468	4390
996	2004	5	12	12	50	2004	5	12	13	35	45	PM	50	922127	475	45	50
997	2004	5	12	14	25	2004	5	12	14	35	10	PM	40	922167	476	10	40
998	2004	5	12	15	15	2004	5	12	15	20	5	PM	10	922177	477	5	10
999	2004	5	12	15	30	2004	5	12	16	20	50	PM	2290	924467	478	50	2290
1000	2004	5	14	6	30	2004	5	14	7	17	47	E	691	925158	479	47	691
1001	2004	5	14	18	48	2004	5	14	19	50	62	PP	2170	927328	480	62	2170
1002	2004	5	16	8	0	2004	5	17	0	45	1005	OS	228	927556	481	1005	228
1003	2004	5	17	4	33	2004	5	17	4	53	20	L	5692	933248	482	20	5692
1004	2004	5	21	3	45	2004	5	21	4	45	60	L	331	933579	483	60	331
1005	2004	5	21	10	16	2004	5	21	12	41	145	PP	7591	941170	484	145	7591
1006	2004	5	26	19	12	2004	5	26	19	47	35	L	2843	944013	485	35	2843
1007	2004	5	28	19	10	2004	5	28	19	22	12	PE	2710	946723	486	12	2710
1008	2004	5	30	16	32	2004	5	31	4	0	688	OS	1660	948383	487	688	1660
1009	2004	6	1	7	40	2004	6	1	9	20	100	PE	2075	950458	488	100	2075
1010	2004	6	2	19	55	2004	6	3	4	15	500	PE	4400	954858	489	500	4400
1011	2004	6	6	5	35	2004	6	6	8	27	172	OS	1323	956181	490	172	1323
1012	2004	6	7	6	30	2004	6	8	22	18	2388	PM	1017	957198	491	2388	1017
1013	2004	6	9	15	15	2004	6	9	19	45	270	PP	514	957712	492	270	514
1014	2004	6	10	4	19	2004	6	10	4	45	26	PE	3754	961466	493	26	3754
1015	2004	6	12	19	19	2004	6	13	11	10	951	OS	1490	962956	494	951	1490
1016	2004	6	14	12	0	2004	6	14	13	40	100	PE	72	963028	495	100	72
1017	2004	6	14	14	52	2004	6	14	15	50	58	PE	386	963414	496	58	386
1018	2004	6	14	22	16	2004	6	14	22	20	4	FC	170	963584	497	4	170
1019	2004	6	15	1	10	2004	6	15	4	0	170	PE	105	963689	498	170	105
1020	2004	6	15	5	45	2004	6	15	6	16	31	PE	72	963761	499	31	72
1021	2004	6	15	7	28	2004	6	15	7	43	15	PE	42	963803	500	15	42
1022	2004	6	15	8	25	2004	6	15	8	28	3	PP	1060	964863	501	3	1060
1023	2004	6	16	2	8	2004	6	16	2	38	30	L	1097	965960	502	30	1097
1024	2004	6	16	20	55	2004	6	17	2	15	320	PP	315	966275	503	320	315
1025	2004	6	17	7	30	2004	6	17	7	45	15	E	1395	967670	504	15	1395
1026	2004	6	18	7	0	2004	6	18	9	0	120	PM	1320	968990	505	120	1320
1027	2004	6	19	7	0	2004	6	19	14	10	430	PP	2500	971490	506	430	2500
1028	2004	6	21	7	50	2004	6	21	8	20	30	PE	3810	975300	507	30	3810
1029	2004	6	23	23	50	2004	6	24	0	1	11	PE	3957	979257	508	11	3957
1030	2004	6	26	17	58	2004	6	26	23	42	344	M	2308	981565	509	344	2308
1031	2004	6	28	14	10	2004	6	28	14	15	5	L	895	982460	510	5	895
1032	2004	6	29	5	10	2004	6	29	13	5	475	M	470	982930	511	475	470
1033	2004	6	29	20	55	2004	6	29	21	55	60	PE	308	983238	512	60	308
1034	2004	6	30	3	3	2004	6	30	6	42	219	PE	160	983398	513	219	160
1035	2004	6	30	9	22	2004	6	30	13	0	218	PM			514	218	
										TOTAL	3321.97	hrs	16389.97	7827154	hrs	1869.5	9723.9

Rapair rate	0.31	per hr	Rapair rate	0.27
MTTR	3.21	hrs	MTTR	3.64
Failure rate	0.06	per hr	Failure rate	0.0528
MTTF	15.85	hrs	MTTF	18.95
Laplace	-4.25		Laplace	-0.43

	Plant A Failure Mode Reliability										
	PM	OS	FC	M	L	PP	PE	E	PLC	W	O
Failure rate	0.00289	0.00112	0.00420	0.00125	0.00213	0.00571	0.00944	0.00309	0.00199	0.00057	0.00213
Repair rate	0.03637	0.07166	6.63594	0.12722	0.58884	0.23287	0.41104	0.79532	0.55527	0.27907	0.58884
Time (hrs)											
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
100	0.7489	0.8941	0.6568	0.8827	0.8081	0.5652	0.3890	0.7340	0.8198	0.9446	0.8081
200	0.5609	0.7994	0.4314	0.7792	0.6530	0.3194	0.1513	0.5387	0.6721	0.8923	0.6530
300	0.4200	0.7147	0.2834	0.6879	0.5277	0.1805	0.0589	0.3954	0.5510	0.8429	0.5277
400	0.3146	0.6390	0.1861	0.6072	0.4264	0.1020	0.0229	0.2902	0.4517	0.7963	0.4264
500	0.2356	0.5714	0.1223	0.5360	0.3445	0.0577	0.0089	0.2130	0.3703	0.7522	0.3445
600	0.1764	0.5108	0.0803	0.4732	0.2784	0.0326	0.0035	0.1563	0.3036	0.7106	0.2784
700	0.1321	0.4567	0.0528	0.4177	0.2250	0.0184	0.0013	0.1147	0.2489	0.6712	0.2250
800	0.0990	0.4084	0.0346	0.3687	0.1818	0.0104	0.0005	0.0842	0.2041	0.6341	0.1818
900	0.0741	0.3651	0.0228	0.3255	0.1469	0.0059	0.0002	0.0618	0.1673	0.5990	0.1469
1000	0.0555	0.3265	0.0149	0.2873	0.1187	0.0033	0.0001	0.0454	0.1372	0.5658	0.1187
1100	0.0416	0.2919	0.0098	0.2536	0.0959	0.0019	0.0000	0.0333	0.1124	0.5345	0.0959
1200	0.0311	0.2610	0.0064	0.2239	0.0775	0.0011	0.0000	0.0244	0.0922	0.5049	0.0775
1300	0.0233	0.2333	0.0042	0.1976	0.0626	0.0006	0.0000	0.0179	0.0756	0.4769	0.0626
1400	0.0175	0.2086	0.0028	0.1745	0.0506	0.0003	0.0000	0.0132	0.0620	0.4505	0.0506
1500	0.0131	0.1865	0.0018	0.1540	0.0409	0.0002	0.0000	0.0097	0.0508	0.4256	0.0409
MTTF	345.867	893.279	237.920	801.818	469.249	175.245	105.907	323.311	503.356	1755.925	469.249
MTTR	27.495	13.954	0.151	7.860	1.698	4.294	2.433	1.257	1.801	3.583	1.698
State Probabilities	0.0680	0.0134	0.0005	0.0084	0.0031	0.0209	0.0196	0.0033	0.0031	0.0017	0.0031
Frequencies	0.0001965	0.0000149	0.0000023	0.0000105	0.0000066	0.0001195	0.0001854	0.0000103	0.0000061	0.0000010	0.0000066
Relative frequency	197.8	15.0	2.3	10.5	6.6	120.3	186.6	10.4	6.1	1.0	6.6
P0	0.8549										

	Plant A Failure Mode Maintainability										
Time	PM	OS	FC	M	L	PP	PE	E	PLC	W	O
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2.5	0.0869	0.1640	1.0000	0.2724	0.7706	0.4413	0.6421	0.8631	0.7505	0.5023	0.7706
5	0.1663	0.3012	1.0000	0.4707	0.9474	0.6879	0.8719	0.9813	0.9377	0.7523	0.9474
7.5	0.2387	0.4158	1.0000	0.6149	0.9879	0.8256	0.9542	0.9974	0.9845	0.8767	0.9879
10	0.3049	0.5116	1.0000	0.7198	0.9972	0.9026	0.9836	0.9996	0.9961	0.9386	0.9972
12.5	0.3653	0.5917	1.0000	0.7961	0.9994	0.9456	0.9941	1.0000	0.9990	0.9694	0.9994
15	0.4205	0.6587	1.0000	0.8517	0.9999	0.9696	0.9979	1.0000	0.9998	0.9848	0.9999
17.5	0.4708	0.7147	1.0000	0.8921	1.0000	0.9830	0.9992	1.0000	0.9999	0.9924	1.0000
20	0.5168	0.7615	1.0000	0.9215	1.0000	0.9905	0.9997	1.0000	1.0000	0.9962	1.0000
22.5	0.5588	0.8006	1.0000	0.9429	1.0000	0.9947	0.9999	1.0000	1.0000	0.9981	1.0000
25	0.5972	0.8333	1.0000	0.9584	1.0000	0.9970	1.0000	1.0000	1.0000	0.9991	1.0000
27.5	0.6322	0.8607	1.0000	0.9698	1.0000	0.9983	1.0000	1.0000	1.0000	0.9995	1.0000
30	0.6642	0.8835	1.0000	0.9780	1.0000	0.9991	1.0000	1.0000	1.0000	0.9998	1.0000
32.5	0.6933	0.9026	1.0000	0.9840	1.0000	0.9995	1.0000	1.0000	1.0000	0.9999	1.0000
35	0.7200	0.9186	1.0000	0.9884	1.0000	0.9997	1.0000	1.0000	1.0000	0.9999	1.0000
37.5	0.7443	0.9319	1.0000	0.9915	1.0000	0.9998	1.0000	1.0000	1.0000	1.0000	1.0000
40	0.7666	0.9431	1.0000	0.9938	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000
42.5	0.7868	0.9524	1.0000	0.9955	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000
45	0.8054	0.9602	1.0000	0.9967	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
47.5	0.8223	0.9668	1.0000	0.9976	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
50	0.8377	0.9722	1.0000	0.9983	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
52.5	0.8518	0.9768	1.0000	0.9987	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
55	0.8647	0.9806	1.0000	0.9991	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
57.5	0.8765	0.9838	1.0000	0.9993	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
60	0.8872	0.9864	1.0000	0.9995	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
62.5	0.8970	0.9887	1.0000	0.9996	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
65	0.9060	0.9905	1.0000	0.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
67.5	0.9141	0.9921	1.0000	0.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
70	0.9216	0.9934	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
72.5	0.9284	0.9945	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
75	0.9346	0.9954	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
77.5	0.9403	0.9961	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
80	0.9455	0.9968	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
82.5	0.9502	0.9973	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
85	0.9546	0.9977	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
87.5	0.9585	0.9981	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
90	0.9621	0.9984	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
92.5	0.9654	0.9987	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
95	0.9684	0.9989	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
97.5	0.9712	0.9991	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
100	0.9737	0.9992	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

14. APPENDIX 7 Plant B Downtime Data

Plant B

Primary Mill No. 1 Combined Failures

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	7	10	2003	6	24	3	20	1210	PM	651	651
2	2003	6	24	14	11	2003	6	24	14	12	1	L	2	653
3	2003	6	24	14	14	2003	6	24	14	17	3	L	1242	1895
4	2003	6	25	10	59	2003	6	25	12	2	63	E	5741	7636
5	2003	6	29	11	43	2003	6	30	10	5	1342	OS	1287	8923
6	2003	7	1	7	32	2003	7	1	8	46	74	FC	7	8930
7	2003	7	1	8	53	2003	7	1	9	27	34	FC	1148	10078
8	2003	7	2	4	35	2003	7	2	4	50	15	PP	262	10340
9	2003	7	2	9	12	2003	7	2	11	7	115	PM	1303	11643
10	2003	7	3	8	50	2003	7	3	8	55	5	O	1286	12929
11	2003	7	4	6	21	2003	7	4	6	24	3	PP	401	13330
12	2003	7	4	13	5	2003	7	4	13	27	22	PP	2913	16243
13	2003	7	6	14	0	2003	7	7	12	0	1320	OS	2985	19228
14	2003	7	9	13	45	2003	7	9	13	48	3	PLC	5572	24800
15	2003	7	13	10	40	2003	7	14	13	21	1601	OS	8589	33389
16	2003	7	20	12	30	2003	7	21	17	58	1768	OS	256	33645
17	2003	7	21	22	14	2003	7	21	23	10	56	PP	155	33800
18	2003	7	22	1	45	2003	7	22	2	10	25	PP	314	34114
19	2003	7	22	7	24	2003	7	22	15	23	479	PM	1235	35349
20	2003	7	23	11	58	2003	7	23	12	1	3	M	221	35570
21	2003	7	23	15	42	2003	7	23	15	53	11	PP	5353	40923
22	2003	7	27	9	6	2003	7	27	9	16	10	OS	706	41629
23	2003	7	27	21	2	2003	7	28	11	36	874	OS	8419	50048
24	2003	8	3	7	55	2003	8	3	8	22	27	M	3969	54017
25	2003	8	6	2	31	2003	8	6	2	32	1	O	2066	56083
26	2003	8	7	12	58	2003	8	7	13	0	2	O	5122	61205
27	2003	8	11	2	22	2003	8	11	13	33	671	OS	1102	62307
28	2003	8	12	7	55	2003	8	12	8	25	30	PLC	375	62682
29	2003	8	12	14	40	2003	8	12	14	48	8	PE	5637	68319
30	2003	8	16	12	45	2003	8	16	12	51	6	M	819	69138
31	2003	8	17	2	30	2003	8	18	13	32	2102	OS	8	69146
32	2003	8	18	13	40	2003	8	18	14	40	60	OS	988	70134
33	2003	8	19	7	8	2003	8	19	15	17	489	PM	866	71000
34	2003	8	20	5	43	2003	8	20	6	7	24	PE	6149	77149
35	2003	8	24	12	36	2003	8	25	12	0	1404	OS	13055	90204
36	2003	9	3	13	35	2003	9	3	14	26	51	PLC	7541	97745
37	2003	9	8	20	7	2003	9	8	20	8	1	PP	1572	99317
38	2003	9	9	22	20	2003	9	10	0	27	127	E	6793	106110
39	2003	9	14	17	40	2003	9	15	10	20	1000	OS	1255	107365
40	2003	9	16	7	15	2003	9	16	14	15	420	PM	160	107525
41	2003	9	16	16	55	2003	9	16	17	10	15	L	1021	108546
42	2003	9	17	10	11	2003	9	17	12	35	144	FC	1263	109809
43	2003	9	18	9	38	2003	9	18	16	20	402	E	160	109969
44	2003	9	18	19	0	2003	9	18	19	7	7	L	417	110386
45	2003	9	19	2	4	2003	9	19	2	6	2	L	21	110407
46	2003	9	19	2	27	2003	9	19	3	23	56	L	114	110521
47	2003	9	19	5	17	2003	9	19	5	21	4	L	213	110734
48	2003	9	19	8	54	2003	9	19	8	57	3	L	2	110736
49	2003	9	19	8	59	2003	9	19	9	57	58	L	2641	113377
50	2003	9	21	5	58	2003	9	22	16	0	2042	OS	7860	121237
51	2003	9	28	3	0	2003	9	29	10	53	1913	OS	522	121759
52	2003	9	29	19	35	2003	9	30	1	0	325	PE		
										TOTAL	340.52	hrs	2029.316667	50877.88333 hrs

Rapair rate	0.15	per hr
MTTR	6.55	hrs
Failure rate	0.03	per hr
MTTF	39.79	hrs
Laplace	-0.02	
	Stop Duration	
Criteria	>0	
Count	52.00	

Plant B

Primary Mill No. 2 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	20	27	1226	OS	2312	2312
2	2003	6	25	10	59	2003	6	25	12	2	63	E	5741	8053
3	2003	6	29	11	43	2003	6	30	10	5	1342	OS	158	8211
4	2003	6	30	12	43	2003	6	30	12	49	6	M	8461	16672
5	2003	7	6	9	50	2003	7	6	10	30	40	FC	210	16882
6	2003	7	6	14	0	2003	7	7	11	0	1260	OS	27	16909
7	2003	7	7	11	27	2003	7	7	13	0	93	E	40	16949
8	2003	7	7	13	40	2003	7	7	14	9	29	M	4196	21145
9	2003	7	10	12	5	2003	7	10	12	46	41	FC	3555	24700
10	2003	7	13	0	1	2003	7	14	7	10	1869	OS	0	24700
11	2003	7	14	7	10	2003	7	14	15	23	493	PM	7549	32249
12	2003	7	19	21	12	2003	7	19	21	16	4	PP	444	32693
13	2003	7	20	4	40	2003	7	20	5	0	20	PP	275	32968
14	2003	7	20	9	35	2003	7	21	17	30	1915	OS	284	33252
15	2003	7	21	22	14	2003	7	21	23	10	56	PP	7819	41071
16	2003	7	27	9	29	2003	7	28	11	28	1559	OS	2762	43833
17	2003	7	30	9	30	2003	7	30	9	36	6	PP	774	44607
18	2003	7	30	22	30	2003	7	31	1	12	162	FC	3258	47865
19	2003	8	2	7	30	2003	8	2	7	33	3	PP	12048	59913
20	2003	8	10	16	21	2003	8	10	22	0	339	OS	121	60034
21	2003	8	11	0	1	2003	8	11	13	41	820	OS	29	60063
22	2003	8	11	14	10	2003	8	11	14	24	14	PP	321	60384
23	2003	8	11	19	45	2003	8	11	19	57	12	PE	723	61107
24	2003	8	12	8	0	2003	8	12	9	48	108	M	2722	63829
25	2003	8	14	7	10	2003	8	14	22	58	948	PM	2943	66772
26	2003	8	17	0	1	2003	8	18	13	32	2251	OS	4	66776
27	2003	8	18	13	36	2003	8	18	14	27	51	E	135	66911
28	2003	8	18	16	42	2003	8	18	16	52	10	L	123	67034
29	2003	8	18	18	55	2003	8	18	19	8	13	L	3668	70702
30	2003	8	21	8	16	2003	8	21	8	17	1	L	17	70719
31	2003	8	21	8	34	2003	8	21	9	21	47	L	14306	85025
32	2003	8	31	7	47	2003	8	31	7	59	12	PP	4656	89681
33	2003	9	3	13	35	2003	9	3	14	26	51	PLC	5820	95501
34	2003	9	7	15	26	2003	9	7	16	49	83	PLC	0	95501
35	2003	9	7	16	49	2003	9	7	16	51	2	PLC	876	96377
36	2003	9	8	7	27	2003	9	8	14	45	438	PM	1754	98131
37	2003	9	9	19	59	2003	9	9	20	46	47	FC	94	98225
38	2003	9	9	22	20	2003	9	10	0	27	127	E	6698	104923
39	2003	9	14	16	5	2003	9	15	10	20	1095	OS	4278	109201
40	2003	9	18	9	38	2003	9	18	10	14	36	E	3701	112902
41	2003	9	20	23	55	2003	9	22	15	52	2397	OS	8940	121842
42	2003	9	28	20	52	2003	9	29	10	50	838	OS		
										TOTAL	332.12	hrs	2030.7	39110.4 hrs

Rapair rate	0.13	per hr
MTTR	7.91	hrs
Failure rate	0.02	per hr
MTTF	49.53	hrs
Laplace	-0.06	
Criteria	Stop Duration >0	
Count	42.00	

Plant B

Primary Mill No. 3 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	20	27	1226	OS	651	651
2	2003	6	24	7	18	2003	6	24	17	19	601	PM	1060	1711
3	2003	6	25	10	59	2003	6	25	12	2	63	E	5741	7452
4	2003	6	29	11	43	2003	6	30	10	5	1342	OS	-1	7451
5	2003	6	30	10	4	2003	6	30	10	8	4	L	2	7453
6	2003	6	30	10	10	2003	6	30	10	20	10	L	8870	16323
7	2003	7	6	14	10	2003	7	7	11	0	1250	OS	27	16350
8	2003	7	7	11	27	2003	7	7	13	0	93	E	1935	18285
9	2003	7	8	21	15	2003	7	8	21	19	4	PP	4701	22986
10	2003	7	12	3	40	2003	7	12	3	44	4	PP	844	23830
11	2003	7	12	17	48	2003	7	14	14	2	2654	OS	8638	32468
12	2003	7	20	14	0	2003	7	21	7	0	1020	OS	0	32468
13	2003	7	21	7	0	2003	7	21	15	0	480	PM	0	32468
14	2003	7	21	15	0	2003	7	21	17	35	155	OS	279	32747
15	2003	7	21	22	14	2003	7	21	23	10	56	PP	7849	40596
16	2003	7	27	9	59	2003	7	28	11	29	1530	OS	19472	60068
17	2003	8	11	0	1	2003	8	11	13	20	799	OS	1410	61478
18	2003	8	12	12	50	2003	8	12	13	12	22	M	5688	67166
19	2003	8	16	12	0	2003	8	16	12	10	10	PP	860	68026
20	2003	8	17	2	30	2003	8	18	7	10	1720	OS	0	68026
21	2003	8	18	7	10	2003	8	18	18	50	700	PM	8266	76292
22	2003	8	24	12	36	2003	8	25	12	0	1404	OS	13055	89347
23	2003	9	3	13	35	2003	9	3	14	26	51	PLC	5273	94620
24	2003	9	7	6	19	2003	9	7	7	46	87	PE	3754	98374
25	2003	9	9	22	20	2003	9	10	0	27	127	E	6963	105337
26	2003	9	14	20	30	2003	9	15	7	0	630	OS	0	105337
27	2003	9	15	7	0	2003	9	15	15	43	523	PM	621	105958
28	2003	9	16	2	4	2003	9	16	2	40	36	FC	3298	109256
29	2003	9	18	9	38	2003	9	18	10	14	36	E	3846	113102
30	2003	9	21	2	20	2003	9	22	15	52	2252	OS	1466	114568
31	2003	9	23	16	18	2003	9	23	16	55	37	M	207	114775
32	2003	9	23	20	22	2003	9	23	22	30	128	M	6524	121299
33	2003	9	28	11	14	2003	9	29	10	50	1416	OS	2	121301
34	2003	9	29	10	52	2003	9	29	10	57	5	PE		
										TOTAL	341.25	hrs	2021.683	33126.15 hrs

Rapair rate	0.10	per hr
MTTR	10.04	hrs
Failure rate	0.02	per hr
MTTF	61.26	hrs
Laplace	-0.01	
	Stop Duration	
Criteria	>0	
Count	34.00	

Plant B

Primary Mill No. 4 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	20	30	1229	OS	0	0
2	2003	6	23	20	30	2003	6	23	21	52	82	M	2227	2227
3	2003	6	25	10	59	2003	6	25	12	2	63	E	22	2249
4	2003	6	25	12	24	2003	6	25	12	29	5	L	6	2255
5	2003	6	25	12	35	2003	6	25	12	49	14	L	99	2354
6	2003	6	25	14	28	2003	6	25	14	31	3	L	746	3100
7	2003	6	26	2	57	2003	6	26	4	24	87	E	36	3136
8	2003	6	26	5	0	2003	6	26	5	7	7	PLC	13	3149
9	2003	6	26	5	20	2003	6	26	5	30	10	PLC	34	3183
10	2003	6	26	6	4	2003	6	26	6	10	6	PLC	10	3193
11	2003	6	26	6	20	2003	6	26	6	52	32	PLC	1458	4651
12	2003	6	27	7	10	2003	6	27	14	29	439	PM	2304	6955
13	2003	6	29	4	53	2003	6	30	9	59	1746	OS	8891	15846
14	2003	7	6	14	10	2003	7	7	0	35	625	OS	2186	18032
15	2003	7	8	13	1	2003	7	8	13	20	19	M	6489	24521
16	2003	7	13	1	29	2003	7	14	13	9	2140	OS	4186	28707
17	2003	7	17	10	55	2003	7	17	15	56	301	PM	3119	31826
18	2003	7	19	19	55	2003	7	19	20	16	21	PP	1066	32892
19	2003	7	20	14	2	2003	7	21	17	30	1648	OS	284	33176
20	2003	7	21	22	14	2003	7	21	23	10	56	PP	-340	32836
21	2003	7	21	17	30	2003	7	21	19	58	148	PLC	807	33643
22	2003	7	22	9	25	2003	7	22	9	30	5	L	1905	35548
23	2003	7	23	17	15	2003	7	23	17	21	6	PP	5432	40980
24	2003	7	27	11	53	2003	7	27	12	1	8	OS	212	41192
25	2003	7	27	15	33	2003	7	28	7	0	927	M	0	41192
26	2003	7	28	7	0	2003	7	28	15	15	495	PM	0	41192
27	2003	7	28	15	15	2003	7	28	17	0	105	OS	12849	54041
28	2003	8	6	15	9	2003	8	6	15	15	6	PP	6286	60327
29	2003	8	11	0	1	2003	8	11	13	53	832	OS	119	60446
30	2003	8	11	15	52	2003	8	11	16	3	11	L	57	60503
31	2003	8	11	17	0	2003	8	11	18	40	100	L	7396	67899
32	2003	8	16	21	56	2003	8	16	22	0	4	OS	121	68020
33	2003	8	17	0	1	2003	8	18	13	50	2269	OS	10	68030
34	2003	8	18	14	0	2003	8	18	14	35	35	E	354	68384
35	2003	8	18	20	29	2003	8	18	22	0	91	FC	1440	69824
36	2003	8	19	22	0	2003	8	19	23	9	69	FC	3147	72971
37	2003	8	22	3	36	2003	8	22	3	46	10	PE	70	73041
38	2003	8	22	4	56	2003	8	22	9	36	280	FC	2910	75951
39	2003	8	24	10	6	2003	8	25	12	0	1554	OS	1156	77107
40	2003	8	26	7	16	2003	8	26	16	0	524	PM	1208	78315
41	2003	8	27	12	8	2003	8	27	12	13	5	PP	4984	83299
42	2003	8	30	23	17	2003	8	30	23	31	14	L	3998	87297
43	2003	9	2	18	9	2003	9	2	18	12	3	L	1163	88460
44	2003	9	3	13	35	2003	9	3	14	26	51	PLC	188	88648
45	2003	9	3	17	34	2003	9	3	17	36	2	L	2797	91445
46	2003	9	5	16	13	2003	9	5	17	1	48	PE	4158	95603
47	2003	9	8	14	19	2003	9	8	15	23	64	PE	1857	97460
48	2003	9	9	22	20	2003	9	10	0	27	127	E	3929	101389
49	2003	9	12	17	56	2003	9	12	18	0	4	L	72	101461
50	2003	9	12	19	12	2003	9	12	19	13	1	L	2950	104411
51	2003	9	14	20	23	2003	9	15	10	22	839	OS	4123	108534
52	2003	9	18	7	5	2003	9	18	14	20	435	PM	4200	112734
53	2003	9	21	12	20	2003	9	22	15	52	1652	OS	7259	119993
54	2003	9	27	16	51	2003	9	27	16	57	6	L	13	120006
55	2003	9	27	17	10	2003	9	27	18	24	74	L	1347	121353
56	2003	9	28	16	51	2003	9	28	16	58	7	L	186	121539
57	2003	9	28	20	4	2003	9	29	11	10	906	OS	35	121574
58	2003	9	29	11	45	2003	9	29	12	7	22	PP		
										TOTAL	337.87	hrs	2026.233	41515.02 hrs

Rapair rate	0.17	per hr
MTTR	5.83	hrs
Failure rate	0.03	per hr
MTTF	35.55	hrs
Laplace	-0.31	

	Stop Duration
Criteria	>0
Count	58.00

Plant B

Primary Mill No. 5 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	20	27	1226	OS	2312	2312
2	2003	6	25	10	59	2003	6	25	12	2	63	E	2188	4500
3	2003	6	27	0	30	2003	6	27	0	39	9	FC	3175	7675
4	2003	6	29	5	34	2003	6	30	10	0	1706	OS	2217	9892
5	2003	7	1	22	57	2003	7	1	22	59	2	L	6581	16473
6	2003	7	6	12	40	2003	7	7	11	27	1367	OS	19	16492
7	2003	7	7	11	46	2003	7	7	12	0	14	PP	2750	19242
8	2003	7	9	9	50	2003	7	9	10	8	18	PE	217	19459
9	2003	7	9	13	45	2003	7	9	13	48	3	PLC	1235	20694
10	2003	7	10	10	23	2003	7	10	10	26	3	PLC	1310	22004
11	2003	7	11	8	16	2003	7	11	9	32	76	PP	204	22208
12	2003	7	11	12	56	2003	7	11	13	24	28	PP	2077	24285
13	2003	7	13	0	1	2003	7	14	7	5	1864	OS	0	24285
14	2003	7	14	7	5	2003	7	14	15	53	528	PM	8529	32814
15	2003	7	20	14	2	2003	7	21	18	12	1690	OS	242	33056
16	2003	7	21	22	14	2003	7	21	23	10	56	PP	4211	37267
17	2003	7	24	21	21	2003	7	24	21	24	3	L	316	37583
18	2003	7	25	2	40	2003	7	25	2	42	2	L	3337	40920
19	2003	7	27	10	19	2003	7	28	11	25	1506	OS	12666	53586
20	2003	8	6	6	31	2003	8	6	7	50	79	O	59	53645
21	2003	8	6	8	49	2003	8	6	8	58	9	L	2602	56247
22	2003	8	8	4	20	2003	8	8	4	28	8	FC	2492	58739
23	2003	8	9	22	0	2003	8	9	22	2	2	L	1064	59803
24	2003	8	10	15	46	2003	8	10	22	0	374	OS	121	59924
25	2003	8	11	0	1	2003	8	11	12	45	764	OS	2487	62411
26	2003	8	13	6	12	2003	8	13	7	0	48	L	200	62611
27	2003	8	13	10	20	2003	8	13	10	42	22	FC	2658	65269
28	2003	8	15	7	0	2003	8	15	15	2	482	PM	519	65788
29	2003	8	15	23	41	2003	8	15	23	44	3	L	1587	67375
30	2003	8	17	2	11	2003	8	18	13	36	2125	OS	0	67375
31	2003	8	18	13	36	2003	8	18	14	29	53	L	60	67435
32	2003	8	18	15	29	2003	8	18	16	55	86	L	166	67601
33	2003	8	18	19	41	2003	8	18	19	54	13	L	8	67609
34	2003	8	18	20	2	2003	8	18	20	7	5	L	987	68596
35	2003	8	19	12	34	2003	8	19	12	36	2	M	7055	75651
36	2003	8	24	10	11	2003	8	25	12	0	1549	OS	652	76303
37	2003	8	25	22	52	2003	8	25	22	54	2	O	5199	81502
38	2003	8	29	13	33	2003	8	29	14	5	32	PP	2415	83917
39	2003	8	31	6	20	2003	8	31	13	30	430	L	310	84227
40	2003	8	31	18	40	2003	8	31	18	52	12	O	33	84260
41	2003	8	31	19	25	2003	8	31	19	38	13	L	17	84277
42	2003	8	31	19	55	2003	8	31	20	0	5	M	241	84518
43	2003	9	1	0	1	2003	9	1	0	10	9	M	15	84533
44	2003	9	1	0	25	2003	9	1	0	35	10	E	171	84704
45	2003	9	1	3	26	2003	9	1	3	27	1	M	59	84763
46	2003	9	1	4	26	2003	9	1	4	35	9	M	100	84863
47	2003	9	1	6	15	2003	9	1	6	54	39	M	376	85239
48	2003	9	1	13	10	2003	9	1	13	25	15	E	118	85357
49	2003	9	1	15	23	2003	9	1	15	28	5	M	56	85413
50	2003	9	1	16	24	2003	9	1	16	28	4	M	47	85460
51	2003	9	1	17	15	2003	9	1	17	22	7	M	69	85529
52	2003	9	1	18	31	2003	9	1	18	50	19	M	252	85781
53	2003	9	1	23	2	2003	9	1	23	7	5	L	133	85914
54	2003	9	2	1	20	2003	9	2	1	35	15	FC	40	85954
55	2003	9	2	2	15	2003	9	2	6	9	234	FC	98	86052
56	2003	9	2	7	47	2003	9	2	8	44	57	M	1731	87783
57	2003	9	3	13	35	2003	9	3	14	26	51	PLC	1116	88899
58	2003	9	4	9	2	2003	9	4	9	21	19	L	7979	96878
59	2003	9	9	22	20	2003	9	10	0	27	127	E	1833	98711
60	2003	9	11	7	0	2003	9	11	15	44	524	PM	4607	103318
61	2003	9	14	20	31	2003	9	15	10	24	833	OS	4274	107592
62	2003	9	18	9	38	2003	9	18	10	14	36	E	4141	111733
63	2003	9	21	7	15	2003	9	22	15	52	1957	OS	4686	116419
64	2003	9	25	21	58	2003	9	25	22	0	2	M	1205	117624
65	2003	9	26	18	5	2003	9	26	18	15	10	PP	2419	120043
66	2003	9	28	10	34	2003	9	29	10	55	1461	OS		
										TOTAL	362.18	hrs	2000.7167	46928.183 hrs

Rapair rate	0.18	per hr
MTTR	5.49	hrs
Failure rate	0.03	per hr
MTTF	30.78	hrs
Laplace	-0.32	

	Stop Duration
Criteria	>0
Count	66.00

Plant B

Primary Mill No. 6 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	20	30	1229	OS	0	0
2	2003	6	23	20	30	2003	6	23	21	42	72	E	2237	2237
3	2003	6	25	10	59	2003	6	25	12	2	63	E	1161	3398
4	2003	6	26	7	23	2003	6	26	15	22	479	PM	2138	5536
5	2003	6	28	3	0	2003	6	28	3	10	10	PP	185	5721
6	2003	6	28	6	15	2003	6	28	6	39	24	FC	1426	7147
7	2003	6	29	6	25	2003	6	30	10	6	1661	OS	1329	8476
8	2003	7	1	8	15	2003	7	1	8	19	4	L	2949	11425
9	2003	7	3	9	28	2003	7	3	9	30	2	FC	4600	16025
10	2003	7	6	14	10	2003	7	7	11	27	1277	OS	3018	19043
11	2003	7	9	13	45	2003	7	9	13	48	3	PLC	4089	23132
12	2003	7	12	9	57	2003	7	12	10	15	18	FC	816	23948
13	2003	7	12	23	51	2003	7	13	0	3	12	FC	5	23953
14	2003	7	13	0	8	2003	7	13	0	16	8	L	623	24576
15	2003	7	13	10	39	2003	7	14	13	9	1590	OS	3903	28479
16	2003	7	17	6	12	2003	7	17	7	27	75	PP	4715	33194
17	2003	7	20	14	2	2003	7	21	14	20	1458	OS	474	33668
18	2003	7	21	22	14	2003	7	21	23	10	56	PP	3297	36965
19	2003	7	24	6	7	2003	7	24	6	28	21	FC	40	37005
20	2003	7	24	7	8	2003	7	24	15	43	515	PM	4309	41314
21	2003	7	27	15	32	2003	7	28	10	1	1109	OS	80	41394
22	2003	7	28	11	21	2003	7	28	11	24	3	PP	37	41431
23	2003	7	28	12	1	2003	7	28	12	5	4	PP	2200	43631
24	2003	7	30	0	45	2003	7	30	0	57	12	FC	15022	58653
25	2003	8	9	11	19	2003	8	9	11	26	7	M	2345	60998
26	2003	8	11	2	31	2003	8	11	2	39	8	L	59	61057
27	2003	8	11	3	38	2003	8	11	6	20	162	M	13	61070
28	2003	8	11	6	33	2003	8	11	17	9	636	M	5387	66457
29	2003	8	15	10	56	2003	8	15	11	32	36	PP	3	66460
30	2003	8	15	11	35	2003	8	15	12	0	25	PP	2209	68669
31	2003	8	17	0	49	2003	8	18	13	52	2223	OS	5355	74024
32	2003	8	22	7	7	2003	8	22	15	16	489	PM	2185	76209
33	2003	8	24	3	41	2003	8	25	12	0	1939	OS	9413	85622
34	2003	9	1	0	53	2003	9	1	7	0	367	OS	1	85623
35	2003	9	1	7	1	2003	9	2	17	0	2039	PM	1	85624
36	2003	9	2	17	1	2003	9	2	18	47	106	E	1128	86752
37	2003	9	3	13	35	2003	9	3	14	26	51	PLC	9114	95866
38	2003	9	9	22	20	2003	9	10	0	27	127	E	2193	98059
39	2003	9	11	13	0	2003	9	11	14	51	111	M	35	98094
40	2003	9	11	15	26	2003	9	11	15	32	6	L	12	98106
41	2003	9	11	15	44	2003	9	11	15	45	1	L	4578	102684
42	2003	9	14	20	3	2003	9	15	8	0	717	OS	0	102684
43	2003	9	15	8	0	2003	9	15	15	54	474	M	1068	103752
44	2003	9	16	9	42	2003	9	16	10	15	33	M	0	103752
45	2003	9	16	10	15	2003	9	16	11	8	53	E	2790	106542
46	2003	9	18	9	38	2003	9	18	10	14	36	E	1788	108330
47	2003	9	19	16	2	2003	9	19	17	11	69	PLC	1227	109557
48	2003	9	20	13	38	2003	9	20	14	55	77	PLC	598	110155
49	2003	9	21	0	53	2003	9	21	0	56	3	L	665	110820
50	2003	9	21	12	1	2003	9	22	16	0	1679	OS	682	111502
51	2003	9	23	3	22	2003	9	23	3	35	13	PP	3059	114561
52	2003	9	25	6	34	2003	9	30	23	59	8245	FC		
										TOTAL	490.62	hrs	1909.35	50389.667 hrs

Rapair rate	0.11	per hr
MTTR	9.43	hrs
Failure rate	0.03	per hr
MTTF	37.44	hrs
Laplace	0.04	

	Stop Duration
Criteria	>0
Count	52.00

Plant B

Primary Mill No. 7 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	20	26	1225	OS	0	0
2	2003	6	23	20	26	2003	6	23	20	30	4	L	24	24
3	2003	6	23	20	54	2003	6	23	20	56	2	L	28	52
4	2003	6	23	21	24	2003	6	23	21	57	33	L	8	60
5	2003	6	23	22	5	2003	6	23	23	50	105	L	117	177
6	2003	6	24	1	47	2003	6	24	1	51	4	L	50	227
7	2003	6	24	2	41	2003	6	24	2	43	2	L	359	586
8	2003	6	24	8	42	2003	6	24	8	47	5	L	1	587
9	2003	6	24	8	48	2003	6	24	8	55	7	L	117	704
10	2003	6	24	10	52	2003	6	24	12	3	71	L	474	1178
11	2003	6	24	19	57	2003	6	24	20	6	9	L	44	1222
12	2003	6	24	20	50	2003	6	24	21	57	67	L	782	2004
13	2003	6	25	10	59	2003	6	25	12	2	63	E	-547	1457
14	2003	6	25	2	55	2003	6	25	3	17	22	FC	6267	7724
15	2003	6	29	11	44	2003	6	30	7	5	1161	OS	0	7724
16	2003	6	30	7	5	2003	6	30	15	43	518	PM	485	8209
17	2003	6	30	23	48	2003	6	30	23	49	1	L	1388	9597
18	2003	7	1	22	57	2003	7	1	22	59	2	L	7952	17549
19	2003	7	7	11	31	2003	7	7	11	38	7	PE	3007	20556
20	2003	7	9	13	45	2003	7	9	13	48	3	PLC	5571	26127
21	2003	7	13	10	39	2003	7	14	12	48	1569	OS	714	26841
22	2003	7	15	0	42	2003	7	15	0	45	3	L	8596	35437
23	2003	7	21	0	1	2003	7	21	8	25	504	OS	83	35520
24	2003	7	21	9	48	2003	7	21	13	11	203	PP	8783	44303
25	2003	7	27	15	34	2003	7	28	7	0	926	OS	0	44303
26	2003	7	28	7	0	2003	7	28	15	30	510	PM	900	45203
27	2003	7	29	6	30	2003	7	29	8	28	118	PLC	2472	47675
28	2003	7	31	1	40	2003	7	31	1	49	9	PP	341	48016
29	2003	7	31	7	30	2003	7	31	7	48	18	PP	5680	53696
30	2003	8	4	6	28	2003	8	4	7	27	59	PLC	1611	55307
31	2003	8	5	10	18	2003	8	5	10	20	2	O	960	56267
32	2003	8	6	2	20	2003	8	6	2	33	13	PLC	6534	62801
33	2003	8	10	15	27	2003	8	10	22	0	393	OS	121	62922
34	2003	8	11	0	1	2003	8	11	9	39	578	OS	3810	66732
35	2003	8	14	1	9	2003	8	14	1	14	5	PP	4451	71183
36	2003	8	17	3	25	2003	8	17	7	23	238	OS	1817	73000
37	2003	8	18	13	40	2003	8	18	13	45	5	PP	6365	79365
38	2003	8	22	23	50	2003	8	22	23	53	3	PP	192	79557
39	2003	8	23	3	5	2003	8	23	3	7	2	L	255	79812
40	2003	8	23	7	22	2003	8	23	7	42	20	L	2843	82655
41	2003	8	25	7	5	2003	8	25	21	15	850	PM	0	82655
42	2003	8	25	21	15	2003	8	25	21	30	15	L	9995	92650
43	2003	9	1	20	5	2003	9	1	20	25	20	PP	0	92650
44	2003	9	1	20	25	2003	9	1	21	35	70	E	291	92941
45	2003	9	2	2	26	2003	9	2	2	35	9	E	1756	94697
46	2003	9	3	7	51	2003	9	3	7	54	3	O	341	95038
47	2003	9	3	13	35	2003	9	3	14	26	51	PLC	6840	101878
48	2003	9	8	8	26	2003	9	8	9	20	54	M	3	101881
49	2003	9	8	9	23	2003	9	8	9	31	8	E	2209	104090
50	2003	9	9	22	20	2003	9	10	0	27	127	E	6143	110233
51	2003	9	14	6	50	2003	9	14	7	15	25	L	0	110233
52	2003	9	14	7	15	2003	9	14	9	10	115	E	716	110949
53	2003	9	14	21	6	2003	9	15	10	30	804	OS	4268	115217
54	2003	9	18	9	38	2003	9	18	10	14	36	E	3503	118720
55	2003	9	20	20	37	2003	9	20	23	54	197	PP	546	119266
56	2003	9	21	9	0	2003	9	21	9	30	30	PE	1	119267
57	2003	9	21	9	31	2003	9	21	10	20	49	E	218	119485
58	2003	9	21	13	58	2003	9	21	14	8	10	PP	2	119487
59	2003	9	21	14	10	2003	9	21	16	40	150	PP	880	120367
60	2003	9	22	7	20	2003	9	22	20	5	765	PM	4895	125262
61	2003	9	26	5	40	2003	9	26	6	23	43	L	3164	128426
62	2003	9	28	11	7	2003	9	29	7	27	1220	OS	145	128571
63	2003	9	29	9	52	2003	9	29	12	35	163	E		
										TOTAL	221.72	hrs	2142.85	38921.75 hrs

Rapair rate	0.28	per hr
MTTR	3.52	hrs

Failure rate	0.03	per hr
MTTF	34.56	hrs
Laplace	-0.47	

	Stop Duration
Criteria	>0
Count	63.00

Plant B

Primary Mill No. 8 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	10	13	612	OS	142	142
2	2003	6	23	12	35	2003	6	23	12	37	2	E	2782	2924
3	2003	6	25	10	59	2003	6	25	12	2	63	E	11233	14157
4	2003	7	3	7	15	2003	7	3	14	46	451	PM	957	15114
5	2003	7	4	6	43	2003	7	4	6	53	10	PP	7389	22503
6	2003	7	9	10	2	2003	7	9	11	1	59	FC	2439	24942
7	2003	7	11	3	40	2003	7	11	4	14	34	FC	3525	28467
8	2003	7	13	14	59	2003	7	13	19	53	294	FC	519	28986
9	2003	7	14	4	32	2003	7	14	4	48	16	PP	1932	30918
10	2003	7	15	13	0	2003	7	15	13	15	15	PP	7883	38801
11	2003	7	21	0	38	2003	7	21	8	25	467	OS	83	38884
12	2003	7	21	9	48	2003	7	21	13	15	207	PP	11220	50104
13	2003	7	29	8	15	2003	7	29	8	16	1	E	4472	54576
14	2003	8	1	10	48	2003	8	1	10	55	7	PP	5723	60299
15	2003	8	5	10	18	2003	8	5	10	20	2	O	4125	64424
16	2003	8	8	7	5	2003	8	8	14	56	471	PM	12506	76930
17	2003	8	17	7	22	2003	8	17	13	5	343	M	0	76930
18	2003	8	17	13	5	2003	8	18	13	40	1475	OS	1435	78365
19	2003	8	19	13	35	2003	8	19	13	39	4	PLC	3637	82002
20	2003	8	22	2	16	2003	8	22	2	27	11	FC	4895	86897
21	2003	8	25	12	2	2003	8	25	12	4	2	PP	1572	88469
22	2003	8	26	14	16	2003	8	26	14	17	1	PP	2461	90930
23	2003	8	28	7	18	2003	8	28	15	0	462	PM	5282	96212
24	2003	9	1	7	2	2003	9	1	19	20	738	PM	0	96212
25	2003	9	1	19	20	2003	9	1	22	0	160	M	1440	97652
26	2003	9	2	22	0	2003	9	2	23	16	76	M	859	98511
27	2003	9	3	13	35	2003	9	3	14	26	51	PLC	7812	106323
28	2003	9	9	0	38	2003	9	9	3	38	180	L	1122	107445
29	2003	9	9	22	20	2003	9	10	0	27	127	E	42	107487
30	2003	9	10	1	9	2003	9	10	1	54	45	L	359	107846
31	2003	9	10	7	53	2003	9	10	8	0	7	FC	7492	115338
32	2003	9	15	12	52	2003	9	15	12	55	3	PP	4123	119461
33	2003	9	18	9	38	2003	9	18	10	14	36	E	4544	124005
34	2003	9	21	13	58	2003	9	21	14	2	4	PP	3	124008
35	2003	9	21	14	5	2003	9	21	14	11	6	PP	4325	128333
36	2003	9	24	14	16	2003	9	24	15	45	89	M	6734	135067
37	2003	9	29	7	59	2003	9	29	16	50	531	PM		
										TOTAL	117.70	hrs	2251.116667	43661.06667 hrs

Rapair rate	0.31	per hr
MTTR	3.18	hrs
Failure rate	0.02	per hr
MTTF	62.53	hrs
Laplace	0.07	
	Stop Duration	
Criteria	>0	
Count	37.00	

Plant B

Primary Mill No. 9 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	10	21	620	OS	81	81
2	2003	6	23	11	42	2003	6	23	11	45	3	L	50	131
3	2003	6	23	12	35	2003	6	23	12	37	2	E	916	1047
4	2003	6	24	3	53	2003	6	24	3	56	3	L	35	1082
5	2003	6	24	4	31	2003	6	24	4	32	1	L	1827	2909
6	2003	6	25	10	59	2003	6	25	12	2	63	E	82	2991
7	2003	6	25	13	24	2003	6	25	14	46	82	L	636	3627
8	2003	6	26	1	22	2003	6	26	1	24	2	L	3	3630
9	2003	6	26	1	27	2003	6	26	1	30	3	L	12	3642
10	2003	6	26	1	42	2003	6	26	1	45	3	L	140	3782
11	2003	6	26	4	5	2003	6	26	4	34	29	FC	43	3825
12	2003	6	26	5	17	2003	6	26	5	31	14	PLC	5905	9730
13	2003	6	30	7	56	2003	6	30	8	1	5	PP	4109	13839
14	2003	7	3	4	30	2003	7	3	4	33	3	L	140	13979
15	2003	7	3	6	53	2003	7	3	6	55	2	L	190	14169
16	2003	7	3	10	5	2003	7	3	10	43	38	L	1257	15426
17	2003	7	4	7	40	2003	7	4	15	0	440	PM	2753	18179
18	2003	7	6	12	53	2003	7	6	18	28	335	FC	178	18357
19	2003	7	6	21	26	2003	7	6	23	59	153	OS	2	18359
20	2003	7	7	0	1	2003	7	7	3	0	179	PP	0	18359
21	2003	7	7	3	0	2003	7	7	10	50	470	OS	89	18448
22	2003	7	7	12	19	2003	7	7	12	22	3	L	108	18556
23	2003	7	7	14	10	2003	7	7	14	13	3	L	259	18815
24	2003	7	7	18	32	2003	7	7	18	38	6	L	43	18858
25	2003	7	7	19	21	2003	7	7	19	23	2	L	26	18884
26	2003	7	7	19	49	2003	7	7	21	0	71	L	7516	26400
27	2003	7	13	2	16	2003	7	13	2	34	18	PP	1413	27813
28	2003	7	14	2	7	2003	7	14	3	32	85	OS	3107	30920
29	2003	7	16	7	19	2003	7	16	7	25	6	PP	295	31215
30	2003	7	16	12	20	2003	7	16	12	25	5	PP	1325	32540
31	2003	7	17	10	30	2003	7	17	10	45	15	PP	75	32615
32	2003	7	17	12	0	2003	7	17	12	32	32	PP	5046	37661
33	2003	7	21	0	38	2003	7	21	8	25	467	OS	83	37744
34	2003	7	21	9	48	2003	7	21	13	10	202	PP	5470	43214
35	2003	7	25	8	20	2003	7	25	9	35	75	M	0	43214
36	2003	7	25	9	35	2003	7	25	9	55	20	M	3902	47116
37	2003	7	28	2	57	2003	7	28	4	37	100	OS	3136	50252
38	2003	7	30	8	53	2003	7	30	9	5	12	PP	21	50273
39	2003	7	30	9	26	2003	7	30	9	48	22	PP	1287	51560
40	2003	7	31	7	15	2003	8	1	2	9	1134	PM	79	51639
41	2003	8	1	3	28	2003	8	1	4	59	91	PP	1	51640
42	2003	8	1	5	0	2003	8	1	7	0	120	L	0	51640
43	2003	8	1	7	0	2003	8	1	11	37	277	E	26883	78523
44	2003	8	20	3	40	2003	8	20	3	42	2	L	2821	81344
45	2003	8	22	2	43	2003	8	22	7	54	311	M	13502	94846
46	2003	8	31	16	56	2003	8	31	16	58	2	L	27	94873
47	2003	8	31	17	25	2003	8	31	19	37	132	L	11	94884
48	2003	8	31	19	48	2003	8	31	22	0	132	L	3815	98699
49	2003	9	3	13	35	2003	9	3	14	26	51	PLC	2755	101454
50	2003	9	5	12	21	2003	9	5	12	38	17	E	304	101758
51	2003	9	5	17	42	2003	9	5	18	45	63	E	2078	103836
52	2003	9	7	5	23	2003	9	7	5	30	7	PP	55	103891
53	2003	9	7	6	25	2003	9	7	7	46	81	PP	824	104715
54	2003	9	7	21	30	2003	9	7	21	32	2	L	1789	106504
55	2003	9	9	3	21	2003	9	9	4	21	60	E	1079	107583
56	2003	9	9	22	20	2003	9	10	0	27	127	E	933	108516
57	2003	9	10	16	0	2003	9	10	19	48	228	L	325	108841
58	2003	9	11	1	13	2003	9	11	1	39	26	L	756	109597
59	2003	9	11	14	15	2003	9	11	14	21	6	L	69	109666
60	2003	9	11	15	30	2003	9	11	16	15	45	L	4190	113856
61	2003	9	14	14	5	2003	9	14	18	30	265	PP	5147	119003
62	2003	9	18	8	17	2003	9	18	8	26	9	PP	4	119007
63	2003	9	18	8	30	2003	9	18	9	1	31	PP	1851	120858
64	2003	9	19	15	52	2003	9	19	17	8	76	E	7100	127958
65	2003	9	24	15	28	2003	9	24	15	31	3	L	7	127965
66	2003	9	24	15	38	2003	9	24	16	55	77	L	889	128854
67	2003	9	25	7	44	2003	9	25	7	46	2	L	1424	130278
68	2003	9	26	7	30	2003	9	26	21	35	845	PM	1043	131321
69	2003	9	27	14	58	2003	9	27	15	7	9	L	189	131510
70	2003	9	27	18	16	2003	9	27	20	10	114	L	4147	135657
71	2003	9	30	17	17	2003	9	30	17	20	3	L		
										TOTAL	132.37	hrs	2260.95	30139.63333 hrs

Rapair rate 0.54 per hr
MTTR 1.86 hrs

Failure rate 0.03 per hr
MTTF 32.30 hrs
Laplace -0.75

	Stop Duration
Criteria	>0
Count	71.00

Plant B

Primary Mill No. 10 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	10	26	625	OS	34	34
2	2003	6	23	11	0	2003	6	23	11	4	4	PP	16	50
3	2003	6	23	11	20	2003	6	23	11	42	22	PP	53	103
4	2003	6	23	12	35	2003	6	23	12	37	2	E	134	237
5	2003	6	23	14	51	2003	6	23	15	15	24	L	2624	2861
6	2003	6	25	10	59	2003	6	25	12	2	63	E	8	2869
7	2003	6	25	12	10	2003	6	25	12	12	2	L	8323	11192
8	2003	7	1	6	55	2003	7	2	15	2	1927	PM	5323	16515
9	2003	7	6	7	45	2003	7	6	7	47	2	PP	9	16524
10	2003	7	6	7	56	2003	7	6	9	40	104	PP	2	16526
11	2003	7	6	9	42	2003	7	6	10	0	18	PP	957	17483
12	2003	7	7	1	57	2003	7	7	2	5	8	PP	154	17637
13	2003	7	7	4	39	2003	7	7	4	45	6	PP	90	17727
14	2003	7	7	6	15	2003	7	7	6	35	20	PP	14	17741
15	2003	7	7	6	49	2003	7	7	6	56	7	PP	97	17838
16	2003	7	7	8	33	2003	7	7	8	35	2	PP	6	17844
17	2003	7	7	8	41	2003	7	7	8	44	3	PP	54	17898
18	2003	7	7	9	38	2003	7	7	9	45	7	PP	1	17899
19	2003	7	7	9	46	2003	7	7	9	51	5	PP	4	17903
20	2003	7	7	9	55	2003	7	7	10	10	15	PP	3105	21008
21	2003	7	9	13	55	2003	7	9	13	56	1	PP	7063	28071
22	2003	7	14	11	39	2003	7	14	13	13	94	FC	1968	30039
23	2003	7	15	22	1	2003	7	15	22	23	22	PP	7119	37158
24	2003	7	20	21	2	2003	8	6	12	38	23976	FC	5087	42245
25	2003	8	10	1	25	2003	8	10	1	31	6	FC	957	43202
26	2003	8	10	17	28	2003	8	10	22	0	272	OS	121	43323
27	2003	8	11	0	1	2003	8	11	3	39	218	OS	3096	46419
28	2003	8	13	7	15	2003	8	13	7	27	12	FC	83	46502
29	2003	8	13	8	50	2003	8	13	9	32	42	M	7376	53878
30	2003	8	18	12	28	2003	8	18	13	4	36	M	484	54362
31	2003	8	18	21	8	2003	8	18	21	11	3	PP	1645	56007
32	2003	8	20	0	36	2003	8	20	0	38	2	PP	4447	60454
33	2003	8	23	2	45	2003	8	23	2	48	3	PP	445	60899
34	2003	8	23	10	13	2003	8	23	10	23	10	PE	3	60902
35	2003	8	23	10	26	2003	8	23	10	39	13	PE	8431	69333
36	2003	8	29	7	10	2003	8	29	15	3	473	PM	6733	76066
37	2003	9	3	7	16	2003	9	3	8	15	59	FC	320	76386
38	2003	9	3	13	35	2003	9	3	14	26	51	PLC	2795	79181
39	2003	9	5	13	1	2003	9	5	13	9	8	L	54	79235
40	2003	9	5	14	3	2003	9	5	14	10	7	PP	6250	85485
41	2003	9	9	22	20	2003	9	10	0	27	127	E	5588	91073
42	2003	9	13	21	35	2003	9	13	22	48	73	FC	412	91485
43	2003	9	14	5	40	2003	9	14	6	5	25	PE	4851	96336
44	2003	9	17	14	56	2003	9	17	15	0	4	PP	9260	105596
45	2003	9	24	1	20	2003	9	24	1	22	2	PP	1817	107413
46	2003	9	25	7	39	2003	9	25	9	49	130	M	5266	112679
47	2003	9	29	1	35	2003	9	29	4	10	155	OS	8	112687
48	2003	9	29	4	18	2003	9	29	4	25	7	PP	2	112689
49	2003	9	29	4	27	2003	9	29	4	30	3	PP		
										TOTAL	478.33	hrs	1878.15	36783.23333 hrs

Rapair rate	0.10	per hr
MTTR	9.76	hrs
Failure rate	0.03	per hr
MTTF	39.13	hrs
Laplace	-0.18	
	Stop Duration	
Criteria	>0	
Count	49.00	

Plant B

Primary Mill No. 11 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	10	13	612	OS	142	142
2	2003	6	23	12	35	2003	6	23	12	37	2	E	448	590
3	2003	6	23	20	5	2003	6	23	21	35	90	PLC	1179	1769
4	2003	6	24	17	14	2003	6	24	18	2	48	PLC	1017	2786
5	2003	6	25	10	59	2003	6	25	12	2	63	E	3738	6524
6	2003	6	28	2	20	2003	6	28	8	19	359	FC	8523	15047
7	2003	7	4	6	22	2003	7	4	6	24	2	L	506	15553
8	2003	7	4	14	50	2003	7	4	14	52	2	L	3383	18936
9	2003	7	6	23	15	2003	7	6	23	22	7	PP	26	18962
10	2003	7	6	23	48	2003	7	7	2	40	172	PP	119	19081
11	2003	7	7	4	39	2003	7	7	4	41	2	PP	94	19175
12	2003	7	7	6	15	2003	7	7	6	20	5	PP	62	19237
13	2003	7	7	7	22	2003	7	7	7	28	6	PP	65	19302
14	2003	7	7	8	33	2003	7	7	8	35	2	PP	6	19308
15	2003	7	7	8	41	2003	7	7	8	44	3	PP	8	19316
16	2003	7	7	8	52	2003	7	7	8	56	4	PP	42	19358
17	2003	7	7	9	38	2003	7	7	9	40	2	PP	15	19373
18	2003	7	7	9	55	2003	7	7	9	58	3	PP	1277	20650
19	2003	7	8	7	15	2003	7	8	18	30	675	PM	107	20757
20	2003	7	8	20	17	2003	7	8	20	58	41	PP	1007	21764
21	2003	7	9	13	45	2003	7	9	13	48	3	PLC	3675	25439
22	2003	7	12	3	3	2003	7	12	3	8	5	PP	797	26236
23	2003	7	12	16	25	2003	7	12	16	27	2	PP	2985	29221
24	2003	7	14	18	12	2003	7	14	19	0	48	PLC	1205	30426
25	2003	7	15	15	5	2003	7	15	15	26	21	M	-584	29842
26	2003	7	15	5	42	2003	7	15	5	49	7	PP	1973	31815
27	2003	7	16	14	42	2003	7	16	14	44	2	L	40	31855
28	2003	7	16	15	24	2003	7	16	15	30	6	L	2440	34295
29	2003	7	18	8	10	2003	7	18	10	50	160	M	359	34654
30	2003	7	18	16	49	2003	7	18	16	55	6	PP	197	34851
31	2003	7	18	20	12	2003	7	18	20	15	3	L	473	35324
32	2003	7	19	4	8	2003	7	19	4	13	5	PP	2172	37496
33	2003	7	20	16	25	2003	7	20	16	30	5	PP	46	37542
34	2003	7	20	17	16	2003	7	20	17	21	5	PP	69	37611
35	2003	7	20	18	30	2003	7	20	19	23	53	PP	102	37713
36	2003	7	20	21	5	2003	7	21	8	27	682	OS	81	37794
37	2003	7	21	9	48	2003	7	21	13	18	210	PP	112	37906
38	2003	7	21	15	10	2003	7	21	15	15	5	PP	21	37927
39	2003	7	21	15	36	2003	7	21	15	52	16	PP	2823	40750
40	2003	7	23	14	55	2003	7	23	14	59	4	PP	9	40759
41	2003	7	23	15	8	2003	7	23	15	20	12	PP	1093	41852
42	2003	7	24	9	33	2003	7	24	9	37	4	PP	1535	43387
43	2003	7	25	11	12	2003	7	25	11	17	5	PP	10	43397
44	2003	7	25	11	27	2003	7	25	11	33	6	PP	11	43408
45	2003	7	25	11	44	2003	7	25	11	50	6	PP	1365	44773
46	2003	7	26	10	35	2003	7	26	10	39	4	PP	1708	46481
47	2003	7	27	15	7	2003	7	27	15	9	2	PP	175	46656
48	2003	7	27	18	4	2003	7	27	18	7	3	L	94	46750
49	2003	7	27	19	41	2003	7	27	19	44	3	L	264	47014
50	2003	7	28	0	8	2003	7	28	0	12	4	PP	41	47055
51	2003	7	28	0	53	2003	7	28	3	15	142	PP	1433	48488
52	2003	7	29	3	8	2003	7	29	3	22	14	PP	283	48771
53	2003	7	29	8	5	2003	7	29	8	9	4	PP	7301	56072
54	2003	8	3	9	50	2003	8	3	10	45	55	PP	0	56072
55	2003	8	3	10	45	2003	8	3	10	58	13	E	597	56669
56	2003	8	3	20	55	2003	8	3	21	2	7	PP	608	57277
57	2003	8	4	7	10	2003	8	4	18	9	659	PM	2744	60021
58	2003	8	6	15	53	2003	8	6	15	57	4	PP	583	60604
59	2003	8	7	1	40	2003	8	7	1	42	2	PP	671	61275
60	2003	8	7	12	53	2003	8	7	12	58	5	PP	4585	65860
61	2003	8	10	17	23	2003	8	10	22	0	277	OS	121	65981
62	2003	8	11	0	1	2003	8	11	4	51	290	OS	619	66600
63	2003	8	11	15	10	2003	8	11	15	22	12	PP	101	66701
64	2003	8	11	17	3	2003	8	11	17	15	12	PP	6741	73442
65	2003	8	16	9	36	2003	8	16	9	40	4	PP	2823	76265

66	2003	8	18	8	43	2003	8	18	8	50	7	PP	1972	78237		
67	2003	8	19	17	42	2003	8	19	17	46	4	PP	7684	85921		
68	2003	8	25	1	50	2003	8	25	1	55	5	L	6180	92101		
69	2003	8	29	8	55	2003	8	29	10	11	76	PP	13	92114		
70	2003	8	29	10	24	2003	8	29	10	55	31	PP	360	92474		
71	2003	8	29	16	55	2003	8	29	17	40	45	PP	884	93358		
72	2003	8	30	8	24	2003	8	30	8	29	5	PP	666	94024		
73	2003	8	30	19	35	2003	8	30	19	40	5	PP	33	94057		
74	2003	8	30	20	13	2003	8	30	20	14	1	PP	221	94278		
75	2003	8	30	23	55	2003	8	31	0	14	19	PP	719	94997		
76	2003	8	31	12	13	2003	8	31	12	20	7	PP	1234	96231		
77	2003	9	1	8	54	2003	9	1	9	8	14	PP	257	96488		
78	2003	9	1	13	25	2003	9	1	13	32	7	PP	1170	97658		
79	2003	9	2	9	2	2003	9	2	9	15	13	M	385	98043		
80	2003	9	2	15	40	2003	9	2	16	32	52	PE	853	98896		
81	2003	9	3	6	45	2003	9	3	7	12	27	M	383	99279		
82	2003	9	3	13	35	2003	9	3	14	26	51	PLC	111	99390		
83	2003	9	3	16	17	2003	9	3	17	29	72	PP	819	100209		
84	2003	9	4	7	8	2003	9	5	4	41	1293	PM	40	100249		
85	2003	9	5	5	21	2003	9	5	7	3	102	O	6677	106926		
86	2003	9	9	22	20	2003	9	10	0	27	127	E	1574	108500		
87	2003	9	11	2	41	2003	9	11	16	15	814	L	-380	108120		
88	2003	9	11	9	55	2003	9	11	10	8	13	PP	222	108342		
89	2003	9	11	13	50	2003	9	11	13	54	4	L	341	108683		
90	2003	9	11	19	35	2003	9	11	19	40	5	PP	3523	112206		
91	2003	9	14	6	23	2003	9	14	6	25	2	PE	21095	133301		
92	2003	9	28	22	0	2003	9	29	7	27	567	OS				
93	0	0	0	0	0	0	0	0	0	0	0	0				
94	0	0	0	0	0	0	0	0	0	0	0	0				
95	0	0	0	0	0	0	0	0	0	0	0	0				
96	0	0	0	0	0	0	0	0	0	0	0	0				
										TOTAL	137.75	hrs	2221.683333	24772.45	hrs	

Rapair rate	0.67	per hr
MTTR	1.50	hrs
Failure rate	0.04	per hr
MTTF	24.41	hrs
Laplace	-1.04	
	Stop Duration	
Criteria	>0	
Count	92.00	

Plant B

Primary Mill No. 12 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time	
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code			
1	2003	6	23	0	1	2003	6	23	10	14	613	OS	93	93	
2	2003	6	23	11	47	2003	6	23	11	51	4	PP	44	137	
3	2003	6	23	12	35	2003	6	23	12	37	2	E	2782	2919	
4	2003	6	25	10	59	2003	6	25	12	2	63	E	521	3440	
5	2003	6	25	20	43	2003	6	25	20	44	1	L	16631	20071	
6	2003	7	7	9	55	2003	7	7	10	9	14	PP	3096	23167	
7	2003	7	9	13	45	2003	7	9	13	48	3	PLC	2236	25403	
8	2003	7	11	3	4	2003	7	11	3	9	5	L	10326	35729	
9	2003	7	18	7	15	2003	7	18	15	12	477	PM	3	35732	
10	2003	7	18	15	15	2003	7	18	15	32	17	PP	3427	39159	
11	2003	7	21	0	39	2003	7	21	8	27	468	OS	81	39240	
12	2003	7	21	9	48	2003	7	21	13	10	202	PP	0	39240	
13	2003	7	21	13	10	2003	7	21	14	40	90	E	4013	43253	
14	2003	7	24	9	33	2003	7	24	9	37	4	PP	798	44051	
15	2003	7	24	22	55	2003	7	24	23	5	10	PP	1421	45472	
16	2003	7	25	22	46	2003	7	25	22	50	4	PP	1436	46908	
17	2003	7	26	22	46	2003	7	26	22	50	4	PP	1988	48896	
18	2003	7	28	7	58	2003	7	28	8	2	4	L	2208	51104	
19	2003	7	29	20	50	2003	7	29	21	30	40	FC	4911	56015	
20	2003	8	2	7	21	2003	8	2	7	24	3	L	25	56040	
21	2003	8	2	7	49	2003	8	2	7	51	2	PP	8875	64915	
22	2003	8	8	11	46	2003	8	8	11	59	13	PP	2691	67606	
23	2003	8	10	8	50	2003	8	10	8	52	2	L	449	68055	
24	2003	8	10	16	21	2003	8	10	22	0	339	OS	121	68176	
25	2003	8	11	0	1	2003	8	11	7	1	420	OS	0	68176	
26	2003	8	11	7	1	2003	8	11	15	33	512	PM	6281	74457	
27	2003	8	16	0	14	2003	8	16	0	18	4	L	7459	81916	
28	2003	8	21	4	37	2003	8	21	4	38	1	PP	16005	97921	
29	2003	9	1	7	23	2003	9	1	12	20	297	M	748	98669	
30	2003	9	2	0	48	2003	9	2	0	52	4	L	664	99333	
31	2003	9	2	11	56	2003	9	2	11	59	3	PP	1041	100374	
32	2003	9	3	5	20	2003	9	3	9	42	262	M	233	100607	
33	2003	9	3	13	35	2003	9	3	14	26	51	PLC	1171	101778	
34	2003	9	4	9	57	2003	9	4	10	14	17	E	68	101846	
35	2003	9	4	11	22	2003	9	4	11	27	5	L	1193	103039	
36	2003	9	5	7	20	2003	9	5	15	31	491	PM	3952	106991	
37	2003	9	8	9	23	2003	9	8	9	31	8	W	1748	108739	
38	2003	9	9	14	39	2003	9	9	14	57	18	M	443	109182	
39	2003	9	9	22	20	2003	9	10	0	27	127	E	10523	119705	
40	2003	9	17	7	50	2003	9	17	8	6	16	FC	6814	126519	
41	2003	9	22	1	40	2003	9	22	3	20	100	OS	8970	135489	
42	2003	9	28	8	50	2003	9	28	9	19	29	PP	1076	136565	
43	2003	9	29	3	15	2003	9	29	3	18	3	PP	27	136592	
44	2003	9	29	3	45	2003	9	29	3	48	3	PP	47	136639	
45	2003	9	29	4	35	2003	9	29	4	38	3	PP			
										TOTAL	79.30	hrs	2277.316667	51155.96667	hrs

Rapair rate	0.57	per hr
MTTR	1.76	hrs
Failure rate	0.02	per hr
MTTF	51.76	hrs
Laplace	0.02	

	Stop Duration
Criteria	>0
Count	45.00

Plant B

Primary Mill No. 13 **Combined Failures**

Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	10	39	638	OS	116	116
2	2003	6	23	12	35	2003	6	23	12	37	2	E	253	369
3	2003	6	23	16	50	2003	6	23	17	42	52	FC	2477	2846
4	2003	6	25	10	59	2003	6	25	12	2	63	E	16316	19162
5	2003	7	6	19	58	2003	7	7	10	15	857	OS	686	19848
6	2003	7	7	21	41	2003	7	7	21	44	3	L	1946	21794
7	2003	7	9	6	10	2003	7	9	6	36	26	FC	4472	26266
8	2003	7	12	9	8	2003	7	12	9	44	36	FC	4176	30442
9	2003	7	15	7	20	2003	7	15	18	30	670	PM	804	31246
10	2003	7	16	7	54	2003	7	16	8	13	19	M	-461	30785
11	2003	7	16	0	32	2003	7	16	0	44	12	PLC	14	30799
12	2003	7	16	0	58	2003	7	16	1	4	6	PLC	7	30806
13	2003	7	16	1	11	2003	7	16	3	35	144	PLC	7024	37830
14	2003	7	21	0	39	2003	7	21	8	27	468	OS	81	37911
15	2003	7	21	9	48	2003	7	21	13	14	206	PP	18	37929
16	2003	7	21	13	32	2003	7	21	14	17	45	PE	373	38302
17	2003	7	21	20	30	2003	7	21	20	34	4	L	2360	40662
18	2003	7	23	11	54	2003	7	23	12	0	6	L	1310	41972
19	2003	7	24	9	50	2003	7	24	13	1	191	PM	434	42406
20	2003	7	24	20	15	2003	7	24	20	18	3	L	497	42903
21	2003	7	25	4	35	2003	7	25	4	37	2	L	6924	49827
22	2003	7	30	0	1	2003	7	30	0	12	11	PP	6461	56288
23	2003	8	3	11	53	2003	8	3	11	54	1	L	323	56611
24	2003	8	3	17	17	2003	8	3	18	10	53	FC	812	57423
25	2003	8	4	7	42	2003	8	4	7	45	3	L	619	58042
26	2003	8	4	18	4	2003	8	4	18	55	51	PE	124	58166
27	2003	8	4	20	59	2003	8	4	21	3	4	L	777	58943
28	2003	8	5	10	0	2003	8	5	12	55	175	FC	6177	65120
29	2003	8	9	19	52	2003	8	9	19	56	4	L	3556	68676
30	2003	8	12	7	12	2003	8	12	15	57	525	PM	891	69567
31	2003	8	13	6	48	2003	8	13	6	50	2	L	11923	81490
32	2003	8	21	13	33	2003	8	21	13	36	3	L	3070	84560
33	2003	8	23	16	46	2003	8	23	16	48	2	L	1584	86144
34	2003	8	24	19	12	2003	8	24	19	18	6	L	461	86605
35	2003	8	25	2	59	2003	8	25	8	53	354	OS	5994	92599
36	2003	8	29	12	47	2003	8	29	13	30	43	PP	1736	94335
37	2003	8	30	18	26	2003	8	30	22	0	214	O	0	94335
38	2003	8	30	22	0	2003	8	30	22	21	21	L	376	94711
39	2003	8	31	4	37	2003	8	31	8	44	247	FC	4588	99299
40	2003	9	3	13	12	2003	9	3	14	25	73	FC	5617	104916
41	2003	9	7	12	2	2003	9	7	15	58	236	PP	1016	105932
42	2003	9	8	8	54	2003	9	8	9	13	19	PE	1317	107249
43	2003	9	9	7	10	2003	9	9	15	57	527	PM	291	107540
44	2003	9	9	20	48	2003	9	9	20	50	2	L	90	107630
45	2003	9	9	22	20	2003	9	10	0	27	127	E	4601	112231
46	2003	9	13	5	8	2003	9	13	5	12	4	L	6102	118333
47	2003	9	17	10	54	2003	9	17	10	57	3	PP	12902	131235
48	2003	9	26	9	59	2003	9	26	10	15	16	M		
										TOTAL	102.98	hrs	2187.25	47870.01667 hrs

Rapair rate 0.47 per hr
MTTR 2.15 hrs

Failure rate 0.02 per hr
MTTF 46.54 hrs
Laplace -0.07

	Stop Duration
Criteria	>0
Count	48.00

Plant B

	Primary Mill No. 14				**Combined Failures**									
Stoppage no.	Start					Stop							Run Duration	Cum Run Time
	Year	Month	Day	Hour	Min	Year	Month	Day	Hour	Min	Stop Duration	Stop Code		
1	2003	6	23	0	1	2003	6	23	10	32	631	OS	2907	2907
2	2003	6	25	10	59	2003	6	25	12	2	63	E	398	3305
3	2003	6	25	18	40	2003	6	25	23	4	264	PLC	248	3553
4	2003	6	26	3	12	2003	6	26	3	15	3	PP	138	3691
5	2003	6	26	5	33	2003	6	26	5	45	12	PP	342	4033
6	2003	6	26	11	27	2003	6	26	11	46	19	PP	370	4403
7	2003	6	26	17	56	2003	6	26	18	27	31	PE	7183	11586
8	2003	7	1	18	10	2003	7	1	20	4	114	M	1000	12586
9	2003	7	2	12	44	2003	7	2	12	56	12	L	509	13095
10	2003	7	2	21	25	2003	7	2	21	28	3	L	282	13377
11	2003	7	3	2	10	2003	7	3	2	16	6	L	9874	23251
12	2003	7	9	22	50	2003	7	9	22	51	1	PP	502	23753
13	2003	7	10	7	13	2003	7	10	15	2	469	PM	14977	38730
14	2003	7	21	0	39	2003	7	21	8	27	468	OS	81	38811
15	2003	7	21	9	48	2003	7	21	13	11	203	PP	11398	50209
16	2003	7	29	11	9	2003	7	29	12	15	66	PP	4208	54417
17	2003	8	1	10	23	2003	8	1	10	48	25	M	5540	59957
18	2003	8	5	7	8	2003	8	5	15	18	490	PM	38218	98175
19	2003	9	1	4	16	2003	9	1	4	18	2	L	1617	99792
20	2003	9	2	7	15	2003	9	2	15	28	493	PM	1327	101119
21	2003	9	3	13	35	2003	9	3	14	26	51	PLC	1130	102249
22	2003	9	4	9	16	2003	9	4	10	35	79	PP	7905	110154
23	2003	9	9	22	20	2003	9	10	0	27	127	E	1928	112082
24	2003	9	11	8	35	2003	9	11	11	11	156	M	10645	122727
25	2003	9	18	20	36	2003	9	18	21	14	38	FC	6112	128839
26	2003	9	23	3	6	2003	9	23	5	45	159	PP		
										TOTAL	66.42	hrs	2147.316667	20613.35 hrs

Rapair rate	0.39	per hr
MTTR	2.55	hrs
Failure rate	0.01	per hr
MTTF	85.89	hrs
Laplace	-0.17	

	Stop Duration
Criteria	>0
Count	26.00

Plant B
System Evaluation

Total number of mills (n)	7	
Minimum no. of mills required for system success (m)	4	
Average Failure rate per mill	0.0246	per hour
Average repair rate per mill	0.2978	per hour
Effective System Failure rate	0.0159	per hour
System MTTF	63.0763	hr
Effective System Repair rate	2.0845	per hour
System MTTR	0.4797	hr
System MTBF	63.5560	

		Rates				
State	Probability	Departure	Return	Frequency	Mean duration	Cycle time
0	0.8323	0.1719	0.8933	0.1431	5.8168	6.9890
1	0.1602	0.9916	2.2564	0.1588	1.0085	6.2966
2	0.0075	2.0845	0.0982	0.0157	0.4797	63.5560

	Plant B Average Failure Mode Reliability										
	PM	OS	FC	M	L	PP	PE	E	PLC	W	O
Failure rate	0.00161	0.00390	0.00355	0.00363	0.00790	0.00732	0.00129	0.00183	0.00269		0.00051
Repair rate	0.10004	0.09182	0.49326	1.37731	6.61614	3.76400	1.00462	0.86819	1.15215		3.45968
Time (hrs)											
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000		1.0000
100	0.8510	0.6773	0.7012	0.6955	0.4539	0.4810	0.8788	0.8331	0.7644		0.9506
200	0.7242	0.4587	0.4917	0.4837	0.2061	0.2314	0.7724	0.6940	0.5843		0.9037
300	0.6163	0.3107	0.3448	0.3364	0.0935	0.1113	0.6788	0.5781	0.4467		0.8591
400	0.5245	0.2104	0.2418	0.2340	0.0425	0.0535	0.5965	0.4816	0.3414		0.8167
500	0.4463	0.1425	0.1695	0.1627	0.0193	0.0258	0.5243	0.4012	0.2610		0.7764
600	0.3798	0.0965	0.1189	0.1132	0.0087	0.0124	0.4607	0.3342	0.1995		0.7381
700	0.3232	0.0654	0.0834	0.0787	0.0040	0.0060	0.4049	0.2784	0.1525		0.7017
800	0.2751	0.0443	0.0585	0.0547	0.0018	0.0029	0.3559	0.2319	0.1166		0.6670
900	0.2341	0.0300	0.0410	0.0381	0.0008	0.0014	0.3127	0.1932	0.0891		0.6341
1000	0.1992	0.0203	0.0287	0.0265	0.0004	0.0007	0.2749	0.1610	0.0681		0.6028
1100	0.1695	0.0138	0.0202	0.0184	0.0002	0.0003	0.2415	0.1341	0.0521		0.5731
1200	0.1443	0.0093	0.0141	0.0128	0.0001	0.0002	0.2123	0.1117	0.0398		0.5448
1300	0.1228	0.0063	0.0099	0.0089	0.0000	0.0001	0.1866	0.0931	0.0304		0.5179
1400	0.1045	0.0043	0.0070	0.0062	0.0000	0.0000	0.1640	0.0775	0.0233		0.4923
1500	0.0889	0.0029	0.0049	0.0043	0.0000	0.0000	0.1441	0.0646	0.0178		0.4680
MTTF	619.7891	256.6328	281.7491	275.3876	126.6127	136.6457	774.2756	547.4725	372.2462		1975.7560
MTTR	9.9956	10.8909	2.0273	0.7261	0.1511	0.2657	0.9954	1.1518	0.8679		0.2890
State Prob	0.0150	0.0394	0.0067	0.0024	0.0011	0.0018	0.0012	0.0020	0.0022		0.0001
Frequencies	0.0000242	0.0001535	0.0000237	0.0000089	0.0000088	0.0000132	0.0000015	0.0000036	0.0000058		0.0000001
el frequency	351.4	2233.3	344.9	129.3	127.3	192.2	22.4	51.9	84.6		1.0
P0	0.9282										

	Plant B Average Failure Mode Maintainability										
Time	PM	OS	FC	M	L	PP	PE	E	PLC	W	O
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2.5	0.2213	0.2051	0.7086	0.9680	1.0000	0.9999	0.9189	0.8859	0.9439	0.0000	0.9998
5	0.3936	0.3681	0.9151	0.9990	1.0000	1.0000	0.9934	0.9870	0.9969	0.0000	1.0000
7.5	0.5278	0.4977	0.9753	1.0000	1.0000	1.0000	0.9995	0.9985	0.9998	0.0000	1.0000
10	0.6323	0.6008	0.9928	1.0000	1.0000	1.0000	1.0000	0.9998	1.0000	0.0000	1.0000
12.5	0.7137	0.6826	0.9979	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
15	0.7770	0.7477	0.9994	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
17.5	0.8264	0.7995	0.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
20	0.8648	0.8406	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
22.5	0.8947	0.8733	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
25	0.9180	0.8993	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
27.5	0.9362	0.9199	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
30	0.9503	0.9364	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
32.5	0.9613	0.9494	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
35	0.9698	0.9598	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
37.5	0.9765	0.9680	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
40	0.9817	0.9746	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
42.5	0.9858	0.9798	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
45	0.9889	0.9839	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
47.5	0.9914	0.9872	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
50	0.9933	0.9899	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
52.5	0.9948	0.9919	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
55	0.9959	0.9936	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
57.5	0.9968	0.9949	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
60	0.9975	0.9960	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
62.5	0.9981	0.9968	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
65	0.9985	0.9974	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
67.5	0.9988	0.9980	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
70	0.9991	0.9984	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
72.5	0.9993	0.9987	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
75	0.9994	0.9990	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
77.5	0.9996	0.9992	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
80	0.9997	0.9994	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
82.5	0.9997	0.9995	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
85	0.9998	0.9996	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
87.5	0.9998	0.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
90	0.9999	0.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
92.5	0.9999	0.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
95	0.9999	0.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
97.5	0.9999	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000
100	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000

		Plant B Mills 1-14 Failure Rates										
		PM	OS	FC	M	L	PP	PE	E	PLC	W	O
Mill No.	1	0.001998	0.006190	0.001068	0.003471	0.003844	0.003647	0.001730	0.000983	0.001489	0.000000	0.002370
	2	0.001515	0.005286	0.001916	0.001948	0.047269	0.005900	0.000000	0.001967	0.020619	0.000000	0.000000
	3	0.001529	0.005789	0.000000	0.001971	0.000000	0.003241	0.001883	0.001475	0.000000	0.000000	0.000000
	4	0.002038	0.006179	0.025712	0.002471	0.005701	0.002910	0.004788	0.001637	0.003010	0.000000	0.000000
	5	0.001430	0.005837	0.002486	0.012293	0.009121	0.002568	0.000000	0.001966	0.001488	0.000000	0.003274
	6	0.001895	0.005139	0.002811	0.005636	0.002551	0.003358	0.000000	0.002415	0.001714	0.000000	0.000000
	7	0.001511	0.004062	0.000000	0.000000	0.007968	0.006063	0.000549	0.003486	0.002984	0.000000	0.001442
	8	0.001926	0.001521	0.002661	0.003299	0.000000	0.004739	0.000000	0.001921	0.002778	0.000000	0.000000
	9	0.001005	0.006150	0.004027	0.003008	0.012697	0.007875	0.000000	0.003325	0.000601	0.000000	0.000000
	10	0.000722	0.001285	0.004666	0.001943	0.001128	0.009825	0.003824	0.001063	0.000000	0.000000	0.000000
	11	0.001460	0.001725	0.000000	0.002524	0.004810	0.036291	0.003599	0.001595	0.002328	0.000000	0.000000
	12	0.001725	0.001856	0.000843	0.010529	0.004132	0.016037	0.000000	0.002129	0.000000	0.000000	0.000000
	13	0.002271	0.002024	0.003499	0.000578	0.009292	0.000000	0.001710	0.001063	0.000000	0.000000	0.000000
	14	0.001562	0.001510	0.000000	0.001165	0.002062	0.000000	0.000000	0.000545	0.000599	0.000000	0.000000
	Ave	**0.001613**	**0.003897**	**0.003549**	**0.003631**	**0.007898**	**0.007318**	**0.001292**	**0.001827**	**0.002686**	**0.000000**	**0.000506**

		Plant B Mills 1-14 Repair Rates										
		PM	OS	FC	M		PP	PE	E	PLC	W	O
Mill No.	1	0.110579	0.048426	0.714286	5.000000	3.624161	3.157895	0.504202	0.304054	2.142857	0.000000	22.500000
	2	0.095796	0.042576	0.827586	1.258741	3.380282	3.652174	0.000000	0.810811	1.323529	0.000000	0.000000
	3	0.104167	0.044833	0.000000	0.962567	0.000000	3.243243	1.304348	0.752351	0.000000	0.000000	0.000000
	4	0.136737	0.053995	0.409091	0.175097	3.373494	3.103448	1.475410	0.769231	1.417323	0.000000	0.000000
	5	0.117340	0.042341	1.041667	4.528302	1.298701	1.666667	0.000000	1.195219	3.157895	0.000000	1.935484
	6	0.068143	0.043282	0.050396	0.252987	12.000000	2.162162	0.000000	0.787746	1.200000	0.000000	0.000000
	7	0.090806	0.069622	0.000000	0.000000	2.714286	0.967742	3.243243	0.843750	1.229508	0.000000	24.000000
	8	0.113080	0.070478	0.740741	0.359281	0.000000	2.214022	0.000000	1.310044	2.181818	0.000000	0.000000
	9	0.074411	0.189974	0.329670	0.443350	1.648936	0.979592	0.000000	0.700730	1.846154	0.000000	0.000000
	10	0.050000	0.188976	0.014864	0.865385	5.294118	5.198556	3.750000	0.937500	0.000000	0.000000	0.000000
	11	0.068519	0.123558	0.000000	1.085973	18.000000	3.493361	2.222222	1.170732	1.250000	0.000000	0.000000
	12	0.121622	0.154639	2.142857	0.311958	17.142857	22.857143	0.000000	1.003344	0.000000	0.000000	0.000000
	13	0.125457	0.103582	0.634441	3.428571	13.714286	0.000000	1.565217	0.937500	0.000000	0.000000	0.000000
	14	0.123967	0.109190	0.000000	0.610169	10.434783	0.000000	0.000000	0.631579	0.380952	0.000000	0.000000
	Ave	**0.100044**	**0.091819**	**0.493257**	**1.377313**	**6.616136**	**3.764000**	**1.004617**	**0.868185**	**1.152145**	**0.000000**	**3.459677**