RELIABILITY ANALYSIS FOR TWO DRAGLINES IN TUNÇBİLEK LIGNITE MINE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF APPLIED AND NATURAL SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

DENİZ TUNCAY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
MINING ENGINEERING

SEPTEMBER 2014

Approval of the thesis:

RELIABILITY ANALYSIS FOR TWO DRAGLINES IN TUNÇBİLEK LIGNITE MINE

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ABSTRACT

RELIABILITY ANALYSIS FOR TWO DRAGLINES IN TUNÇBİLEK LIGNITE MINE

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September 2014, 120 pages

In modern mining activities, high-capacity complex machines are used and their availability plays a big role on the mine productivity. Draglines are one of the high capacity mining machines which result in decrease in production in case of failure or unavailability. This study aims to determine the effects of different components of two draglines (PAGE 736 and MARION 7820) to their availability and operability by choosing adequate reliability models and conducting fault tree analyses. Reliability analysis was conducted using the failure data of the draglines provided by the Western Lignite Enterprises (GLİ) lignite mine in Tunçbilek/Kütahya to determine the change in the draglines' reliability with respect to time. Reliability analyses were conducted by determining failure probability models. Fault tree analysis helped us understand the relations between the sub-units of each dragline with the help of a symbolic logic model. These analyses were also used to determine the critical elements which mostly affect the draglines reliability. Bucket units were distinguished to be more prone to failure for both draglines but when looked at components, components from other units were determined to have lower reliability, hence may need special attention. Also, the components with the highest reliability importance values were found to be changing with time when the draglines are operating. The results of this study should be considered when preparing a maintenance plan to concentrate on the components that have higher effect on the dragline's reliability.

Keywords: Dragline, System Reliability, Fault Tree Analysis (FTA), Mean Lifetime, Data Independency

ÖZ

TUNÇBİLEK LİNYİT MADENİNDE KULLANILAN İKİ ÇEKME KEPÇELİ YERKAZARIN GÜVENİLİRLİK ANALİZİ

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Eylül 2014, 120 sayfa

Modern madencilikte, yüksek kapasiteli makinalar kullanılmaktadır ve bu makinaların kullanılabilirliğinin ocağın üretimine büyük etkisi vardır. Çekme kepçeli yerkazarlar, yüksek kapasiteli maden makinalarındandır ve arıza veya kullanılamazlık durumunda üretimde büyük kayıplara neden olur. Bu çalışmanın amacı iki farklı çekme kepçeli yerkazarın (PAGE 736 and MARON 7820) bileşenlerinin, yerkazarın kullanılabilirliği ve işlerliğine olan etkilerinin, uygun güvenilirlik analizleri ve hata ağacı analizi yardımıyla belirlenmesidir. Güvenilirlik analizinde, Tunçbilek, Kütahya'daki Garp Linyit İşletmeleri (GLİ) linyit madeninden alınan arıza verileri ile arıza olasılık modeli oluşturularak, bu yerkazarların zamana bağlı güvenilirliklerindeki değişimi belirlenmiştir. Hata ağacı analizi ise, sembolik bir mantık modeli ile, yerkazarların altsistemlerinin arasındaki ilişkiyi anlamamızı sağlamıştır. Ayrıca, bu analizlerden yararlanarak, sistemin güvenirliğine en çok etkisi olan kritik elemanlar belirlenmiştir. Kepçe altsistemi, her iki yerkazar için de arızaya en meyilli ünite olarak belirlenmiştir ancak bileşen bazında bakıldığında, farklı altsistemlerin bileşenlerinin en düşük güvenilirlik değerlerine sahip olduğu görülmüştür ve özel ilgi gerektiğine karar verilmiştir. Ayrıca, en yüksek güvenilirlik önem değerlerine sahip bileşenlerin, yerkazarların çalışma süreleri boyunca farklılık gösterdiği belirlenmiştir. Bu çalışmanın sonuçları bakım onarım planlaması yapılırken dikkate alınmalı ve sistem güvenilirlğine etkisi en yüksek olan bileşenlere önem gösterilmedir.

Anahtar Kelimeler: Çekme Kepçeli Yerkazar, Sistem Güvenilirliği, Hata Ağacı Analizi (FTA), Oralama Yaşam Süresi, Veri Bağımsızlığı

ACKNOWLEDGEMENTS

First of all, I would like to express my deep and sincere gratitude and appreciation to my supervisor, Assoc. Prof. Dr. Nuray Demirel for her invaluable supervision, kind support, endless patience, and continuous guidance in preparation of this thesis. I also present my special thanks to the examining committee members, Prof. Dr. Celal Karpuz, Assoc. Prof. Dr. Sevtap Kestel, Assoc. Prof. Dr. Mehmet Ali Hindistan, and Assist. Prof. Dr. Ferhat Akgül for their valuable contributions and for serving on the M.Sc. thesis committee.

I would like to thank The Scientific and Technological Research Council of Turkey (TÜBİTAK – 111M320) for supporting this research.

I must express my special thanks to my officemate Onur Gölbaşı for all his help and contributions. I would also like to thank my friends and colleagues; Doğukan Güner, Mustafa Çırak, Uğur Alkan, and Selahattin Akdağ for their support and motivation.

Finally, I owe my loving thanks to my family. Without their encouragement and understanding it would have been impossible for me to finish this thesis.

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CHAPTER 1

INTRODUCTION

1.1 General Remarks

The productivity of a mine is highly affected by availabilities of the mining machinery and draglines are one of the highest capacity equipment causing immense direct and indirect costs when unavailable. This study aims to improve the availability and operability of two draglines (PAGE 736 and MARION 7820) by utilizing reliability and fault tree analysis and determining critical components responsible for the breakdowns. The analyses were conducted using the failure data provided by the GLİ mine in Tunçbilek/Kütahya. The reliability analysis provides failure probability distributions for the draglines' components to determine failure behavior of the components and the fault tree analysis determines the relations between the components, sub-units and their effects on the system reliability utilizing a symbolic logic model.

1.2 Statement of the Problem

The draglines consist of many sub-units and their maintenance directly effects the down times and frequencies of the dragline. The reliability of the dragline can be increased by regular maintenance and renewal but since these operations also have a cost, the optimum frequency should be determined. In order to determine the intervals for maintenance and repair, the change in the reliability of the dragline with time should be observed and a suitable distribution should be provided.

In order to determine the distribution of the relationship between reliability and time, some data should be gathered which are: failure times, times units regain function, failing sub-units, frequency of failure, and the duration of the repair and maintenance operations. The probability distribution of these data, their dependence or independence with each other and the similarity of the distributions should be tested. Also the relations between sub-units and the effect of their reliability on the reliability of the system should be examined. Determining the weakest and the most critical units is also important considering the overall reliability.

1.3 Objectives and Scope of Study

The objective of this study is to construct reliability models with the help of fault tree analysis for both draglines in order to determine the roles of different components in the draglines' overall reliability.

The elements of the main objectives are:

i. Carrying out reliability analysis
   - Obtaining a distribution model and verifying the suitability
   - Reliability estimation

ii. System characterization by fault tree analysis
   - System reliability estimation and analysis

iii. Determination of critical system components

The scope of this thesis is the reliability analysis of the draglines considering both the system and the sub-units using statistical modeling software and characterization of the system by fault tree analysis.

1.4 Research Methodology

The study mainly includes identifying the probability distributions of the failure data, determining reliability changes through time for each component of the draglines and determining a reliability model for the system. These analyses are achieved using probabilistic software called Weibull++ 7 (2011) and BlockSim 7 (2011) developed by ReliaSoft.

The main stages of the research methodology are listed as:

i. Collection of failure data from the GLİ coal mine for 2 operating draglines (PAGE 736 and MARION 7820),
ii. Classification of the failure data and calculations to find intervals between failures and failure occurrence times,
iii. Determination of the sub-units and their components considering expert opinion,
iv. Determination of probability distributions of the failure data for each sub-unit using the computer software Weibull++ 7,
v. Checking randomness and independence properties for the data sets by utilizing "Runs Tests",
vi. Reliability modeling of the sub-units, determining the change in reliability through time for the components,
vii. Fault tree analysis to combine sub-unit reliabilities and determining the reliability of the whole system using the software BlockSim 7, and
viii. Determination of critical components.

CHAPTER 2

LITERATURE SURVEY

2.1 General Remarks on Draglines

Draglines are large capacity excavators, used usually in open cast coal mining in the stripping operation. The biggest factor that affects the cost in coal mining is the stripping ratio thus, the stripping cost. Draglines have low unit cost due to the fact that they can remove up to 25 m thick overburden without the need for re-handling (Köse and Yalçın, 1985).

Using draglines is the most cost efficient technique up to 30-35 m of overburden thickness since there is no need for other equipment. In larger thicknesses of overburden, the draglines can't be used alone and requires a combination with bucket wheel excavator or excavator + mobile crusher + belt conveyor (Köse and Yalçın, 1985).

Draglines are commonly used in open cast coal mining in most countries. In the United States, 101 draglines with at least 40 yd^3 capacities carried out 40% of the stripping operations in the world. Following United States, the countries that utilizes the highest number of draglines are Australia with 61, South Africa with 25, Canada with 22, and India with 17 draglines (Gilewicz, 2000).

In Turkey, there are total of nine draglines, eight in government use and one in private sector.

2.2 Reliability Analysis

Reliability is commonly defined as the probability of a product not to fail under a certain condition during a defined duration (VDI Guideline, 2006). Reliability analysis is the calculation and evaluation of the reliability of a system, sub-units of a system or the critical parts of a system (Uzgören and Elevli, 2010).

The purpose of a reliability engineer is to examine the relation between the system operation and failure by studying:

- The reasons for system failure,
- The ways to develop reliable systems,
- The ways to measure and test reliability in design, operation and management, and
- The ways to maintain reliable systems by maintenance, fault diagnosis and prognosis.

The problems a reliability engineer to solve are: representation and modeling of the system, quantification of the model and representation, propagation and quantification of the system behavior uncertainties. (Zio, 2009).

The reliability of a system depends on the analysis of the failure times, times between failures and number of failures of a system during a given time. The main goal in reliability analysis is to define a statistical model which fits these data best. There are five main stochastic process models used in the modeling of repairable systems which are: Renewal Process, Homogeneous Poisson Process, Branching Poisson Process, Superposed Renewal Process and the Non-Homogeneous Poisson Process.

Before selecting a process, a trend test should be conducted. There are two main types of trend testing methods: graphical method and analytical method. The main graphical methods used are: cumulative failure vs. time plot, scatter plot of successive service lives, Nelson-Aalen plot and total time on test (TTT) plot. The main analytical methods are: the Mann test, Laplace test, Lewis-Robinson test and the military handbook test (Louit *et al*., 2009).

For the reliability analysis of mining machinery, usually Renewal Process or Non-Homogenous Poisson Process models are utilized (Uzgören *et al*., 2010). If a system can be repaired into a "good as new" condition, the failure process is stationary and called renewal process. If there is a trend in the numbers of failure in relation with the total age of the system, the process is called non-homogenous Poisson process (Uzgören *et al*., 2010).

The intensity function in non-stationary models is usually defined as a Weibull distribution. Weibull distributions are divided into 7 groups (I-VII). In failure times modeling, mostly two-parameter Weibull distributions (Model I) are used. Since they have wide range of shapes for the density and hazard functions, they are suitable for modeling complex failure data sets (Murthy *et al*., 2004).

2.3 Reliability Analysis in Mining Machinery

The production machinery in the mining industry tends to improve and evolve rapidly with the new technology, usually regarding the increase in capacity. Decisions concerning which equipment to get and what kind of maintenance plans to implement become more important (Hall *et al*., 2000). The improvement in the technology also results in the increase of the equipment costs. Due to this increase, having substitute equipment becomes economically ineffective and pushes the buyers to prefer more reliable equipment (Dhillon, 2008). Some of the reliability studies done for mining equipment are listed in Table 2.1.

Table 2.1 Reliability studies of mining machines (modified from Uzgören *et al.*, 2010)

Year	Author(s)	Machine
1989	Kumar, U.	LHD
1992	Kumar, U. and Klefsjö, B.	LHD
1993	Kumar, D. and Vagenas, N.	LHD
1994	Paraszczak, J. and Perreault, J.F.	LHD
1995	Majumadar S.K.	Hydraulic Excavator
1997	Vagenas *et al*.	LHD
2001	Pulcini G.	Rear Dump Truck, LHD
2001	Rao K. R. M and Prasad P. V. N	LHD
2001	Samanta, B. *et al*.	Hydraulic Shovel
2003a	Hall, R.A. and Daneshmend, L.K.	Hydraulic Shovel
2003b	Hall, R.A. and Daneshmend, L.K.	Scoops and Trucks
2004	Lhorente *et al*.	Electric Haul Truck
2005	Barabady J. and Kumar U.	Crushing Plant
2007	Barabady J. and Kumar U.	Crushing Plant
2008	Elevli S. *et al*.	Electric Shovel
2008	Barabady J. and Kumar U.	Crushing Plant
2009	Gupta S. *et al*.	Armoured Flexible Conveyor
2009	Louit D.M. *et al*.	Backhoe
2009	Vagenas, N. and Wu X.	LHD
2010	Uzgören *et al.*	Dragline
2010	Uzgören and Elevli	Dragline

The objective of the study conducted by Barabady and Kumar (2007) was to increase the reliability of a crushing plant at Jajarm bauxite mine in Iran by systematic maintenance. The procedure followed is similar in most cases. First of all the time to fail and repair time data are collected for each sub-unit and the reliabilities of these units are calculated statistically. Using these data, the sub-units, affecting the system reliability and availability the most, are determined and the maintenance intervals for the system to have a required reliability are calculated for each sub-unit. As a result of the study, more frequent maintenance for the most critical units considering the system reliability and availability was found to be required for higher system efficiency.

Roy *et al.* (2001) conducted a study to determine maintenance intervals for four different shovels by examining their failure patterns. The times between failures and repair times were evaluated; characteristics of the shovels' reliability and maintainability were determined and fitted into a distribution. After the most suitable reliability distributions were determined for both the sub-units and the system, the most critical units were designated and appropriate maintenance policies were selected. As a result, the most influential units for the system reliability were found to be the dipper and the electrical sub-units. Calculations showed that in order to keep the system reliability at 75%, these sub-units' maintenance should be carried out in 18.9 h and 28.7 h intervals respectively.

Samanta *et al.* (2004) analyzed the performance of an LHD by reliability modeling. The aim of the study was to evaluate and model the reliability, availability and maintainability data of the LHD according to the Markov Model. First of all, the block diagram of the reliabilities of the sub-units was created. Then the failure data were analyzed to see whether it fits the Markov Model and the effects of the sub-units to the system reliability and maintainability were evaluated. As a result, transmission and the hydraulic systems were found to be the most critical units to affect the LDH's reliability.

In addition to these studies, Uzun and Özdoğan (2011) additionally considered the economic aspects. The aim of the study was to analyze failure data of a production line and determining a maintenance model considering maintenance cost. Firstly the failure data are examined to determine an appropriate probability distribution and the reliability of the system and the sub-units were calculated for different time intervals.

Another study focusing on the economic aspects was conducted by Lhorente *et al.* (2004). The study aimed to determine an appropriate age-based maintenance strategy for the motor armature of a mine truck. The four year maintenance data of the armatures were used to determine fitting failure distributions and the effects of preventive and corrective maintenance on the armature's failure distribution were investigated. Optimum preventive maintenance intervals were determined by examining the unit costs for different preventive maintenance intervals. The optimum interval was found to be 14,500 hours and comparing that to the previous maintenance interval, which was 10,000 hours, showed that the yearly revenue would increase by US$ 163,900 and the unit's availability would increase by 2.33%.

There are various studies on kinematic and dynamic behavior of draglines' working components. They mostly deal with kinematics of working components of draglines or optimization of operational parameters (Dayawansa *et al.*, 2006; Demirel, 2011; Demirel and Frimpong, 2009; Frimpong and Demirel, 2009; Townson *et al.*, 2003; Hal *et al.*, 2000). There are few studies in the literature focusing on the reliability of draglines. One of the studies that focus on dragline reliability was conducted by Uzgören and Elevli (2010). Their study aimed to determine if the failure data from the dragline follows a trend by analyzing the data. Trend analyses were conducted on the time between failure (TBF) data to see if there is a trend and according to those analyses, appropriate distribution model was determined and reliability analyses were carried out. It was suggested that the renewal process models were not appropriate since there occurs a trend in the data. Considering the trend, power law process model was decided to be appropriate and according to this model, it was seen that the time between failures were decreasing with time hence, the reliability of the dragline was decreasing. As a conclusion, it was suggested that preventive maintenance planning would be beneficial.

Another reliability study focusing on draglines was conducted by Uzgören *et al.* (2010) which was a comparison of two draglines. The study aimed to determine the reliabilities of two different draglines for different time intervals, calculate necessary maintenance frequencies and compare the results for each dragline. The procedure followed in reliability analysis was determining the appropriate probability distributions and calculating the reliabilities for different time intervals. Maintenance intervals were established considering the calculations. It was concluded that the working conditions for the same kind of machinery may result in different reliability characteristics; therefore, maintenance planning should be done accordingly. Different from those two studies where the failure data for the whole dragline were processed, the components of the draglines were analyzed individually in our study. Studying components individually would help planning component based preventive maintenance.

2.4 Fault Tree Analysis

Fault tree analysis (FTA) is an analytical technique used to analyze a system to determine all the credible ways in which a single undesired event (top event) can occur. FTA is a top to down, failure oriented symbolic logic model used to determine the probability of the top event by identifying failure paths leading to it. (Ericson II, 1997)

FTA is firstly applied to the Minuteman Launch Control System in 1961 by H. Watson in the Bell Labs together with U.S Air Force (Lee *et al.*, 1985). Then, Boeing Company used it for complete quantitative safety analysis of the Minuteman weapon system. The Boeing Company enhanced the technique, developed the first FT computer codes and used it for many other products. Then the FTA was discovered by nuclear power industry and enhanced and refined further (Ericson II, 1999).

FTA consists of the generation of the fault tree, determination of the failure probabilities of each event, determining probability of the top event by propagating failure probabilities and determining cut sets and path sets. The cut set is any set of events where if they all occur, the top event occurs. The path set is a group of sets which guarantees that the top event cannot occur if none of them occurs.

Fault tree analysis can be used for different purposes:

- to understand the logical path leading to the top event
- to determine the prior contributors to the top event
- to anticipate actions to prevent the top event
- to monitor the performance of the system
- to optimize resources
- to help with the system design
- to determine the cause of the top event and determine a solution

FTA can be used throughout the life cycle of the system. FTA has a wide variety of uses in decision making as seen above from design process through system implementation and improvement (Stamatelatos and Vesely, 2002).

The terminology in fault tree analysis is of great importance for defining the problem. There are some standard definitions and mechanics provided to define the problem completely. Some of these standard definitions are as follows (Ericson II, 1997):

- Tree: a fault tree composed of all events and logic connections which lead to the occurrence of the undesired incidence, i.e. top event.
- Tree Top (Top Event): the ultimate undesired event that is being investigated. A fault tree can only have one top event.
- Branch: a section of the fault tree with events and logic gates.
- Module: an independent branch with a sub-top event that does not occur anywhere else.
- Event: a general term used to define every event on the tree; failure, gate, condition etc.
- Gate: a logical Boolean operator with a specific function that combines input events.
- MOE (Multiple Occurring Event): an event that occurs in multiple places in the fault tree causing branch dependencies.

- Cut Set: a set of events that their occurrence cause the top event to occur (failure path)
- Minimum Cut Set: a cut set with the minimum number of events that still cause the top event to occur.
- Critical Path: a cut set with highest probability which consequently has the biggest effect on the probability of the top event. Improvements in this path results in most dramatic system improvements.

More precise definitions were added since some of these terms were loosely defined, interchangeable with each other and out of date. Some of these terms are given as (Ericson II, 1997):

- Node: a general term to define each event, gate, input or condition in a fault tree
- Basic Event: a node that represents a failure event that failure probability is given as input.
- Gate Event: a node with an operator that combines input events. (AND, OR, Inhibit, Priority AND and Exclusive OR gates)
- Condition Event: a basic event which is a condition before a gate event.
- Intermediate Event: Cause-effect relations used to reach a basic event.

Fault trees are generally evaluated according to their cut sets. Cut sets form the basis for the function of systems by enabling the quantification of event probabilities or the expected frequencies (Hauptmanns, 2010).

Logic operators used in fault tree analysis are defined as (Ericson II, 1997):

Gates:

- OR gate: occurrence of at least one input is enough for the output to occur.
- AND gate: all input events must occur for the output event to occur.

- Inhibit gate: inputs must occur and a condition should be satisfied for the output event to occur.
- Exclusive OR gate: only one input should occur for the output event to occur.
- Priority AND gate: all input events must occur in a specific sequence for the output to occur.

Events:

- Condition: a node (conditional event) in a branch that inflicts a conditional restriction or a probability to the sequence of events.
- Primary Failure: a basic component failure.
- Secondary Failure: a failure event that can be further developed but left for convenience.
- External Event: an expected event in the failure path and necessary to be included.

The symbols assigned to these operators are shown in Figure 2.1

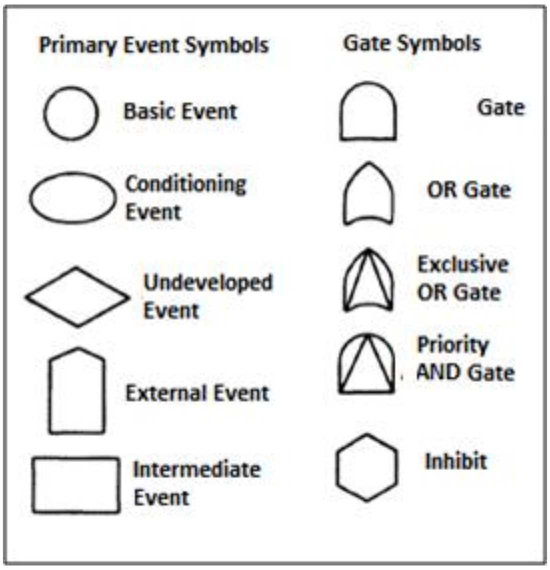


Figure 2.1 Symbols used for operators in Fault Tree Analysis (Vesely *et al.*, 1981)

The main advantages of fault tree analysis can be listed as (Limnios, 2007):

- Enables us to calculate compound failure probabilities in complex systems.
- Enables us to diagnose single point failures and take precautions accordingly.
- The sensitivities of the system and the low effect solutions can be determined and more efficient use of resources in risk reduction can be achieved.
- Alterations on the system can be made in order to reduce the failure probabilities.
- Comparison of different practices to reduce failure in terms of cost and effectiveness.

In addition to these advantages, fault tree analysis also has some constraints and disadvantages such as:

- Fault tree analysis allows only one top event to be analyzed so more than one fault trees may be required for a system
- Probability calculations for large and complicated systems may require advanced computers and software.
- Determining a definite failure probability may be time and resource consuming and limiting the fault trees extent may be needed.
- It is not possible to make a definite calculation without putting all of the important failure components into account.
- Every event in a logic gate should be independent.
- Considering natural events are important in the reliability of the analysis.
- The events in each level of the fault tree should be independent and they should be directly related to the events in adjacent levels.
- Each event should have a constant and predictable failure probability. Generally, it is difficult to calculate precise failure probabilities, so relative analyses help us to get better results.

Since fault tree analysis is highly dependent on the knowledge and expertise of the analyst, it is difficult to make a clear definition on how to construct a fault tree. Fault tree requires detailed analysis and may require comprehensive assumptions, but other than those, the main steps to be followed are as follows (Öktem, 2006):

- Determining the top event: the undesired event to be analyzed is chosen.
- Combining the known causes: existing faulty states and failure events are determined with the available knowledge. Even though the failure list can be lacking, it is important for the fault tree construction.
- Construction of the fault tree: independent events that may cause the top event are determined. These events are connected with an OR gate and the construction continues from top to bottom trying to find other failure causes.
- Revision, addition and testing: fault tree construction is a trial and error process no failure causes should be overlooked.
- Evaluation of the results: the completed fault tree is evaluated according to the purpose of the analysis. The evaluation can include various stages: listing minimum cut sets, grading minimum cut sets, and calculation of probabilities etc.

One of the important results acquired from fault tree analysis are "Importance Measures". These measures determine each event's effect on the top event or determine the sensitivity of the top event to the changes in probabilities of each event. The most convenient property of these importance measures is that it shows that, only a little portion of basic events are actually influential on the top event. Former studies showed that less than 20% of the basic events have significant effect on the top event.

There are 4 different importance measures that can be calculated for different purposes and these are (Vesely *et al*., 2002):

- Fussell-Vesely (F-V) Importance Measure: an event's contribution to the top event.
- Risk Reduction Worth (RRW): reduction in the top event's probability when a basic event is definitely not occurring.

- Risk Achievement Worth (RAW): increase in the top event probability when a basic event is sure to occur.
- Birnhaum's Importance Measure (BM): change in the top event's probability when a basic event's probability is changed.

2.5 Applications of Fault Tree Analysis in Engineering

There have been numerous studies conducted on the subject of fault tree analysis. Figure 2.2 shows the number of studies on this subject from 1961, the year the concept was introduced, until 1997 (Ericson II, 1999). It can be seen that there is an increasing interest for fault tree analysis.

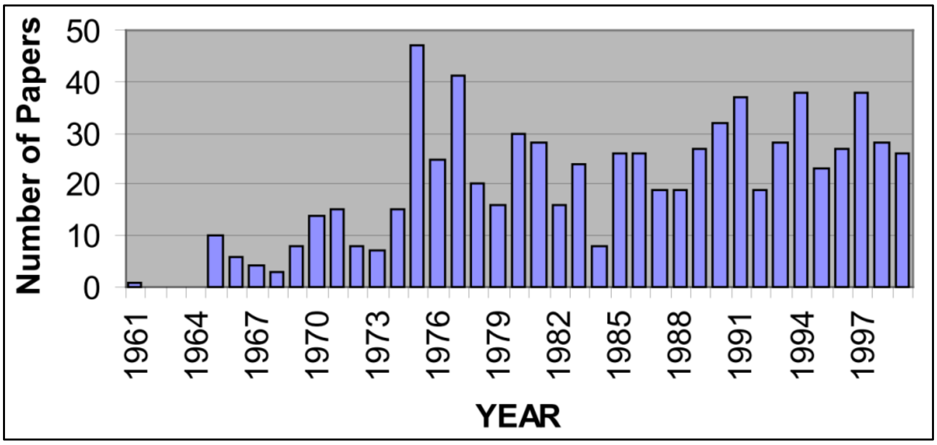


Figure 2.2 Number of studies conducted about fault trees till 1997 (Ericson II, 1999)

If looked at some recent studies in fault tree analysis, the study conducted by Samanta *et al*. (2002) uses fault tree analysis to analyze the reliability of a hydraulic shovel system. Shovel-truck systems are widely used in surface mining operations and the shovel's reliability plays a big role in the production efficiency.

In former reliability studies for mining machinery, reliability calculations are done by combining the probability distributions of the systems and sub-units with analytical methods. In their study, the steps followed for the reliability analysis are as follows;

i. Generation of a reliability block diagram
ii. Generation of the fault tree
iii. Determination of the minimum cut sets
iv. Determination of minimum path sets
v. Evaluation of the reliability

Block diagram is a combined view of components of a system with a reliability point of view. In their study, the shovel system is divided into three subsystems: power generating unit, power development unit and power utilization unit. The reliability block diagram is generated as seen in Figure 2.3 with the units: power generating unit (PGU), power development unit (PDU), and power utilization unit (PUU). Each x in the figure represents a component of the shovel. This block diagram was later represented as fault tree by using event and condition symbols as seen in Figure 2.4.

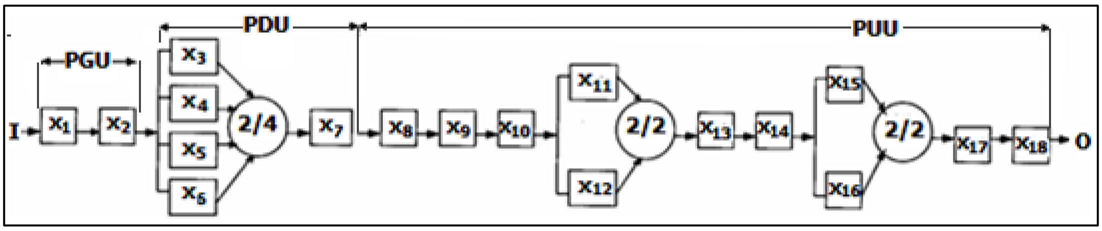


Figure 2.3 System reliability block diagram (Samanta *et al.*, 2002)

The graphical representation of the gates, their Boolean equations and the probability relations are explained in Table 2.2.

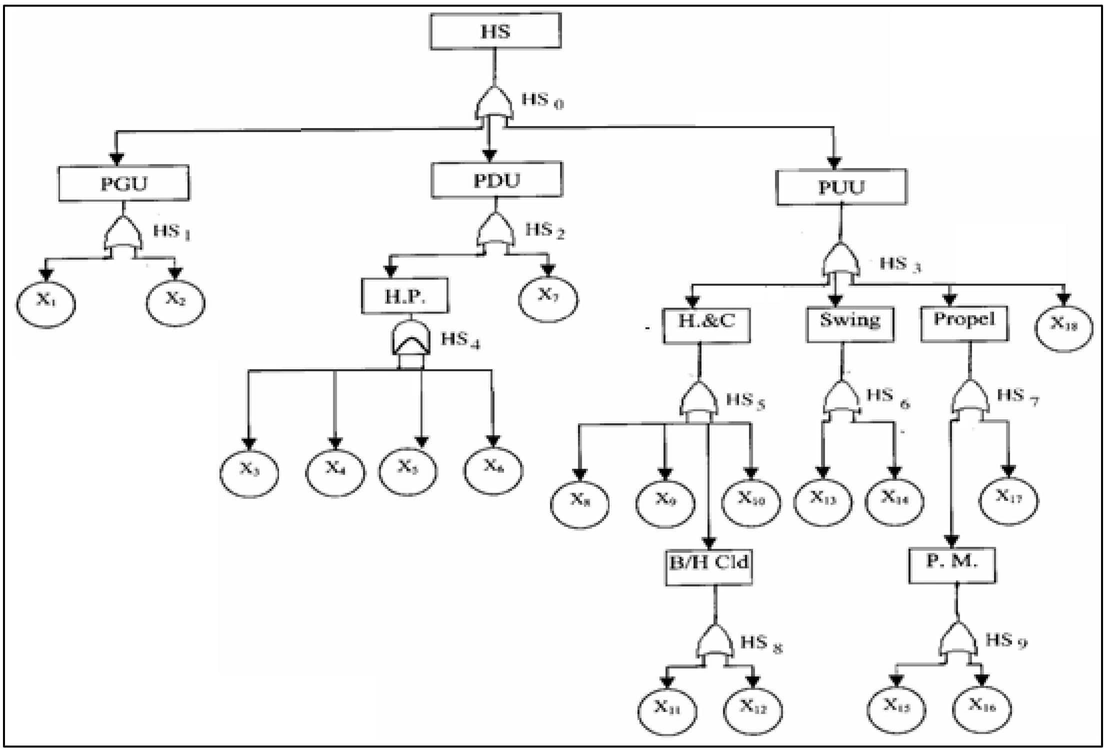
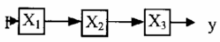
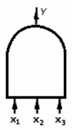
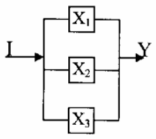
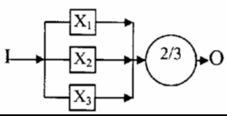


Figure 2.4 Fault tree representation of the system (Samanta *et al.*, 2002)

Table 2.2 The graphical representation of the gates, their Boolean equations and the probability relations (Samanta *et al.*, 2002)

Logic gate	Logic symbol	Graph in terms of fault tree	Boolean equation	Probability relation
OR			$Y = x_1 + x_2 + x_3$	$P(y) = P(\bar{x}_1 + \bar{x}_2 + \bar{x}_3)$ $= P(\bar{x}_1) + P(\bar{x}_2) + P(\bar{x}_3) -$ $P(\bar{x}_1)P(\bar{x}_2) - P(\bar{x}_1)P(\bar{x}_3) -$ $P(\bar{x}_2)P(\bar{x}_3) + P(\bar{x}_1)P(\bar{x}_2)P(\bar{x}_3)$
AND			$Y = x_1 x_2 x_3$	$P(x_1 x_2 x_3) = P(\bar{x}_1)P(\bar{x}_2)P(\bar{x}_3)$
Voting gate			$Y = x_1x_2 + x_1x_3 + x_2x_3 + x_1x_2x_3$ $= x_1x_2 + x_1x_3 + x_2x_3$ after decomposing	$P\{\bar{x}_1\bar{x}_2 + \bar{x}_1\bar{x}_3 + \bar{x}_2\bar{x}_3\}$ $= P(\bar{x}_1\bar{x}_2) + P(\bar{x}_1\bar{x}_3) + P(\bar{x}_2\bar{x}_3)$ $- P(\bar{x}_1\bar{x}_2)(P(\bar{x}_1\bar{x}_3) - P(\bar{x}_1\bar{x}_2)(P(\bar{x}_2\bar{x}_3)$ $- P(\bar{x}_1\bar{x}_3)(P(\bar{x}_2\bar{x}_3)$ $+ P(\bar{x}_1\bar{x}_2)P(\bar{x}_1\bar{x}_3)P(\bar{x}_2\bar{x}_3)$

For the system reliability analysis, cut sets must be determined after the fault tree is generated. Minimum cut set I calculated using Fussel's algorithm and Boolean logic expression. Simplified fault tree after determining the cut sets is represented in Figure 2.5.

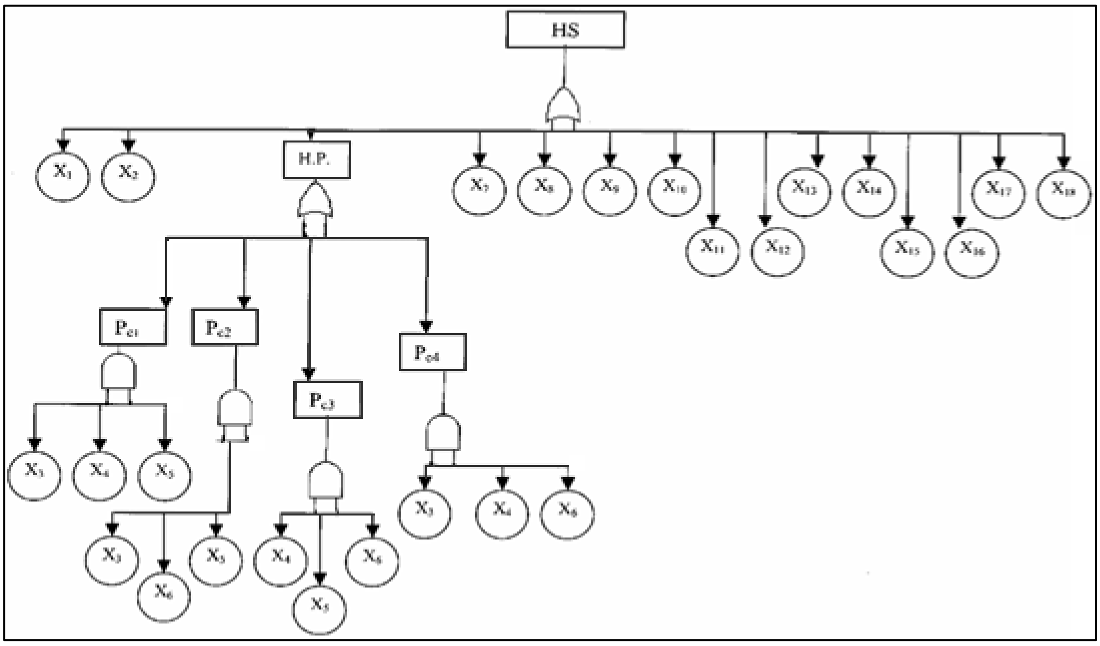


Figure 2.5 Simplified fault tree of the system (Samanta *et al.*, 2002)

The fault tree analysis showed that the elements that require most attention were found to be $x_{1,2,7,8,9,10,11,12,13,14,15,16,17,18}$. Occurrence of any of these events guarantees the occurrence of the top event.

Figure 2.6. was obtained as a result of reliability calculations, and it was seen that the most reliable subsystem was the "power development unit (PDU)". The subsystem with the highest rate of decrease in reliability was found to be the "power utilization unit (PUU)" due to many events being connected by OR gates. Improving the reliability of this unit can be achieved by improving the maintenance planning.

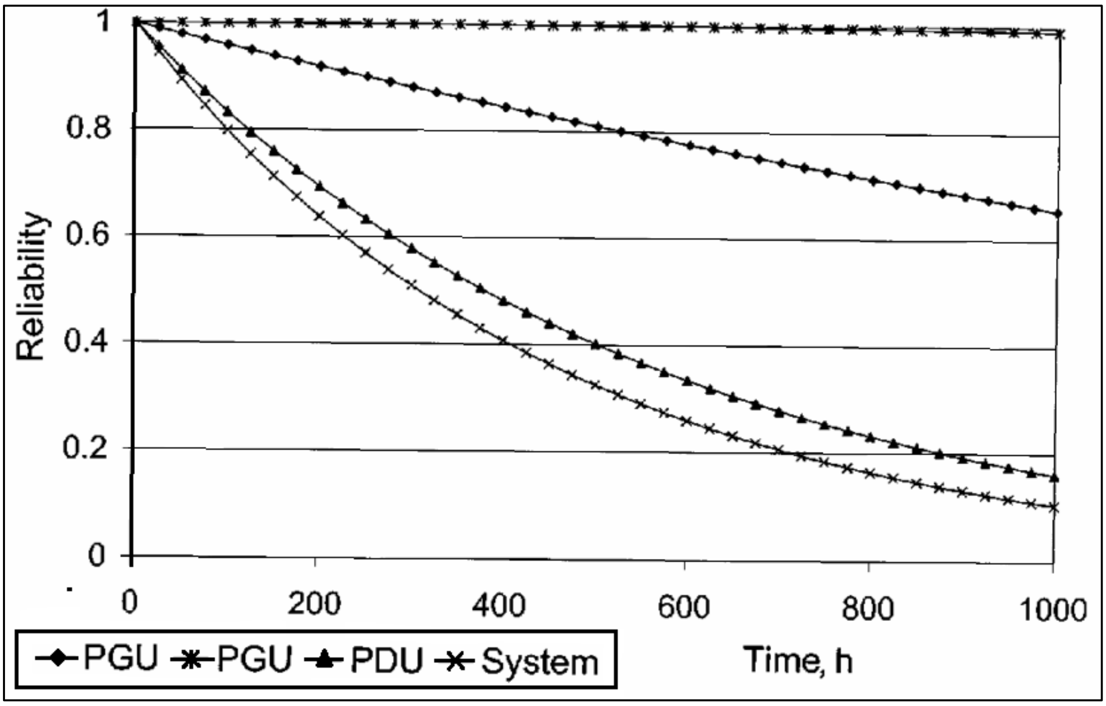


Figure 2.6 Reliability changes with time for the shovel and the subsystems (Samanta *et al.*, 2002)

As a result of the study, it was concluded that the fault tree analysis is a powerful tool in evaluating the reliability and working behavior of machines, preparing maintenance planning and determining critical units of a system.

Another study conducted by Hong and Lee (2009) aimed to determine the reliability of a composite system by combining deterministic approach with fault tree analysis. The subject of the study was the Taipower transmission system in Taiwan. Firstly, it was decided that the system condition was divided into three sets: normal, local trouble and system trouble. Some examples of local troubles are line overload, low voltage and high voltage and the system troubles are voltage collapse and non-convergence. Local troubles can be fixed by load curtailment; however the system troubles usually lead to system blackouts.

The fault tree analysis both contain local and system troubles. In the study, two criteria were used to classify failure;

- N1: a transmission line, transformer or a generator has an outage
- N2: divided into two sub-criteria
    - Two transmission lines are out (N2(LL))
    - Maximum capacity generator is out and a transmission line is out (N2(GL))

If any of the events N1 and N2 occurs, the system cannot continue operating. This means the fault tree is composed of three sub-top events (N1, N2(LL) and N2(GL)) connected by an OR gate. Each of these sub-top events are represented by a fault tree. After constructing the fault tree, minimum cut sets are determined for each sub-top event by using Boolean calculations.

In their study, in order to determine reliabilities, the availabilities of the components were utilized. Three parameters were used in the calculations (F, D and U). F is the failure frequency of the component, D is the mean failure time and U is the component's unavailability. The relationship between these parameters is shown in Equations 1 – 4 (Hong and Lee, 2009).

$$F = P_{IN} \times \lambda = P_{OUT} \times \mu \quad (1)$$

$$D = \frac{P_{OUT}}{F} \quad (2)$$

$$U = F \times D \quad (3)$$

$$\lambda = \frac{F}{1 - F \times D} \quad (4)$$

P_{IN} and P_{OUT} are the probability of the component to be available and unavailable, respectively. λ is the failure rate and μ is the repair rate of the component. Using these equations, F, D and U parameters are calculated for the sub-components and using cut sets, these parameters are calculated for sub-top events. Table 2.3 shows these parameters calculated for the sub-top events.

Table 2.3 F, D and U parameters calculated for top and sub-top events (Hong and Lee, 2009)

	U	**F**	**D**
N1	10.0316	0.5770	15.23
N2 (LL)	1.3034	0.0661	17.27
N2 (GL)	0.2338	0.0120	17.02
N1 and N2 (top event)	11.5689	0.6546	15.48

In addition to these parameters, Risk Reduction Worth (RRW) for each transmission line is calculated and the lines with the highest effect on failure are determined. Table 2.4 gives the RRW values of five most effective transmission lines for each sub-top event. As seen in Table 2.4, the most effective lines for N1, N2 (LL), and N2 (GL) are 2491, 710, and 94 respectively.

Table 2.4 RRW values of three most effective transmission lines for each sub-top event (modified from Hong and Lee, 2009)

SUB-TOP	**Transmission**	**RRW**
N1	**2491**	**1.25**
	944	1.14
	2499	1.11
N2 (LL)	**710**	**5.98**
	602	1.19
	707	1.04
N2 (GL)	**94**	**1.00**
	199	1.00
	5	1.00

Five most effective transmission lines for the top event and their RRWs are given in Table 2.5. It can be seen that the most important transmission line for the top event is line 2491 which is 46 km long with 161 kW.

Table 2.5 Five most effective transmission lines for the top event (modified from Hong and Lee, 2009)

TOP EVENT	LINE	RWW
N1 and N2	**2491**	**1.213**
	944	1.121
	710	1.103
	2499	1.099
	471	1.057

In another reliability study (Wang, 2010), precautions for possible oil tank fires and explosions were investigated using fault tree analysis. Importance degrees were calculated after determining cut sets, main causes for top events and possible precautions were discussed. The top event for the fault tree analysis is chosen as oil tank fire or explosion and 25 possible reasons were determined for the top event to occur. The generated fault tree is shown in Figure 2.7. After generating the fault tree, 7 cut sets (P_1 – P_7) were found as seen in Figure 2.8.

Using these cut sets, importance degree coefficients for each event are calculated. For each event x_i, an $I\varphi(i)$ value is calculated and the results are shown in Figure 2.9. In order to give an example to the calculations, in determining the importance degree coefficient for x_1 ($I\varphi(1)$), the numbers 13 and 10 represent the number of elements of the cut sets in which x_1 is present (P_1, P_2).

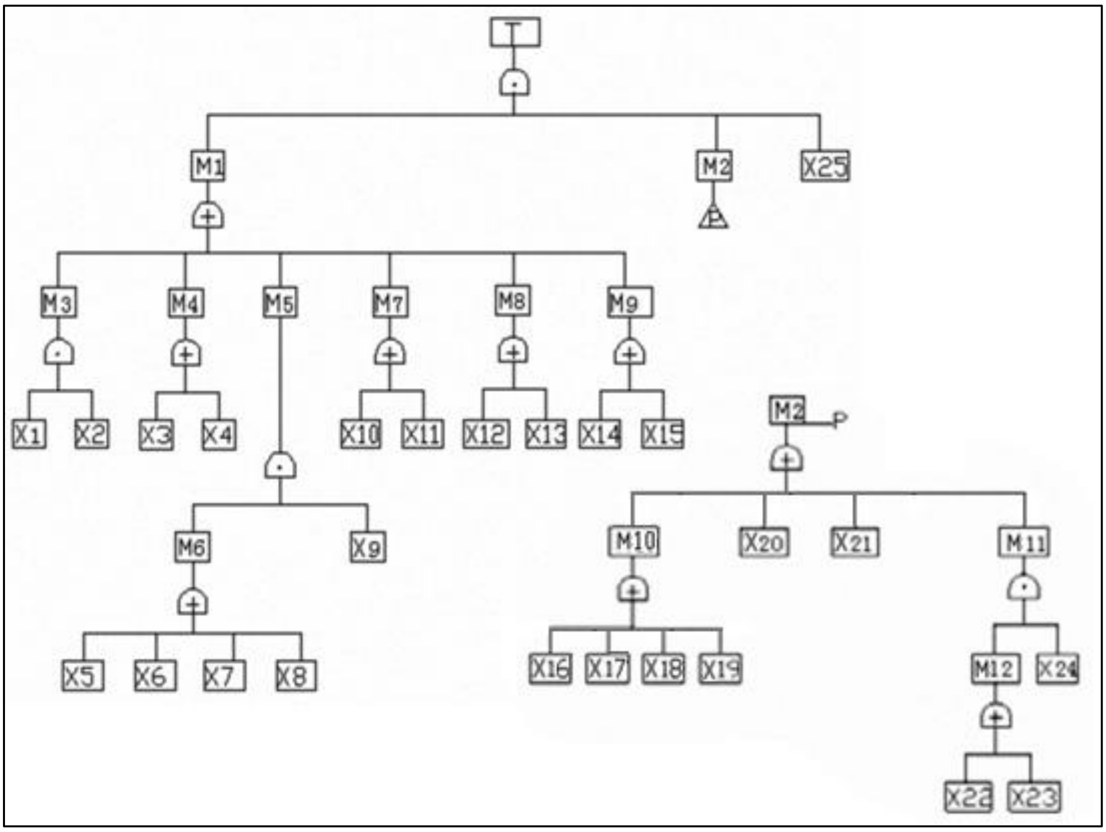


Figure 2.7 Fault tree representation of the system (Wang, 2010)

$P_1 = \{ x'_1 x'_3 x'_4 x'_5 x'_6 x'_7 x'_8 x'_{10} x'_{11} x'_{12} x'_{13} x'_{14} x'_{15} \}$

$P_2 = \{ x'_1 x'_3 x'_4 x'_9 x'_{10} x'_{11} x'_{12} x'_{13} x'_{14} x'_{15} \}$

$P_3 = \{ x'_2 x'_3 x'_4 x'_5 x'_6 x'_7 x'_8 x'_{10} x'_{11} x'_{12} x'_{13} x'_{14} x'_{15} \}$

$P_4 = \{ x'_2 x'_3 x'_4 x'_9 x'_{10} x'_{11} x'_{12} x'_{13} x'_{14} x'_{15} \}$

$P_5 = \{ x'_{16} x'_{17} x'_{18} x'_{19} x'_{20} x'_{21} x'_{22} x'_{23} \}$

$P_6 = \{ x'_{16} x'_{17} x'_{18} x'_{19} x'_{20} x'_{21} x'_{24} \}$

$P_7 = \{ x'_{25} \}$

Figure 2.8 Cut sets of the fault tree (Wang, 2010)

$$I_\varphi(1) = I_\varphi(2) = \frac{1}{2^{13-1}} + \frac{1}{2^{10-1}} = 0.002197$$

$$I_\varphi(3) = I_\varphi(4) = I_\varphi(10) = I_\varphi(11) = I_\varphi(12) = I_\varphi(13) = I_\varphi(14) = I_\varphi(15) = \frac{1}{2^{13-1}} + \frac{1}{2^{10-1}} + \frac{1}{2^{13-1}} + \frac{1}{2^{10-1}} = 0.008789$$

$$I_\varphi(5) = I_\varphi(6) = I_\varphi(7) = I_\varphi(8) = \frac{1}{2^{13-1}} + \frac{1}{2^{13-1}} = 4.88 \times 10^{-4}$$

$$I_\varphi(9) = \frac{1}{2^{10-1}} + \frac{1}{2^{10-1}} = 0.003906$$

$$I_\varphi(16) = I_\varphi(17) = I_\varphi(18) = I_\varphi(19) = I_\varphi(20) = I_\varphi(21) = \frac{1}{2^{8-1}} + \frac{1}{2^{7-1}} = 0.0234375$$

$$I_\varphi(22) = I_\varphi(23) = \frac{1}{2^{8-1}} = 0.0078125$$

$$I_\varphi(24) = \frac{1}{2^{7-1}} = 0.015625$$

$$I_\varphi(25) = 1$$

Figure 2.9 Iφ(i) values for each event x_i (Wang, 2010)

As a result of these calculations, it was concluded that the event with the highest effect on the top event was X_{25} (oil and gas mixture concentration reaching explosion limit). The most important events for the top-sub events M_1 and M_2 are found as:

for M_1: X_3, X_4, X_{10}, X_{11}, X_{12}, X_{13}, X_{14} and X_{15}
for M_2 : X_{16}, X_{17}, X_{18}, X_{19}, X_{20} and X_{21}

After that possible precautions were discussed. Since oil and gas mixing cannot be prevented as long as there is free space and oil evaporation occurs, precautions to eliminate ignition sources were considered. Other than that, since leakage and inadequate ventilation may cause mixing, it was suggested that precautions for those circumstances to be also taken.

The study conducted by Halme and Aikala (2012) utilized fault tree analysis to analyze reliability and failure probabilities of a crane. In the study, real time and dynamic information from various data sources were implemented to the fault tree and any abnormalities, service actions, cumulative loadings or the time past can trigger new calculations.

Using fault tree analysis, branches and events that are more prone to failure were determined and primary components that need maintenance were listed accordingly. Figure 2.10 illustrates the fault tree generated for the crane system.

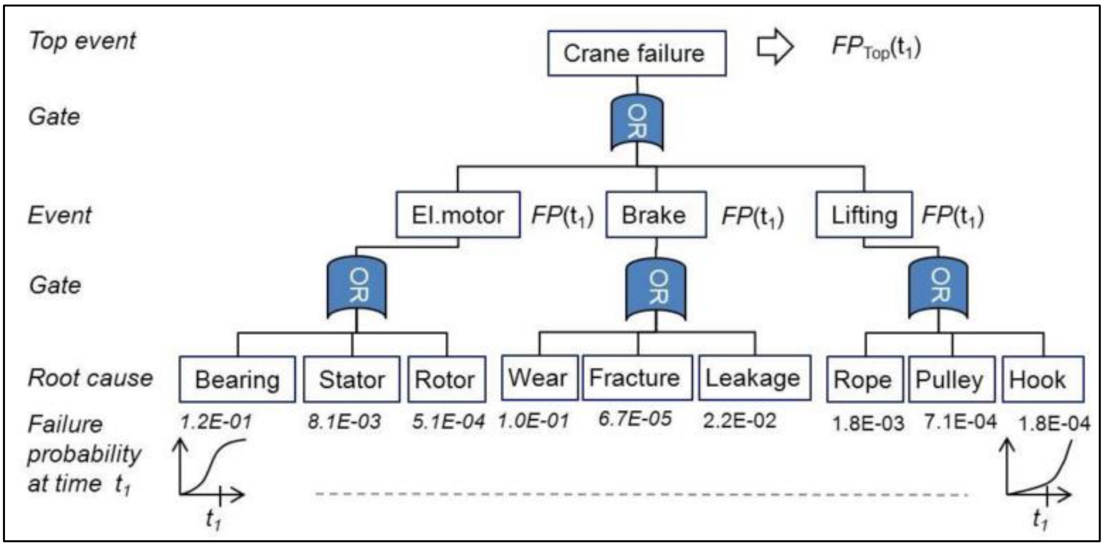


Figure 2.10 Fault tree representation of the crane system (Halme and Aikala, 2012)

Failure probabilities of the root causes at a certain time point (t_1) can be seen in Figure 2.10 and the failure probabilities for the system and sub systems derived from these values as shown in Table 2.6.

Table 2.6 Failure probabilities for the system and the sub systems at a certain time point (Halme and Aikala, 2012)

Event Type	Event Name	Failure probability value at time point
Top Event	Crane failure	0.236
Event	Electrical motor failure	0.129
Event	Brake failure	0.120
Event	Lifting Failure	0.002

The values in this table are calculated from bottom to top and they are renewed in case of changes in root causes' probability values (after maintenance or after operational progress). The renewed values can be used in determining the importance ranks for maintenance. Diagnostic importance factors (DIF) were used in calculating the failure probabilities. In this method, the fraction of the system failure probability that involves the failure of the selected component is calculated.

In addition to evaluating failure probabilities, fault tree is used for determining the most probable failure causes. Five most probable causes for the failure and the maintenance ranks are determined for the crane system and can be seen in Table 2.7.

Table 2.7 Most probable causes for the crane failure (Halme and Aikala, 2012)

Priority Order	Failure branch with events and sub			
1	Event	Crane Failure	Electrical Motor Failure	Bearing Failure
	DIF	1	0.546	0.514
2	Event	Crane Failure	Brake Failure	Wearing
	DIF	1	0.512	0.429
3	Event	Crane Failure	Brake Failure	Leakage
	DIF	1	0.512	0.091
4	Event	Crane Failure	Electrical Motor Failure	Stator Failure
	DIF	1	0.546	0.034
5	Event	Crane Failure	Lifting Failure	Rope Failure
	DIF	1	0.011	0.075

As seen in the table, the most distinct cause of failure is the bearing failure in the electrical motor which is followed by the wearing of the brake. If the maintenance crew does not find any failure in the bearing, they can change the failure probability of the bearing as zero (healthy) and update the list accordingly. The new list generated by putting 0 for bearing failure probability and one for lifting can be seen in Table 2.8.

Table 2.8 Most probable causes for the crane failure after the update (Halme and Aikala, 2012)

Priority Order	Failure branch with events and sub			
1	Event	Crane Failure	Lifting Failure	Rope Failure
	DIF	1	1	0.667
2	Event	Crane Failure	Lifting Failure	Rope Pulley Failure
	DIF	1	1	0.267
3	Event	Crane Failure	Brake Failure	Wearing
	DIF	1	0.121	0.102
4	Event	Crane Failure	Lifting Failure	Hook Failure
	DIF	1	1	0.067
5	Event	Crane Failure	Brake Failure	Leakage
	DIF	1	0.121	0.021

As a conclusion it was suggested that considering component specific situations, more appropriate solutions can be proposed and maintenance models can be developed by retrieving more frequent data from the low reliability components. In addition to these suggestions, updating the probability values for the components that are found healthy during service and revising priority order list was found to be helpful in making logical maintenance planning and using the resources more efficiently.

Gupta *et al*. (2006) conducted a study aiming to determine a replacement and maintenance policy for a longwall shearer using the fault tree analysis technique. Four major steps followed in calculating the system reliability are:

- Gathering necessary field data,
- Classification of the data to determine “time to failure” values,
- Determination of reliability parameters and calculation of basic events’ reliabilities, and
- Calculation of the probabilities of gates and intermediate events in the fault tree.

Firstly, from the failure and maintenance data, the times between consecutive failures for each component were calculated. These times were then adapted to 2-parameter Weibull distributions and scale and shape parameters for the Weibull distributions were determined. The shape parameter indicates the components’ stage of life. Shape parameter less than one indicates that the component has not yet reached a constant hazard rate period and the failure rate is decreasing with time.

These components should be monitored until they have constant hazard rates and the maintenance should be carried out accordingly. Components with shape parameter equals to one are in their constant hazard rate periods and it is sufficient to implement a routine maintenance plan. If the shape parameter is larger than one, it means the component has completed its useful life, has increasing failure rate and should be replaced.

The study showed that 60% of the shearer components are in their useful life period with constant hazard rate, and 15% of the components were found to have completed their useful lives, and 25% were yet to enter their useful life period.

After implementing the distribution data of the components to the fault tree, reliability analysis was conducted. The reliability vs. time graph for the shearer is presented in Figure 2.11. It was determined that the probability of the shearer to operate without failure for 5 hours was 43% and with 93% probability, the shearer was expected to fail during 20 hours of operation.

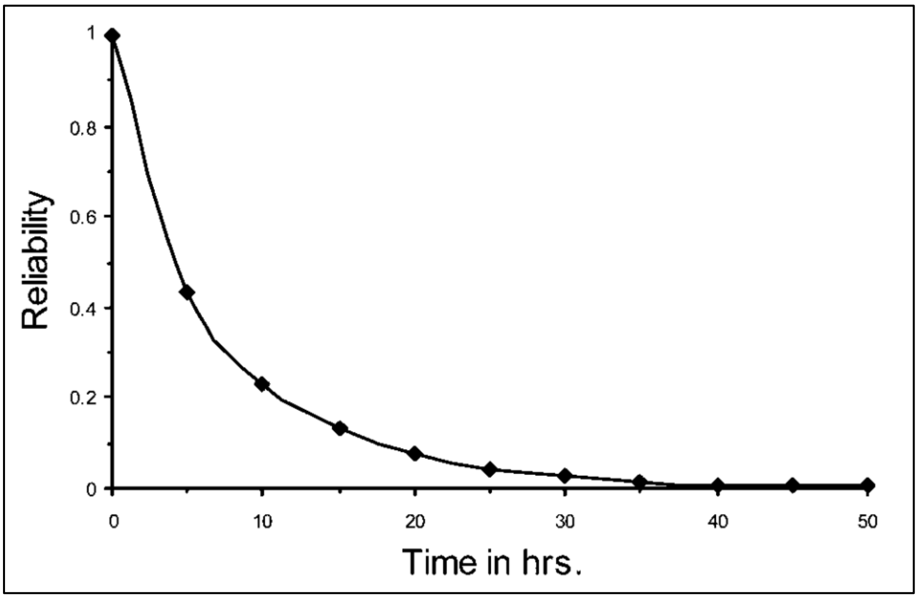


Figure 2.11 Reliability vs. Time graph of the shearer (Gupta *et al.*, 2006)

"Birnbaum's Measure" (BM) for each component was calculated and components' importance rankings for different time intervals were determined to generate a maintenance policy of the shearer. BM can be simply described as the effect of a change in component's reliability to the system reliability. The ranks of the components for t equals to 5, 20 and 40 h periods were calculated. The ranking is dynamic and changes with time. As a result, it was concluded that failure models aid us in determining the components that require replacements and the BM calculations help deciding the maintenance sequence.

There are different importance factors that can be used other than the Birnbaum's Measure mentioned earlier. These are;

i. Conditional Probability – CP
ii. Risk Achievement Worth – RAW
iii. Risk Reduction Worth – RRW
iv. Diagnostic Importance Factor – DIF
v. Criticality Importance Factor – CIF
vi. Improvement Potential – IP

These factors were compared by experimental results by Xing (2004) in his study conducted. CP and RAW values cannot distinguish the difference between components which are on a similar level in a series system and despite the great difference between probabilities, no difference was observed in those values. RRW, CIF and IP values assign higher importance values to the low reliability components of the system, but assign the same values to the components in a parallel system. CP, RAW and BM values always indicate higher importance for the components in a series system than the components in a parallel system. Additionally, BM values give higher importance to the high reliability components in a parallel system, which is meaningless from maintenance point of view. Among these seven importance factors, DIF method gives the most dynamic and sensitive measures in case of ranking. DIF method assigns different values for components in similar positions for both parallel and series systems.

Aside from mechanical systems, Veldhius *et al.* (2011) used fault tree analysis to study the mechanisms that cause flooding in urban areas. The data used in the study are collected from flood call centers in two different cities and seven major mechanisms causing the floods were determined. For each mechanism, the data were investigated and analyses were conducted to determine $p_x(x)$ values assuming Poisson distributions. This value gives the probability of an event to occur "x" times in a certain time interval and the Poisson equation used is;

$$p_x(x) = \frac{(\lambda t)^x \, e^{-\lambda t}}{x!} \quad (5)$$

In Equation 5, the x value is the number of occurrences of the event, "t" is the time interval and λ is the average rate of occurrence of the event. The λ values were determined from the collected data from the call centers.

In their study, the distributions were assumed to be Homogenous Poisson Distribution and thus the λ values were accepted as constant. Since the flood occurs when any of these events occur, the probability calculations were carried out using Equation 6.

$$P(X \geq 1) = 1 - p_x(0) = 1 - e^{-\lambda t} \quad (6)$$

P(X≥1) gives the probability that the event occurs at least once in that time interval. t was taken as one week for their study. The generated fault tree can be seen in Figure 2.12.

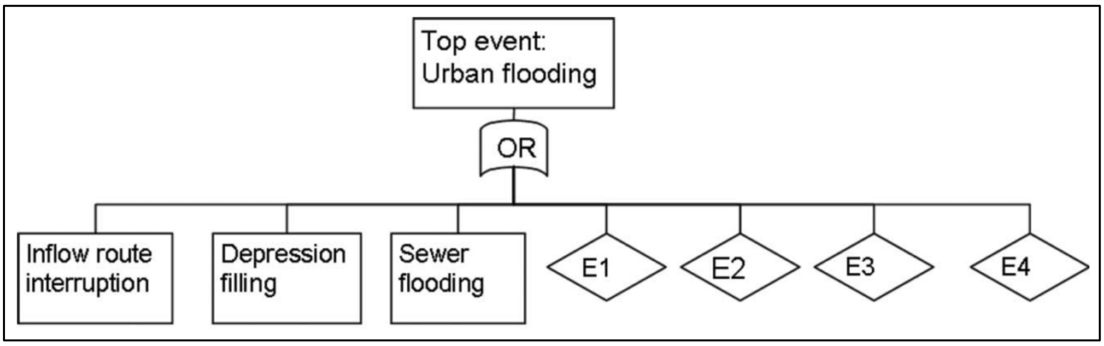


Figure 2.12 Fault tree representation for the urban flooding (Veldhius *et al*, 2011)

In Figure 2.12:

E1: Drinking water leakage

E2: Groundwater table above ground level

E3: Surface water flooding

E4: External water discharged onto surface

Inflow route interruption contains different sub-mechanisms such as: blockage of gutters, gully pots, gully pot manifolds and high road verges. The subject cities of their study were chosen to be Haarlem and Prinsenbeek of Netherlands. The most effective mechanisms for the flooding were determined by analyses and found to be; for Haarlem: gully pot blockage (71%), gully pot manifold blockage (25%), and pipe blockage (1%) and for Prinsenbeek: sewer blockage (73%). Even though most studies on flooding focus on sewer overloading by heavy rainfall, it contributed to only 3% of the floods according to the collected data. The study concluded that the fault tree analysis can help us better understand the mechanisms, thus determine important causes which were possibly ignored before.

CHAPTER 3

DATA AND STUDY AREA

3.1 Research Area

There are nine draglines in Turkey, and for the study, the two draglines that are operating in Garp Lignite Enterprises (GLİ) owned by Turkish Coal Enterprises (TKİ) in Tunçbilek/Kütahya were selected. Production has been continuing since 1940. The mine is located on the Tavşanlı-Domaniç freeway and it is at 13 km distance to Tavşanlı and 63 km to Kütahya as presented in Figure 3.1. The mine site is 13.477 hectares and the proved lignite reserve is 70.5 million tons for surface mining and 264.3 million tons for underground mining with a total of 334.7 million tons.

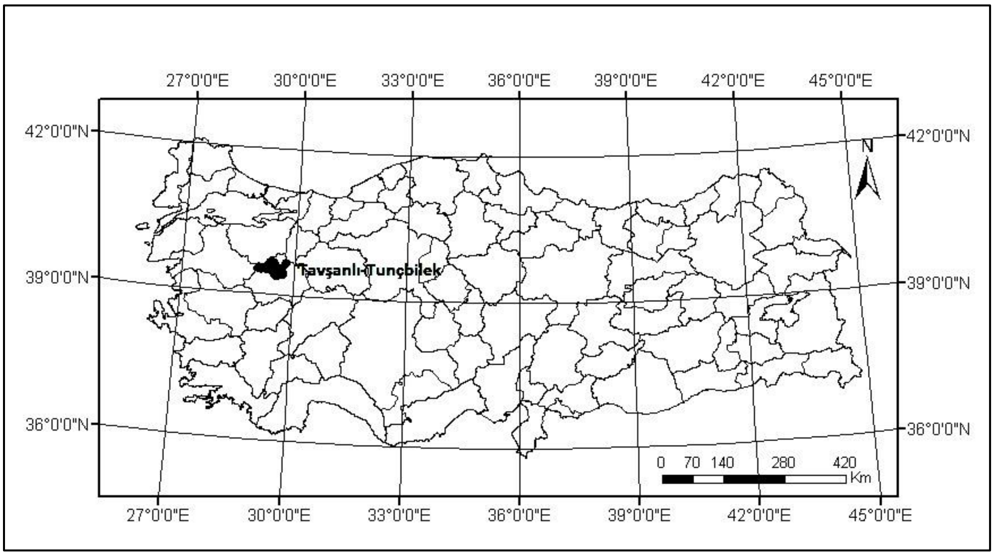


Figure 3.1 Site location map

The geological formation in the area was named Tunçbilek formation and Demirbilek member is the most abundant member in the mining area. Demirbilek member gives outcrops in large areas at the north-west and south-west parts of Tunçbilek. The member is composed mostly of; clay, marl, and coal with some intrusions of silt stone, conglomerate, and limestone. The region at north-west of the town covered by Demirbilek member is used as mining operational area. Excavation is easily carried out in this area with machines (Kani Mühendislik, 2008). The draglines were mostly operated in stripping of marl, and the mechanical and physical properties of marl in Tunçbilek formation are presented in Table 3.1. Although rock mass properties have minor impact on excavation performance, they have significant affects on productivity for draglines since they have huge production capabilities.

Table 3.1 Rock material and rock mass properties of Tunçbilek formation (Demirel, 2011)

Property	Value
Rock Type	Marl
UCS, MPa	(16.18-24.32) 18.92
Young's Modulus, 10^5 MPa	4.835
Poisson's ratio	0.28
Cohesion, MPa	5.88
Internal friction angle, deg	37
Natural density, g/cm^3	2.043
Moisture	7.97
Hardness	38
Core indent index	2.38
Indirect tensile strength, MPa	5.23
Slake durability index, %	0.994-0.991
Toughness, N.cm/cm^3	1.13

3.2 Method of Production and Stripping

Tunçbilek has 4.6% of Turkey’s lignite reserves and the yearly production is 4.25 million tons of run off lignite, 80% of which is supplied from surface mining. The production in GLİ is carried out by; stripping with draglines and excavator-truck combination and lignite production by hydraulic and electrical excavators. In order to prepare the panels for the dragline to form strips, stripping is carried out primarily by excavator-truck method and 60-65 million m^3 stripping is done yearly with 25-26 million m^3 of which is carried out by GLİ and rest by contractors.

The two draglines used in the mine are; (a) Page 736 with 20 yd^3 capacity and (b) Marion 7820 with 40 yd^3 capacity (Figure 3.2). Page has been operating since 1970 and Marion is operating since 1977. The technical specifications of the draglines are presented in Table 3.2.

(a) (b)

Figure 3.2 Draglines operating in GLİ (a) Page 736 (b) Marion 7820

Table 3.2 Technical specifications of the draglines (Parlak, 1985)

	Page 736	Marion 7820
Manufacturer's Origin	USA	USA
Bucket Capacity (m^3/yd^3)	15.30/20	30.60/40
Bucket Width (m)	2.85	3.56
Number of Bucket Teeth	5	5
Empty Bucket Weight (kN)	182.80	365.70
Specific Breakout Energy (kWh/m)	2.30±0.75	3.95±0.86
Bucket Filling Time (sn)	12.48	16.95
Boom Length (m)	62.5	72
Boom Angle (◦)	33	33
Dump Length (m)	59	70
Dump Height (m)	29	32
Digging Depth (m)	20	35
Working Mass (ton)	795	1500
Digging Cycle (turn) (sec)	55	57

3.3 Data Collection

The failure data since 1998 to 2011 for the draglines mentioned before were obtained from GLİ. Data before 1998 were not obtained so the duration those draglines operated before 1998 were not taken into account. The data included type of failure, failure reason and explanation, time of failure, and time the failure is fixed. After picking out the duplicate data, there were 1,168 failure data for the Page 736 and there were 1,321 failure data for the Marion 7820. Later, the failure times for each failure and the times to failure (operational time) were calculated considering that the draglines work 21 hours a day. Some part of the sample data used in the analysis can be seen in Table 3.3.

Table 3.3 Sample data used in analysis (MARION)

Failure Code	Failure Type	Unit No.	General Code	Failure Explanation	Failure Start Date / Time	Failure End Date / Time	TBF (hours)	CUM TBF (hours)
7	Mechanical	2	227	HOISTING BRAKES FAILED	05.02.2001 16:30	05.02.2001 17:30	45,5	7386,58
3	Electrical	1	143	DRAGGING FAILURE	05.02.2001 17:30	05.02.2001 20:30	0,0	7386,58
7	Mechanical	4	447	RINGBOLT BROKEN (BUCKET)	07.02.2001 21:15	07.02.2001 22:15	42,8	7429,33
7	Mechanical	1	157	DRAGGING SOCKET BROKEN	08.02.2001 02:45	08.02.2001 10:20	4,5	7433,83
7	Mechanical	1	147	SOUND FROM DRAGGING GEAR BOX	09.02.2001 22:30	10.02.2001 01:00	33,2	7467,00
7	Mechanical	6	617	ROTATION BRAKE VALVE FAILED	13.02.2001 10:40	13.02.2001 11:30	72,7	7539,67
7	Mechanical	1	137	DRAGGING ROPE BROKEN	13.02.2001 14:30	13.02.2001 21:30	3,0	7542,67
7	Mechanical	4	457	BUCKET RINGBOLT REPLACED	17.02.2001 09:00	17.02.2001 11:30	74,5	7617,17
7	Mechanical	1	117	DRAGGING ROPE BROKEN	18.02.2001 10:30	18.02.2001 14:30	23,0	7640,17
7	Mechanical	1	127	DRAGGING RINGBOLT BROKEN	19.02.2001 22:30	20.02.2001 01:15	29,0	7669,17
7	Mechanical	4	437	CHAIN BROKEN (BUCKET)	20.02.2001 05:30	20.02.2001 10:30	4,3	7673,42
7	Mechanical	3	317	RIGGING ROPE BROKEN	22.02.2001 23:40	23.02.2001 01:30	55,2	7728,58
7	Mechanical	4	457	BUCKET BODY FAILED	24.02.2001 17:45	24.02.2001 18:30	37,3	7765,83
3	Electrical	1	143	DRAGGING FAILURE	02.03.2001 10:30	02.03.2001 14:00	121,0	7886,83
3	Electrical	7	713	GENERATOR FAILURE	02.03.2001 23:00	11.03.2001 12:00	9,0	7895,83
7	Mechanical	1	117	DRAGGING CHAIN BROKEN	13.03.2001 18:30	13.03.2001 21:30	48,5	7944,33
3	Electrical	1	143	DRAGGING FAILURE	14.03.2001 22:15	15.03.2001 00:10	21,8	7966,08
7	Mechanical	7	737	LUBRICATION FAILURE	20.03.2001 00:30	20.03.2001 01:00	105,3	8071,42
7	Mechanical	1	137	DRAGGING ROPE SHORTENED	24.03.2001 08:30	24.03.2001 10:15	91,5	8162,92
7	Mechanical	4	427	BUCKET PIN REPLACED	24.03.2001 18:00	24.03.2001 19:30	7,8	8170,67
7	Mechanical	6	627	WALKING FAILURE	26.03.2001 09:00	26.03.2001 12:00	34,5	8205,17

CHAPTER 4

FAULT TREE ANALYSIS OF WALKING DRAGLINES

4.1 Classification of the Data

In reliability analysis, the system is disintegrated into sub-units and their components since the reliability of the system is based on the reliability of its components. Draglines are complex systems composed of numerous mechanical and electrical parts connected together. The main components of a dragline are shown in Figure 4.1. The components may vary according to manufacturers but mainly walking draglines are machines that operate by the motion of the boom, bucket and the ropes on top of the movement mechanism.

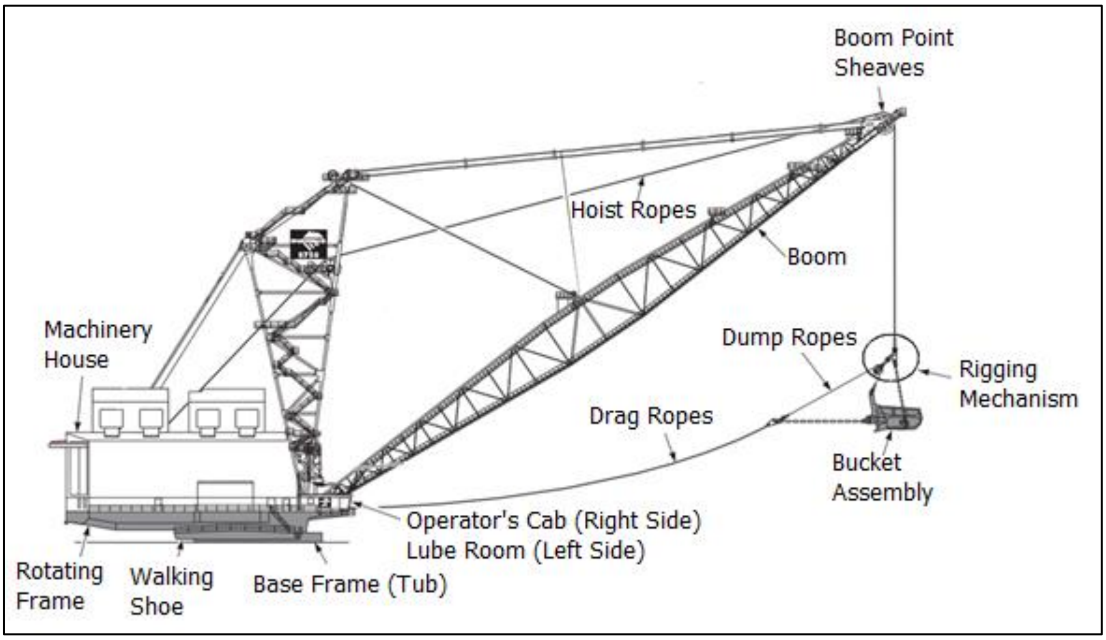


Figure 4.1 Main components of a dragline (modified from Oresome Resources, n.d.)

For this study, the draglines were separated into seven main sub-units:

1. **Drag Unit**

Drag unit is the combination of components that drags the bucket towards the machine itself in order to fill the bucket with loose material. This motion enables the stripping of overburden. This unit is composed mainly of the drag chain, rope, socket, ringbolt and the control components.

2. **Hoisting Unit**

The hoisting unit lifts the bucket after it is filled by the dragging motion and it is composed of elements such as, hoisting rope and hoisting brakes.

3. **Rigging Unit**

The rigging mechanism is responsible for the bucket's balance as a connection between the drag and hoisting units and it governs the motion of the bucket's mouth. When the bucket is filled, the dragging engine pulls the rigging rope, lifting the bucket mouth, hence preventing the spilling of material off the bucket during the swing motion. When the dragline completes its swing motion and is ready to dump the material, the mouth is released. The rigging unit has main components such as rigging rope, rope socket, the rigging pulley and the ringbolt.

4. **Bucket**

The bucket is the front unit interacting with the ground. The teeth of the bucket sinks into ground when the hoisting unit lowers the bucket and with the dragging motion, the bucket is filled. The main body, bucket teeth, pins, chain and the ringbolts are the components of the bucket unit.

5. **Boom**

The boom is the structural body that enables the dragline to dump the material away and consists of the boom body and the pulley for the hoisting rope at its tip.

6. **Movement Unit**

The movement unit enables the dragline to change its place and also it is responsible for the dragline's rotation/swinging. The dragline changes its position by the eccentric walking mechanism where the feet are thrown forward. After getting to a suitable position, dragline continues production the continuous cycle of filling, swinging and dumping. Walking, rotation and the warning system are included in the movement unit. Walking system is responsible for changing dragline's place and the rotation governs the swinging motion of the draglines.

7. **Machinery House**

Finally, the machinery house has the motors and the generators of the dragline that provide the required power by converting electrical energy to mechanical energy. The dragline has different motors and generators for different purposes. The unit's components are mainly: motors, generators, lubrication, and in addition, Marion has the air conditioning in that unit.

In case of a failure in any of these components result in the system failure and the dragline stops working till the failure is repaired. In other words, all the components are connected in series in terms of system reliability.

4.2 Preliminary Data Processing

After the sub-units are determined, the failure data are distributed to each sub-unit. Calculations are carried out to determine number of failures, failure times and times

between failures. After the preliminary calculations, the number of failures and the failure times for the two draglines' sub-units are presented in Table 4.1.
As seen in Table 4.1., even though the most number of failures occur in the dragging unit taking up 27% of all failures in Page with 281 failures, the downtime due to the failures in the machinery house is 7,805 hours which is more than 50% of the total down time.

For Marion, the highest numbers of failures occur in the rigging unit, bucket and the machinery house (each about 20%), but the down time due to the failures in the machinery house is 7,741 hours which is 46% of all down time. The movement unit of Marion also has a significant failure time with 4,004 hours.

Table 4.1 Comparison of draglines' sub-unit failure data

Unit	Page 736		Marion 7820	
	# of failures	**Failure Time (hr)**	**# of failures**	**Failure Time (hr)**
Dragging	**281**	1,491.58	187	863.33
Hoisting	101	1,229.83	102	899.92
Rigging	182	380.25	**241**	665.67
Bucket	182	653.50	213	646.50
Boom	10	99.00	10	1,946.60
Movement	121	2,307.70	117	4,004.00
Machinery House	146	**7,805.11**	233	**7,740.91**
TOTAL	1,023	13,948.52	1,103	16,766.92

Graphical representation of these values is shown in Figure 4.2 and 4.3. These graphs are constructed for the components individually in order to see the contribution of the constituent parts to the failure of the components and presented in the Appendix A (Figure A.1 and A.2).

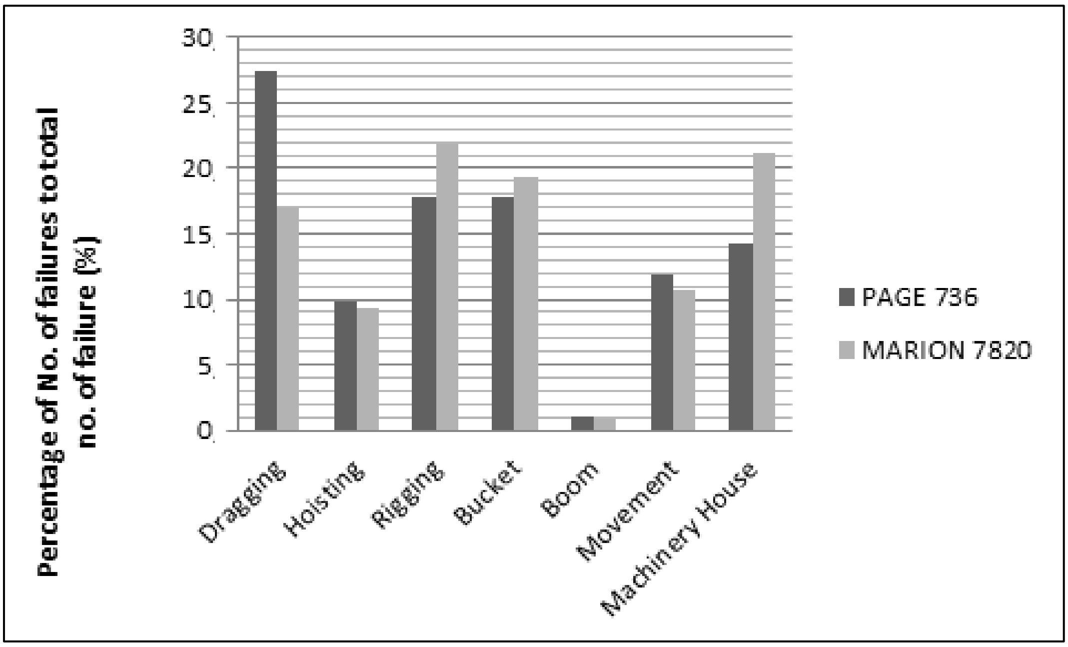


Figure 4.2 The contribution of each component to the total number of failures

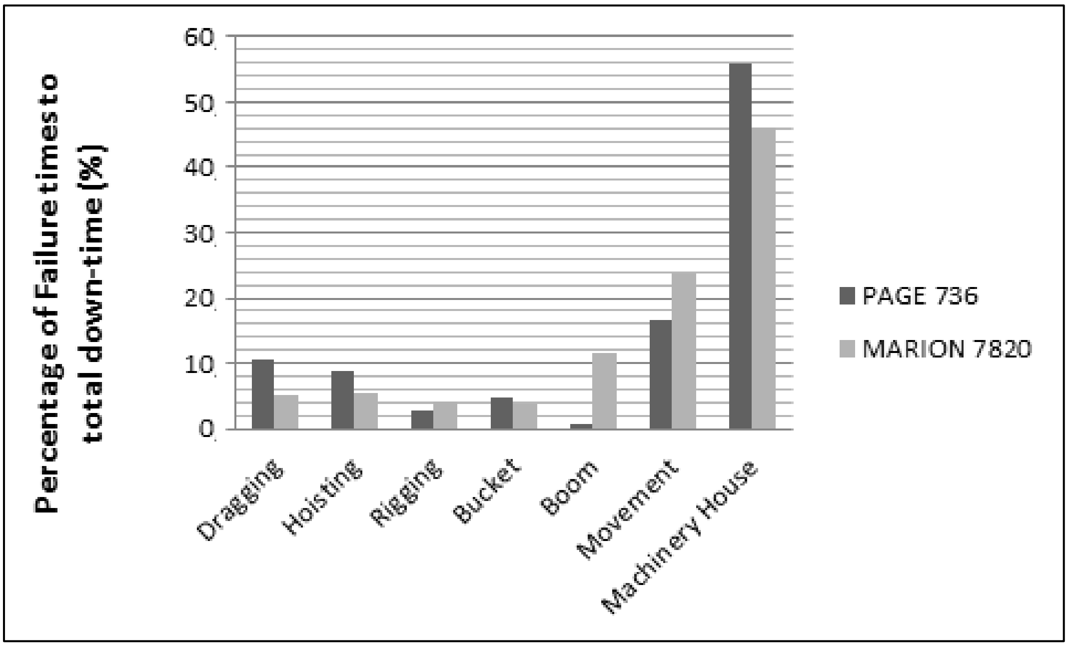


Figure 4.3 The contribution of each component to the total downtime

4.2.1 Testing the Randomness of the Data

The data used for the reliability analysis is the time between failure data, i.e. the active time passed before another failure occurs. Those data are collected for each component and before the reliability analysis; the data are checked for randomness by runs test.

The runs test can be used to decide if a data set is from a random process. Series of increasing or decreasing values are called a run. In the test, the median of the data set is used to determine runs where the data below the median are coded as negative and above are coded as positive. In this case, a run is defined as a series of consecutive positive or negative values.

The null hypothesis (H_0) for the runs test is that, the sequence has random behavior. The "p values" obtained from the test determines the randomness of the data. Smaller p values suggest that the data is not random. The limit p value is taken as 0.01 and results are evaluated accordingly. Runs tests for the units of the draglines determined that the data are randomly distributed and the p values found are presented in Table 4.2-4.7 for each unit. The lower p values obtained are due to data clustering and can be seen in the run charts presented in Appendix A (Figure A.3-A.14).

Table 4.2 Runs tests results of dragging units

Runs test for Marion Dragging	**Runs test for Page Dragging**
Runs above and below K = 321.52	Runs above and below K = 278.25
The observed number of runs = 70	The observed number of runs = 123
The expected number of runs = 83.22	The expected number of runs = 131.41
62 observations above K; 122 below	101 observations above K; 184 below
P-value = 0.03	**P-value = 0.28**

Table 4.3 Runs tests results of hoisting units

Runs test for Marion Hoisting	Runs test for Page Hoisting
Runs above and below K = 606.51	Runs above and below K = 725.70
The observed number of runs = 46	The observed number of runs = 38
The expected number of runs = 46.55	The expected number of runs = 48.41
34 observations above K; 69 below	38 observations above K; 63 below
P-value = 0.90	**P-value = 0.03**

Table 4.4 Runs tests results of rigging units

Runs test for Marion Rigging	Runs test for Page Rigging
Runs above and below K = 289.84	Runs above and below K = 425.12
The observed number of runs = 101	The observed number of runs = 86
The expected number of runs = 105.80	The expected number of runs = 87.55
77 observations above K; 164 below	68 observations above K; 119 below
P-value = 0.48	**P-value = 0.81**

Table 4.5 Runs tests results of bucket units

Runs test for Marion Bucket	Runs test for Page Bucket
Runs above and below K = 324.09	Runs above and below K = 420.53
The observed number of runs = 102	The observed number of runs = 71
The expected number of runs = 97.66	The expected number of runs = 80.62
72 observations above K; 147 below	57 observations above K; 132 below
P-value = 0.51	**P-value = 0.10**

Table 4.6 Runs tests results of movement units

Runs test for Marion Movement	Runs test for Page Movement
Runs above and below K = 482.10	Runs above and below K = 566.82
The observed number of runs = 60	The observed number of runs = 46
The expected number of runs = 64.47	The expected number of runs = 55.35
51 observations above K; 84 below	42 observations above K; 77 below
P-value = 0.41	**P-value = 0.06**

Table 4.7 Runs tests results of machinery houses

Runs test for Marion MH	**Runs test for Page MH**
Runs above and below K = 272.59	Runs above and below K = 542.58
The observed number of runs = 102	The observed number of runs = 61
The expected number of runs = 103.42	The expected number of runs = 66.52
76 observations above K; 157 below	50 observations above K; 95 below
P-value = 0.83	**P-value = 0.31**

4.2.2 Determining the Probability Distributions of the Failure Data

After testing the data for randomness, appropriate probability distributions for the data are determined. Weibull++ 7 software is used in determining the distributions (ReliaSoft 2012). The data introduced to the software are the virtual ages of the components between consequent failures. In other words, the time that component actively worked after a failure until another failure occurred in the same component.

4.2.2.1 Probability Distributions of the Dragging Units

The dragging units consist of three components; rope, chain and pins and others. The probability distributions determined for each component is presented in the Table 4.8. As seen from the table, the distribution for the failure data of the dragging control and socket of Page is 2-parameter Weibull distribution and it is 3-parameter Weibull distribution for the remaining units. The distributions for the Page's dragging unit are 3-parameter Weibull for the rope, chain and socket units, and it is 2-parameter Exponential for the ringbolt and it is 2-parameter Lognormal for the control failures.

Table 4.8 Distribution parameters of components of dragging units

Components	PAGE		MARION	
	Distribution	Distribution Constants	Distribution	Distribution Constants
Rope	Weibull-3P	β 0.95 η 551.00 γ 3.25	Weibull-3P	β 1.49 η 940.33 γ -39.37
Control	Weibull-2P	β 0.93 η 1,820.23	Lognormal-2P	μ 5.66 Std 1.22
Ringbolt	Weibull-3P	β 1.18 η 1,130.30 γ -20.72	Exponential-2P	λ 1.25E-03 γ 68
Chain	Weibull-3P	β 0.85 η 822.51 γ 15.79	Weibull-3P	β 0.79 η 1,298.08 γ -7.28
Socket	Weibull-2P	β 0.97 η 5,508.90	Weibull-3P	β 0.36 η 4,892.60 γ 1,135.45

Weibull distribution is widely used for failure data and can be with 2 or 3 parameters. 2 parameter weibull distributions contain the scale and shape parameters determines the life characteristics. The cumulative density function of a weibull distribution can be defined as (Reliasoft, 2014);

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (7)$$

The cumulative density function is the same function used to calculate the failure probability, and the reliability is given as 1 – F(t).

3-parameter Weibull distribution has a location parameter in addition to those of 2-parameter Weibull distribution and it has a cumulative distribution function of (Reliasoft, 2014):

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta-\gamma}\right)^{\beta}} \quad (8)$$

In Equation 8, β is the shape parameter, η is the scale parameter, γ is the location parameter and t is time.

Lower shape parameters ($\beta < 1$) suggest that the failure frequency is high at start and decreases continuously which is similar to an exponential distribution which occurs when β equals to one. Shape parameters greater than one suggest that the failure frequency increases to maximum and then decreases with time.

The scale parameter is an estimate of the mean and gives the time when the failure probability is 63.2%. The location parameter in the 3-parameter Weibull distribution suggests that no failure occurs before a certain time. In other words, a location parameter greater than one indicates that the curve does not start from the origin, but starts from the right-hand side.

Exponential distribution suggests a failure behavior starting with high failure frequency and decreasing continuously. The exponential distribution has one parameter which is the failure rate (λ) which is the inverse of mean. There can also be 2-parameter Exponential distributions where the other parameter is the location parameter similar to the one in the weibull distribution which shifts the curves t_0 location to the right or left. The failure probability from an exponential distribution is calculated as (Reliasoft, 2014);

$$F(t) = 1 - e^{-\lambda t} \quad (9)$$

In Equation 9, t is replaced by t-γ for the 2-parameter Exponential distribution.

The mean life estimations obtained from the determined distributions are presented in Table 4.9.

Table 4.9 Mean life estimations (in hours) of components of dragging units

	PAGE	MARION
Chain	908	1,478
Rope	**567**	810
Control	1,880	**607**
Ringbolt	1,048	866
Socket	5,582	2,307

The socket units of both draglines' dragging units have the highest mean life with 5,582 hours for Page and 2,307 hours for Marion. The unit with the lowest mean life estimation for Page is the dragging rope with 567 hours where it is the control unit for Marion with 607 hours.

The probability density function curves and the reliability versus time graphs are presented in the Appendix A (Figure A.15-A.21).

4.2.2.2 Probability Distributions of the Hoisting Units

The hoisting units consist of three main failure components which are; rope, brakes, and control failures. Page has additional socket failures compared to the Marion's hoisting unit. The probability distributions determined for the failure data of these components are presented in Table 4.10.

Except for the failure data for the rope component of Marion, all other component failures of both draglines have 3-parameter Weibull distribution for their failure data. The rope component of the Marion's hoisting unit is determined to have a 2-parameter Weibull distribution. The mean life estimations for the components determined from the distributions are presented in Table 4.11.

Table 4.10 Distribution parameters of components of hoisting units

Components	PAGE		MARION	
	Distribution	Distribution Constants	Distribution	Distribution Constants
Rope	Weibull-3P	β 1.57 η 1,438.97 γ -113.31	Weibull-2P	β 1.54 η 2,836.34
Brakes	Weibull-3P	β 0.45 η 2,112.67 γ 39,28	Weibull-3P	β 0.50 η 1,349.00 γ 13.223
Control	Weibull-3P	β 1.51 η 1,0562.57 γ -1,405.50	Weibull-3P	β 0.69 η 1,109.19 γ -10.31
Socket	Weibull-3P	β 0.67 η 9811.93 γ 568.78		

Table 4.11 Mean life estimations (in hours) of components of hoisting units

	PAGE	MARION
Rope	**1,179**	2,552
Brakes	5,223	2,684
Control	8,124	**1,419**
Socket	1,352	

It is observed that the rope component has the lowest mean life for Page with 1,179 hours and it is the control unit for Marion with 1,419 hours. The probability density function curves and the reliability versus time graphs are presented in the Appendix A (Figure A.24-A.28).

4.2.2.3 Probability Distributions of the Rigging Units

The rigging units of the draglines are divided into four main components; rope, socket, ringbolt and pulley. The failure data are introduced to the software and the determined probability distributions for each component are presented in the Table 4.12.

Table 4.12 Distribution parameters of components of rigging units

Components	PAGE		MARION	
	Distribution	Distribution Constants	Distribution	Distribution Constants
Rope	Weibull-3P	β 1.66 η 663.91 γ -6.92	Loglogistic	μ 5.60 σ 0.53
Socket	Weibull-3P	β 0.95 η 2,553.02 γ -28.73	Gumbel-2P	μ 1,1579.26 σ 5,442.64
Pulley	Weibull-2P	β 1.054 η 1,232.87	Weibull-3P	β 1.25 η 1,599.63 γ -56.95
Ringbolt	Weibull-3P	β 0.63 η 3,348.66 γ 82.74	Weibull-3P	β 0.84 η 3,553.70 γ 61.48

Since lower scale parameters (η) suggest lower reliability, it can be concluded that the rope components of the rigging units have higher failure probability compared to the other components for Page. The components of the Page's rigging unit are best described by 2 and 3-parameter Weibull distributions. For Marion's rigging unit, the pulley and ringbolt failures are described by 3-parameter Weibull distributions while the rope and the socket units are represented by Log-logistic and Gumbel distributions respectively.

The Loglogistic distribution is a 2-parameter distribution with parameters "μ" and "σ" and the pdf is given by the equation (reliawiki.org, 2014):

$$f(t) = \frac{e^z}{\sigma t(1 + e^z)^2} \tag{10}$$

$$z = \frac{t' - \mu}{\sigma} \quad (11)$$

$$t' = \ln(t) \quad (12)$$

μ is the scale parameter and σ is the shape parameter.

$0 < t < \infty$, $-\infty < \mu < \infty$ and $0 < \sigma < \infty$.

The σ in our case is <0 which suggests a distribution with a similar shape to a lognormal or a Weibull distribution. The distribution starts at 0 and increases to its mode and then decreases back. The reliability function is given by (reliawiki.org, 2014):

$$R = \frac{1}{1 + e^{z}} \quad (13)$$

$$z = \frac{t' - \mu}{\sigma} \quad (14)$$

$$t' = \ln(t) \quad (15)$$

The Gumbel distribution is also a 2-parameter distribution with parameters μ and σ. Gumbel distribution; also called Smallest Extreme Value (SEV) distribution; has a left skewed pdf distribution opposed to Weibull distribution which has a right skewed pdf. The pdf for the Gumbel distribution is obtained from the equation (reliawiki.org, 2014):

$$f(t) = \frac{1}{\sigma} e^{z - e^{z}} \quad (16)$$

$f(t) \geq 0$, $\sigma > 0$ with μ as the scale parameter and σ as the shape parameter and;

$$z = \frac{t - \mu}{\sigma} \quad (17)$$

and the reliability function is given by;

$$R(t) = e^{-e^{z}} \quad (18)$$

The mean life estimations obtained can be seen in Table 4.13.

Table 4.13 Mean life estimations (in hours) of components of rigging units

	PAGE	MARION
Rope	**587**	**448**
Socket	2,583	8,438
Ringbolt	4,788	3,969
Pulley	1,207	1,433

The mean life estimations confirms that the rope components of the rigging units have the lowest mean life values, thus have more failure probability. The ringbolt has the highest reliability for Page, while the socket has the highest reliability for Marion. The probability density function curves and the reliability versus time graphs are presented in the Appendix (Figure A.31 and A.36).

4.2.2.4 Probability Distributions of the Bucket Units

The bucket units are composed of five parts with respect to failure. These components are; teeth, pins, chain, ringbolts, and bucket main body. Appropriate probability distributions are determined for the failure data of each component and the obtained results are presented in Table 4.14.

The failure data from the chain and the teeth of the Marion's and the main body of Page's bucket is best explained by 2-parameter Weibull distribution where the distribution for the data from other components is determined as 3-parameter Weibull. From the scale parameters obtained from the distributions, the components expected to have the lowest reliability are the teeth and the pins for both draglines. Mean life estimations from the determined distributions are shown in Table 4.15.

Table 4.14 Distribution parameters of components of bucket units

Components	PAGE		MARION	
	Distribution	Distribution Constants	Distribution	Distribution Constants
Teeth	Weibull-3P	β 0.67 η 842.17 γ 14.58	Weibull-2P	β 0.87 η 737.39
Pins	Weibull-3P	β 0.82 η 845.31 γ 5.44	Weibull-3P	β 0.81 η 647.63 γ 12.66
Chain	Weibull-3P	β 0.38 η 8,323.39 γ 54.12	Weibull-2P	β 0.84 η 2,973.34 γ 5,452.92
Ringbolt	Weibull-3P	β 0.67 η 870.47 γ 50.50	Weibull-3P	β 0.92 η 1,137.83 γ 28.47
Main Body	Weibull-2P	β 0.95 η 2,661.28	Weibull-3P	β 0.80 η 982.86 γ 20.75

The mean life estimations determined that the bucket teeth have lower reliability for Marion and it's pins for the Page. The estimation shows that the Page's bucket has higher reliability than the Marion's since almost the Page's entire bucket components have higher mean life estimations.

The probability density function curves and the reliability versus time graphs are presented in the Appendix A (Figure A.39-A.45).

Table 4.15 Mean life estimations (in hours) of components of bucket units

	PAGE	MARION
Teeth	1,125	790
Pin	**950**	**738**
Chain	31,787	8,709
Ringbolt	1,197	1,215
Main body	2,726	1,137

4.2.2.5 Probability Distributions of the Movement Units

The failure data for the movement unit is divided into three components namely; rotation, walking and warning. All failure data for both draglines are assigned a 3-parameter Weibull distribution. The distributions and their constants for the movement units are presented in Table 4.16.

Table 4.16 Distribution parameters of components of movement units

Components	**PAGE**			**MARION**		
	Distribution	**Distribution Constants**		**Distribution**	**Distribution Constants**	
Rotation	Weibull-3P	β	0.52	Weibull-3P	β	0.90
		η	732.58		η	1,852.63
		γ	7.61		γ	-8.82
Walking	Weibull-3P	β	1.03	Weibull-3P	β	0.66
		η	1,754.70		η	664.27
		γ	-34.15		γ	14.40
Warning	Weibull-3P	β	0.66	Weibull-3P	β	1.05
		η	757.25		η	3,786.30
		γ	133.16		γ	151.46

Rotation and warning components for Page is more likely to have lower reliability since the scale parameters are lower for those two components with 732.58 and 757.25 respectively. The results of mean life estimations are presented in Table 4.17.

The probability density function curves and the reliability versus time graphs are presented in the Appendix A (Figure A.48-A.52).

Table 4.17 Mean life estimations (in hours) of components of movement units

	PAGE	MARION
Rotation	1,370	1,938
Walking	1,698	**906**
Warning	**1,157**	3,862

4.2.2.6 Probability Distributions of the Machinery Houses

The components for the machinery house are generators motors and lubrication, and there is an additional component of air conditioning for Marion. All of these components are best fit by the Weibull distribution. Determined constants for the Weibull distributions are presented in Table 4.18.

Table 4.18 Distribution parameters of components of machinery houses

Components	PAGE		MARION	
	Distribution	**Distribution Constants**	**Distribution**	**Distribution Constants**
Generators	Weibull-3P	β 0.54 η 2,263.62 γ 9.10	Weibull-3P	β 0.74 η 838.76 γ 12.33
Motors	Weibull-3P	β 0.62 η 960.89 γ 10.17	Weibull-2P	β 0.99 η 1,322.71
Lubrication	Exponential-2P	λ 1.05E-03 γ 12.5	Weibull-3P	β 0.88 η 586.87 γ 8.57
Air Conditioning			Weibull-3P	β 0.744 η 3,293.23 γ 502.03

Marion’s lubrication has the lowest scale parameter and it is expected to have a lower reliability. The motors and generators for Page has both 3-parameter Weibull distribution and the motors have lower scale parameter suggesting they have lower reliability compared to the generators. The lubrication component’s failure data fits a 2-parameter exponential distribution. Mean life estimates for the components are determined and presented in Table 4.19.

The lubrication component has the lowest mean life for Marion with 632 hours. The lubrication of Page has smaller mean life estimation with 968 hours. The motors for page have lower mean life than the generators as suggested before. The probability density function curves and the reliability versus time graphs are presented in the Appendix A (Figure A.55-A.60).

Table 4.19 Mean life estimations of components (in hours) of machinery houses

	PAGE	MARION
Generators	3,944	1,026
Motors	1,390	1,331
Lubrication	**968**	**632**
air conditioning		4,449

4.3 Reliability Analysis Using Fault Tree Analysis

4.3.1 Fault Tree Analysis of the Dragging Units

The dragging units are composed of 5 components as shown in Figure 4.4, namely the rope, chain, socket, ringbolt and the control components. These components are connected by an OR gate which indicates a series configuration. This configuration suggests that a failure in any of these components result in the failure of the dragging system. The fault tree is constructed identically for both draglines.

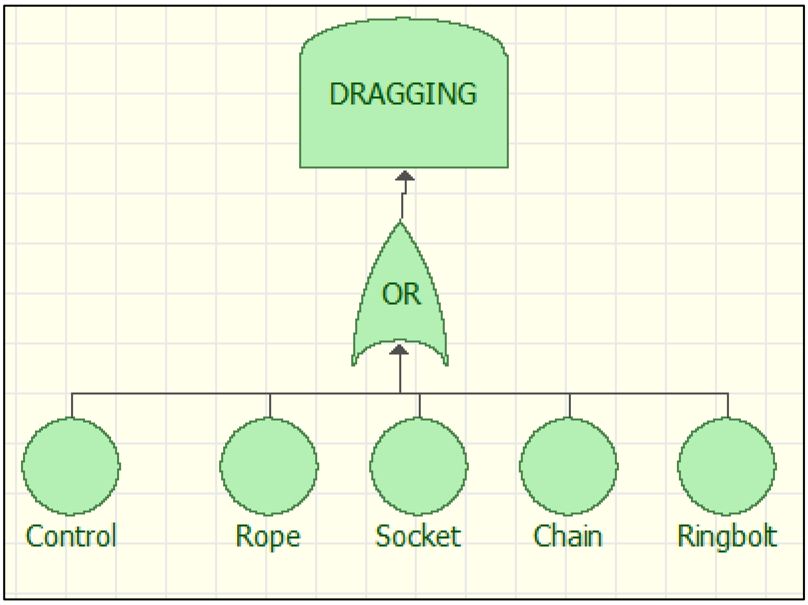


Figure 4.4 Fault tree representation of dragging units

The reliability equation obtained from the fault tree is:

$$R_{dragging}=R_{rope} \times R_{control} \times R_{chain} \times R_{ringbolt} \times R_{socket} \tag{19}$$

The multiplication is due to the OR gate used in the fault tree. The component reliabilities can be multiplied since the events do not have correlation and they are independent. If an AND gate were to be used, the equation would be:

$$R_{System}= 1 – [(1 – R_1) (1 – R_2) (1 – R_3)] \tag{20}$$

since the system failure would occur only if all components fail.

The reliability values (R) of the components are obtained from the probability distributions determined previously and using this equation, the change in reliability of the dragging unit is determined. The reliability changes with time for the dragging units of both draglines are shown in Figure 4.5.

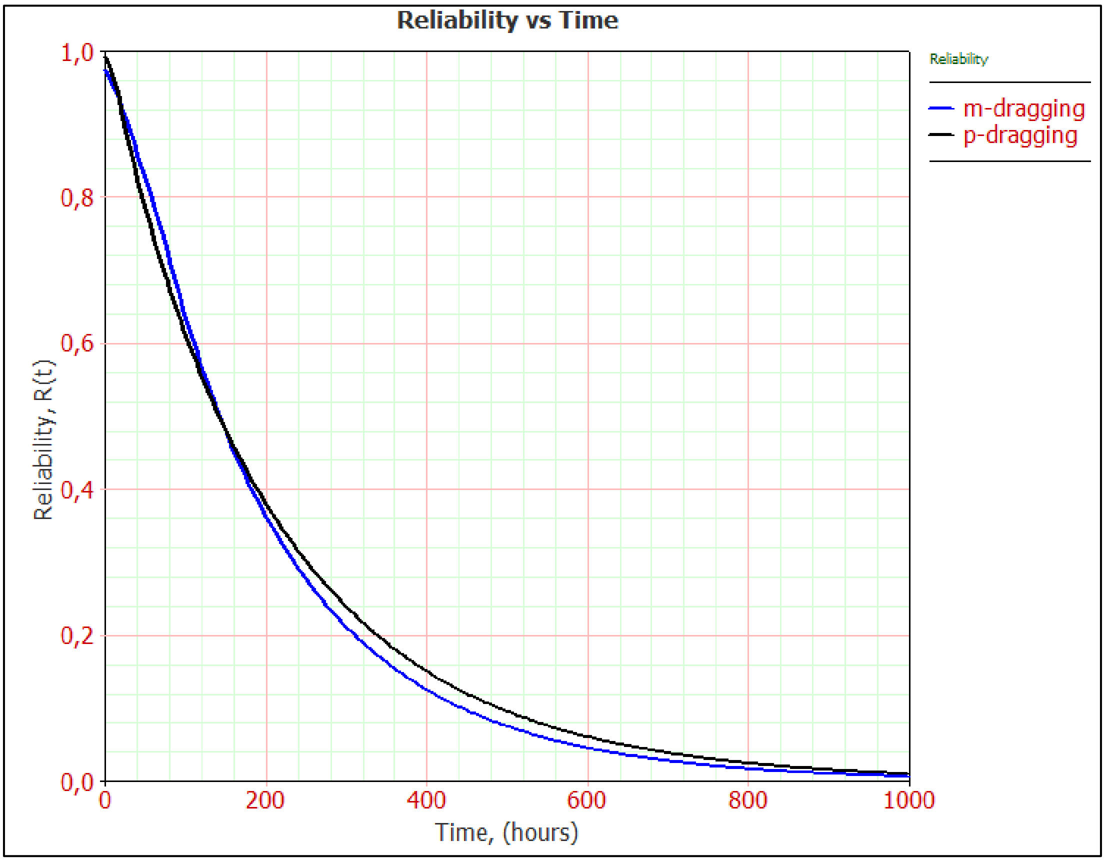


Figure 4.5 Reliability graph of dragging units

As seen in the Figure 4.5, the dragging unit of Page shows slightly higher reliability values compared to Marion's. The reliability values at 200 hours are 36.3% for Marion and 38% for Page. The mean lives for the draglines' dragging units are estimated as 200 hours for Marion and 211 hours for Page.

Another important value obtained from the fault tree analysis is reliability importance. These give the reliability importance values of components at a given time which is:

$$RI = R_{system}/R_{component} \tag{21}$$

In Table 4.20, importance factors of the components at the estimated mean lives of the dragging units are shown. In Appendix (Figure A.22 and A.23), the changes in importance factors with time are illustrated graphically. The control unit for Marion and the rope for Page have the highest considering their estimated mean lives.

Table 4.20 Importance values of the dragging components at estimated mean life times

	PAGE	MARION
Chain	0.484	0.459
Rope	**0.536**	0.413
Control	0.413	**0.588**
Ringbolt	0.421	0.428
Socket	0.376	0.363

4.3.2 Fault Tree Analysis of the Hoisting Units

The hoisting unit of Page is mainly categorized into four components that are; rope, brakes, socket and control failures. These units are connected by an OR gate as seen in Figure 4.6. The fault tree for the Marion's hoisting unit does not contain socket failures so it has three components.

The system reliability for Page's hoisting unit is given by the following equation;

$$R_{hoisting}=R_{rope} \times R_{brakes} \times R_{socket} \times R_{control} \quad (22)$$

where the R_{socket} is omitted for Marion's reliability calculation. Using the reliability values obtained from the distributions, the change in reliability with time for the both hoisting units is presented in Figure 4.7.

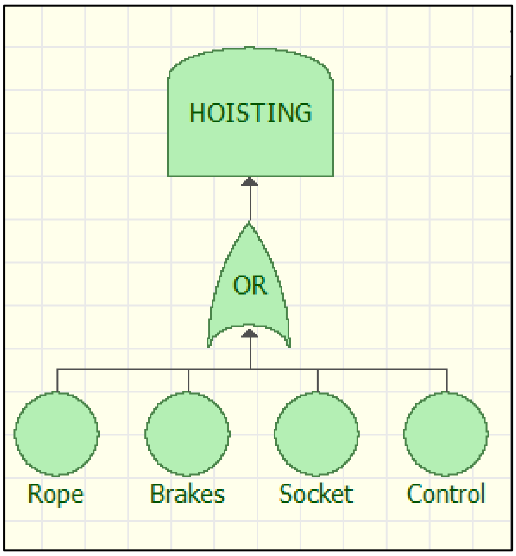


Figure 4.6 Fault tree representation of hoisting units

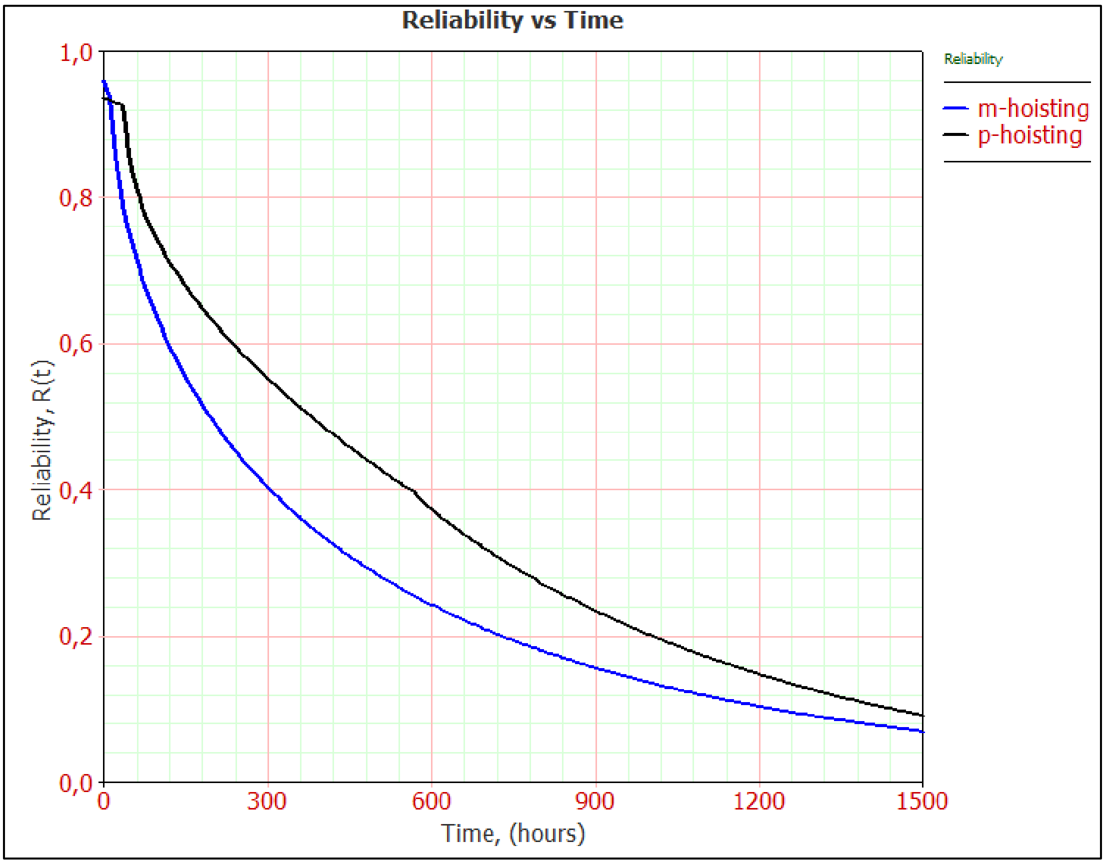


Figure 4.7 Reliability graph of hoisting units

There is a significant difference between the hoisting units of Marion and Page. The reliability of the hoisting unit of Marion decreases rapidly with time compared to that of Page. While the reliability for Page's hoisting unit is 80% at 60 hours; that value decreases to 71.4% for Marion. Although the hoisting brakes for both draglines have almost identical reliability behavior (Appendix A Figure A.24), the rope and other failures create the seen difference in two units.

The mean lives for the draglines' hoisting units are estimated as 448 hours for Marion and 582 hours for Page. In Table 4.21, the importance factors are given for the estimated mean lives of the units. For both Page's and Marion's hoisting units, the brake failures have the highest importance. The changes in importance factors with time are illustrated graphically in Appendix A (Figure A.29 and A.30).

Table 4.21 Importance values of the hoisting components at estimated mean life times

	PAGE	MARION
Rope	0.531	0.329
Brakes	**0.663**	**0.547**
Control	0.418	0.536
Socket	0.390	

4.3.3 Fault Tree Analysis of the Rigging Units

The rigging units have four components assigned that are: rope, socket, pulley and ringbolt. Similar to previous units, OR gate is assigned to connect the components since any failure in these result in system failure. The constructed failure tree is presented in Figure 4.8. The rigging units' reliabilities are calculated using the equation;

$$R_{rigging} = R_{rope} \times R_{socket} \times R_{pulley} \times R_{ringbolt} \qquad (23)$$

The obtained reliability versus time curves for both rigging units are presented in Figure 4.9. The rigging unit of Marion shows faster decrease in reliability compared to the rigging unit of Page. In 200 hours the reliability of Page's rigging unit is around 60% where it is around 50% for Marion. The difference is mainly caused by the rope and socket components of Marion's rigging unit while other 2 components (ringbolt and pulley) show similar reliability behavior for both draglines when compared (Appendix A Figure A.31-A.34).

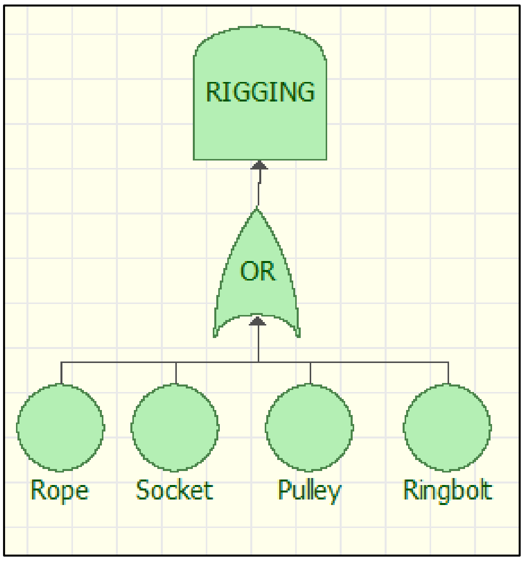


Figure 4.8 Fault tree representation of rigging units

The mean life estimations for the rigging units are 267 hours for Marion and 329 hours for Page. The importance factors calculated at the mean lives are presented in Table 4.22.

The rigging rope has the highest importance for both rigging units at their estimated mean lives. The graphical representations of the change in importance values with time are presented in Appendix (Figure A.37 and A.38).

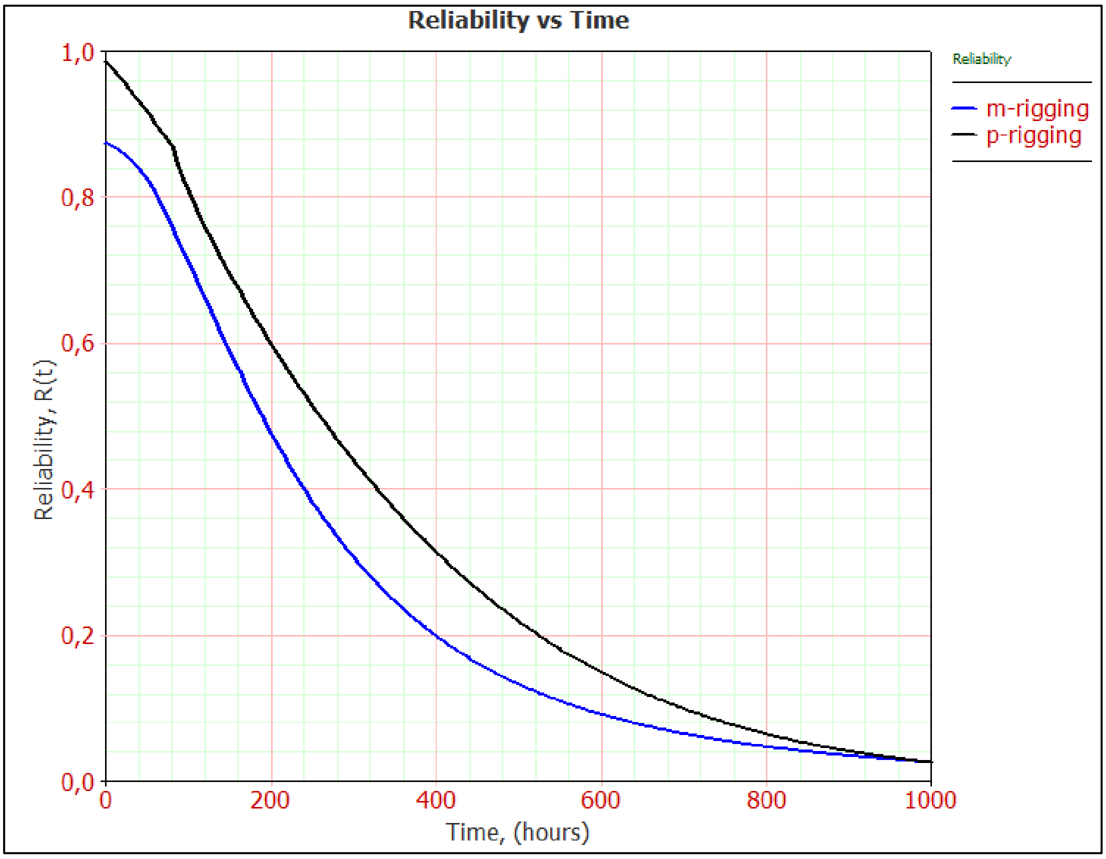


Figure 4.9 Reliability graph of rigging units

Table 4.22 Importance values of the rigging components at estimated mean life times

	PAGE	MARION
Rope	**0.522**	**0.702**
Socket	0.466	0.452
Ringbolt	0.484	0.437
Pulley	0.512	0.457

4.3.4 Fault Tree Analysis of the Bucket Units

The bucket units consist of teeth, chains, pins, main body, and ringbolts. Different from other units, the part containing the teeth has a VOTING gate connecting the teeth. This gate suggests that the top event occurs when more than one failure occurs in the components. It is assumed for the teeth that two of them should fail for the system to fail. Other than that, all components are connected by an OR gate before the top event suggesting series configuration. The constructed fault tree is presented in Figure 4.10.

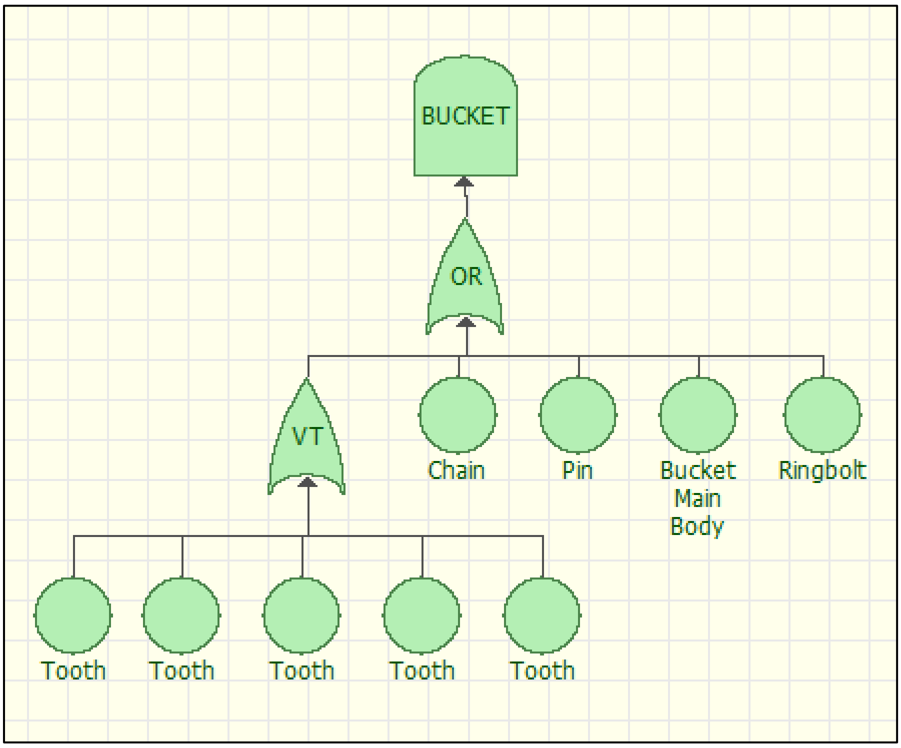


Figure 4.10 Fault tree representation of bucket units

The equation to be used in determining the buckets' reliability is different from others due to the voting gate and as follows:

$$R_{bucket}=R_{chain} \times R_{pin} \times R_{bucket\ main\ body} \times R_{ringbolt} \times (5R_{tooth}^4 - 4R_{tooth}^5) \quad (24)$$

The obtained reliability curves are presented in Figure 4.11. Both of the units have similar reliability behavior where Marion is observed to be slightly more reliable than Marion after around 56 hours.

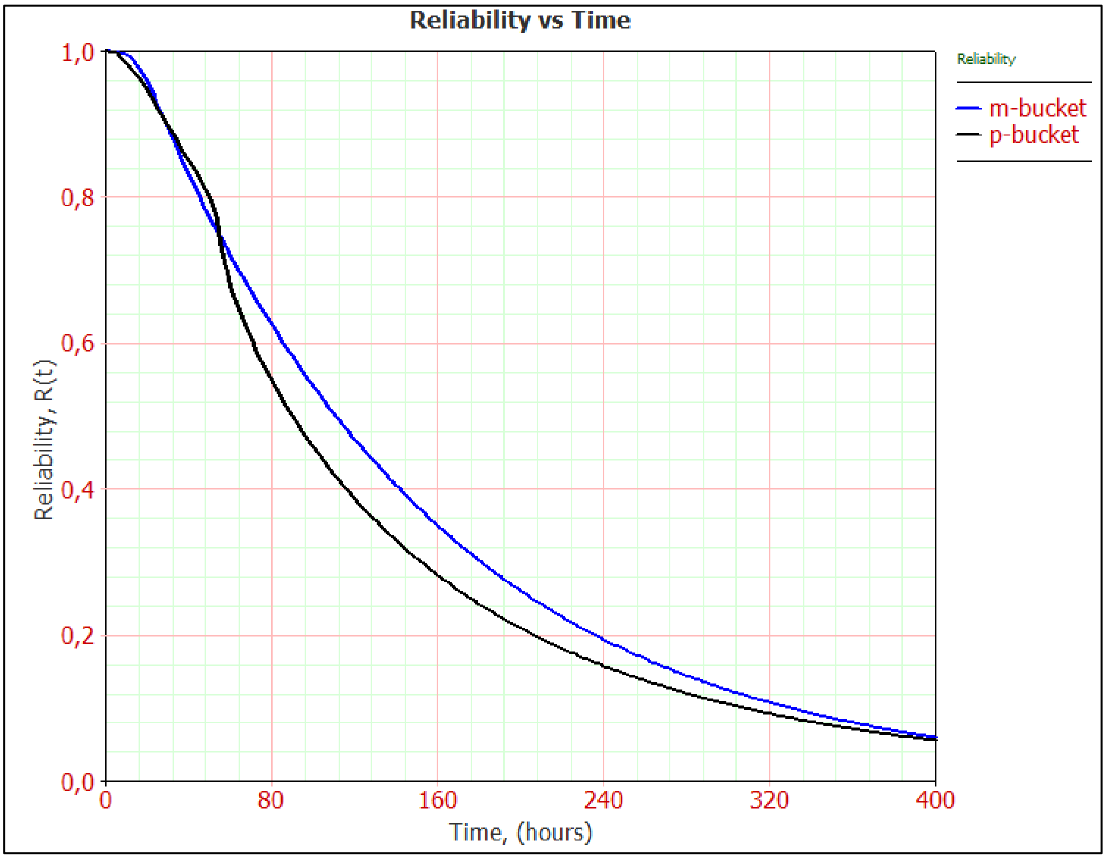


Figure 4.11 Reliability graph of bucket units

The estimated mean life values for the bucket units are 152 hours for Marion and 139 hours for Page. The importance values for the components for both dragline bucket units in mean life values are shown in Table 4.23. Pins are calculated to have the highest importance for both units but for Page, the ringbolt has approximately the same importance value. In Appendix A (Figure A.45 and A.46), importance factor versus time graphs are presented.

Table 4.23 Importance values of the bucket components at estimated mean life times

	PAGE	MARION
Teeth	0.215	0.225
Pin	**0.415**	**0.495**
Chain	0.395	0.371
Ringbolt	**0.412**	0.423
Main body	0.353	0.454

4.3.5 Fault Tree Analysis of the Movement Units

The fault tree of the movement units consist of four components connected with an OR gate. The components are namely; rotation, walking and warning. The constructed fault tree is same for both draglines' movement units and shown in Figure 4.12.

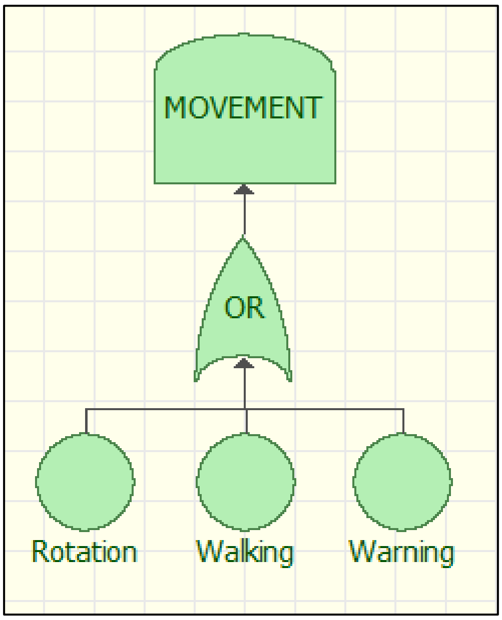


Figure 4.12 Fault tree representation of movement units

The acquired reliability equation for the movement units is:

$$R_{movement} = R_{rotation} \times R_{walking} \times R_{warning} \quad (25)$$

The decrease in reliability for both draglines' movement units during a 1000 hour period is shown in Figure 4.13. Marion's movement unit shows relatively better reliability behavior compared to Page's. Their mean life estimations are found to be 452 hours for Marion and 302 hours for Page. Table 4.24 shows the importance values of the components at those given time (mean life) and it is seen that the walking unit for Marion and rotation unit for Page has the highest importance value. The changes in importance factors with time are presented in Appendix A (Figure A.53 and A.54).

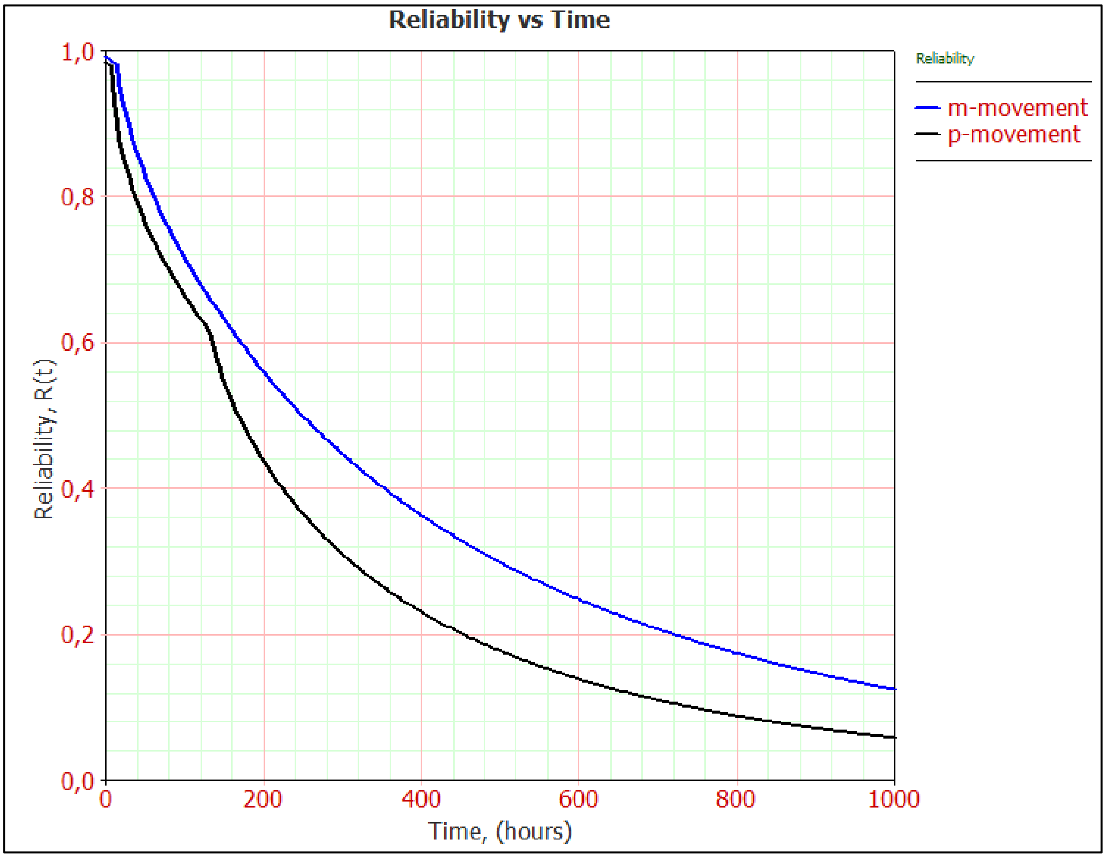


Figure 4.13 Reliability graph of movement units

Table 4.24 Importance values of the movement components at estimated mean life times

	PAGE	MARION
Rotation	**0.574**	0.437
Walking	0.370	**0.701**
Warning	0.448	0.352

4.3.6 Fault Tree Analysis of the Machinery Houses

The machinery house has all of the motors and generators along with lubrication and air conditioning units. There were no failure data for the Page's air conditioning, thus the fault tree for the Page's machinery house does not include the air conditioning different from that of Marion. Figure 4.14 shows the constructed fault tree for Marion's machinery house.

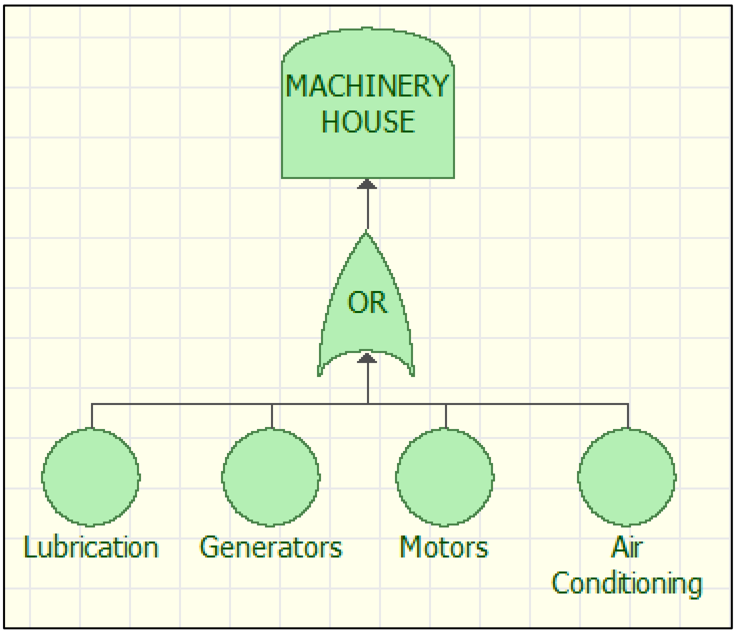


Figure 4.14 Fault tree representation of machinery houses

The reliability equations are:

$$R_{\text{machinery house (MARION)}} = R_{\text{lubrication}} \times R_{\text{generators}} \times R_{\text{motors}} \times R_{\text{air conditioning}} \quad (26)$$

$$R_{\text{machinery house (PAGE)}} = R_{\text{lubrication}} \times R_{\text{generators}} \times R_{\text{motors}} \quad (27)$$

The comparison of the reliability curves for both machinery houses is given in Figure 4.15.

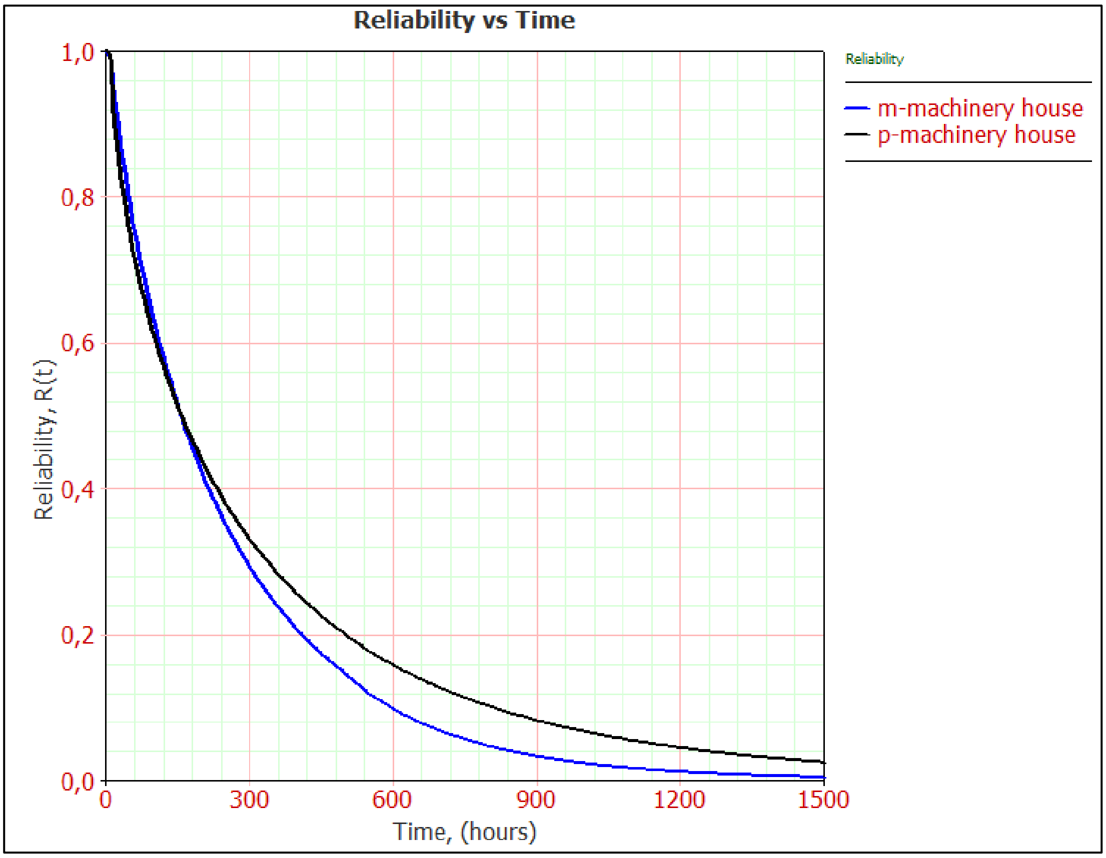


Figure 4.15 Reliability graph of machinery houses

It can be suggested that the reason Marion's machinery house's reliability decreases more rapidly is that it contains an additional components (air conditioning).

However, that is not the only reason. The generator and lubrication units of Marion's machinery house also have lower reliability than those of Page.

After 300 hours, the reliability for the machinery house of Page is 33% where this value is 29% for Marion. Even with the air conditioning removed from the Marion's fault tree, Page's reliability still remains higher.

The estimated mean life values are 250 hours for Marion's machinery house and 315 hours for Page's. The importance values of the components at the given times are presented in Table 4.25. Lubrication and generator have close importance values for Marion with higher being lubrication where the component with the highest importance value is motors for Page. See Appendix A (Figure A.61 and A.62) for the importance value versus time graphs.

Table 4.25 Importance values of the machinery house components at estimated mean life times

	PAGE	MARION
Generators	0.447	0.522
Motors	**0.520**	0.427
Lubrication	0.438	**0.555**
Air conditioning		0.352

4.3.7 Fault Tree Analysis of the System

For the overall system, all the units mentioned above are connected by an OR gate and the constructed system fault tree is presented in Figure 4.16. Since all the units are independent and connected by an OR gate, the reliability equation is the multiplication of the previous equations:

$$R_{System}=R_{machinery\ house} \times R_{hoisting} \times R_{movement} \times R_{dragging} \times R_{bucket} \times R_{rigging} \quad (28)$$

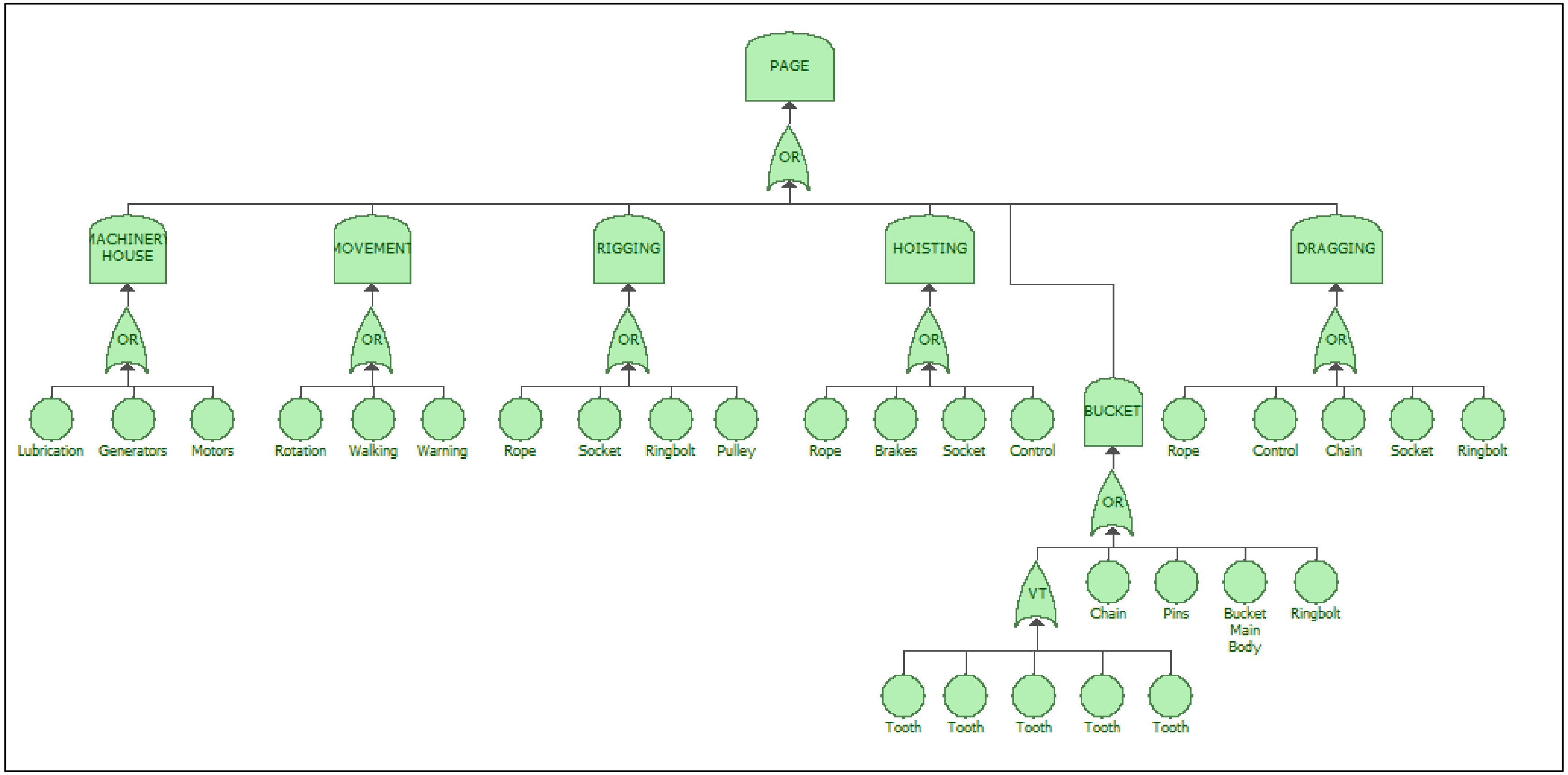


Figure 4.16 Fault tree representation of the dragline system (PAGE)

The overall reliability change with time curves for both draglines are presented in Figure 4.17. Since most units of Page have higher reliability compared to Marion's, the overall reliability of Page is also higher than Marion as expected. The time causing the reliability to drop down to 50% is around 27 hours for Page and this number is around 24 hours for Marion. The mean life estimations for the draglines are 37.9 hours for Page and 35.9 hours for Marion.

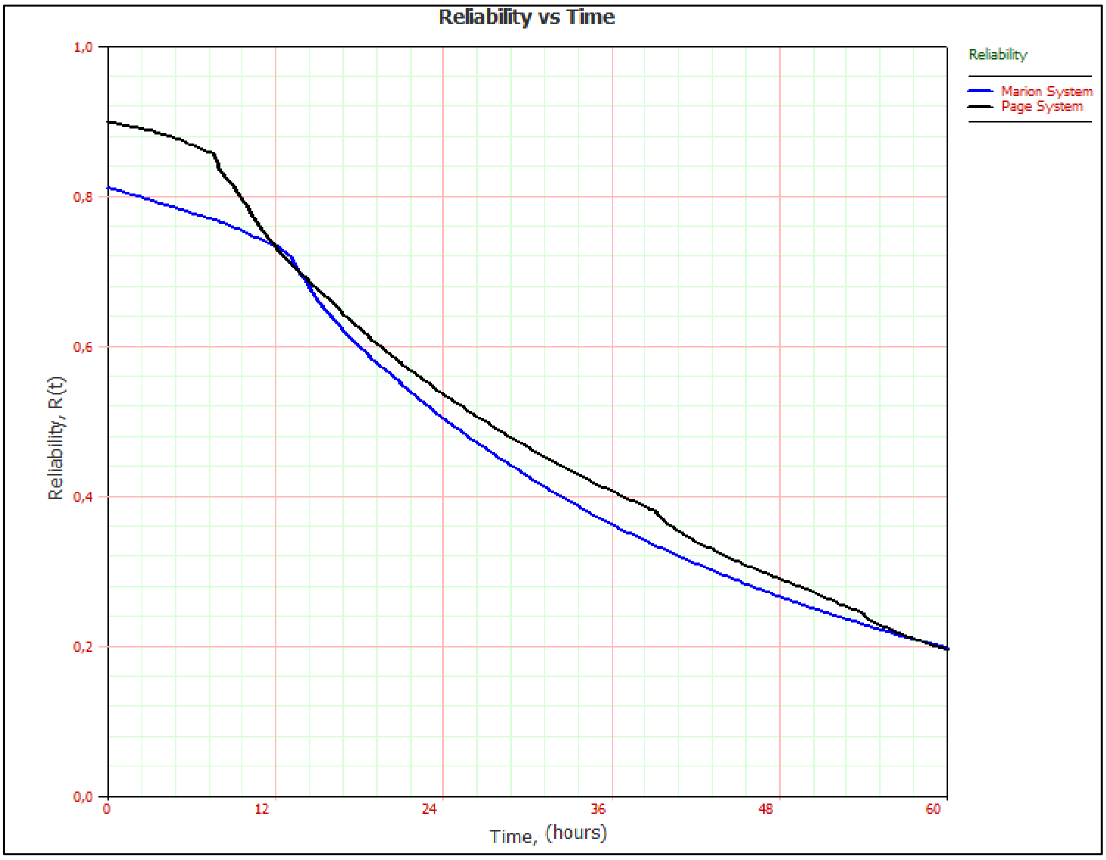


Figure 4.17 Reliability graph of the draglines

Page being the higher reliability dragline can be explained by the fact that has a higher bucket capacity of 30.6 m^3 (40 yd^3), where the bucket capacity of Page is 15.3 m^3 (20 yd^3). Also, the rock mass properties of the stripped material may have an impact on the reliability. The properties of the rock formations affect the fill factors, cycle times and stripping capabilities of draglines (Demirel, 2011). Changes in fill

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factors may affect stresses occurring on different components. Aside from manufacturing differences, the way operators utilize these machines can have an impact on the machine reliability. Although, reducing cycle time can increase productivity, it also cause fast changes in stress amplitudes on various components causing fatigue, and consequently failures (Demirel, 2009). The mean life estimations for all units are carried out and presented in Table 5.1 to determine the most and least reliable units of both draglines.

Table 4.26 Mean life estimations of dragline units from fault tree analysis

	MARION	PAGE
Dragging	200	211
Hoisting	448	**582**
Rigging	267	329
Bucket	**152**	**139**
Movement	**452**	302
Machinery H.	250	315

The unit with the lowest mean life is bucket for both draglines with 152 hours for Marion and 139 hours for Page. The estimated mean lives suggest that for example the bucket unit of Marion is expected to operate for 152 hours without failure. Comparing two draglines, their dragging and bucket units have close mean lifetimes which have the lowest two estimations. The movement unit has the highest mean lifetime with 452 hours for Marion and it is the hoisting unit with 582 hours for Page. For both draglines, the hoisting units have high mean life estimations.

Although as a unit, bucket unit has the lowest reliability for both draglines; components from different units have higher importance values. The higher reliability importance values suggest that at that given time, those components have the lowest reliability values. Although the bucket units have the lowest mean life estimations, the components with the highest reliability importance values are from other units. 5 components with the highest importance values at the draglines' mean lives can be seen in Figure 4.17 and 4.18.

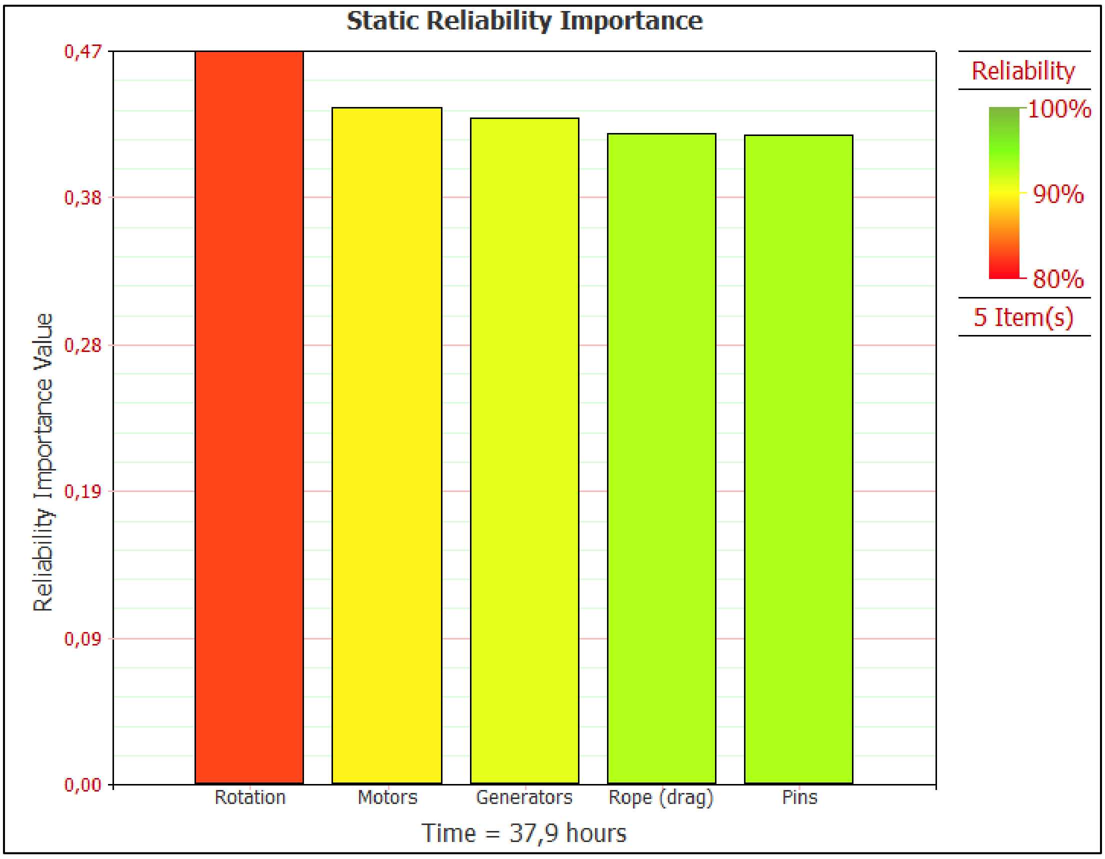

Figure 4.18 5 components with highest RI values at Page's mean life

As seen in Figure 4.18, at 37.9 hours, the component with the lowest reliability is the rotation which is a component of the movement unit for Page. These reliability importance values are basic measures that give the ratio of the system reliability to component reliability. Since all components are in the same system, the higher RI values suggest lower reliabilities. RI values are effective measures in systems with series configurations. In parallel systems, RI factors can give inaccurate results since the RI measure doesn't take into account the location of the components in the system configuration. In Figure 4.19, it is seen that the lowest reliability component for Marion at 35.9 hours is the brakes of the hoisting unit.

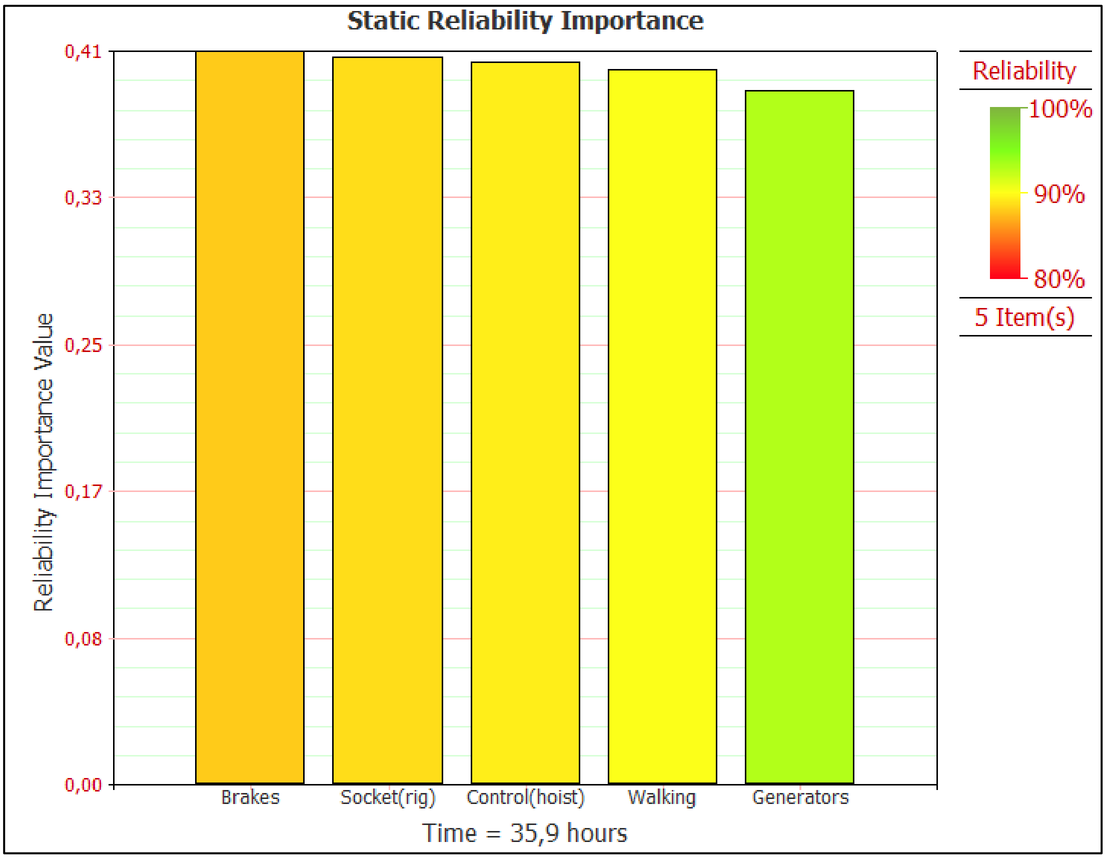

Figure 4.19 5 components with highest RI values at Marion's mean life

These values can be calculated for different time intervals to determine the components to be maintained. For example, after 60 hours of operation of Marion, hoisting brakes have the lowest reliability but the walking unit becomes the second least reliable component. For Page, although the hoisting brakes are not shown in Figure 4.18 among the 5 most important components, at 100 hours, it becomes the third most important component which is caused by different reliability behavior of components. Some of the component reliabilities decrease more rapidly with time.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This study is conducted in order to increase the availability and operability of two different draglines (PAGE 736 and MARION 7820-G), using reliability models and fault tree analysis. The failure data of the two draglines are obtained from GLİ coal mine for years between 1998 and 2011. Those data are classified into different components of the draglines and then introduced to the software “Weibull 7” in order to determine their probability distributions and reliability modelling. The results of those analyses are then combined using fault tree analysis in order to acquire the system reliability model.

The main conclusions drawn from this study are listed as:

i. Pre-processing of data using Runs Test is critical for detecting trends (clustering, trends, mixtures, oscillations) in data distributions.

ii. Fault tree analysis is an effective tool in determining complex system reliability.

iii. Reliability Importance (RI) factor can be utilized effectively to detect the critical elements in series systems in varying operation periods.

iv. According to the data acquired from GLİ, the overall reliability of the Page dragline operating in that mine is higher compared to the Marion. This may be due to the capacity differences between the two draglines or the differences in working conditions.

v. Bucket units of both draglines have the lowest mean life estimations, meaning they are prone to failure more frequently.

vi. Movement unit for Marion and hoisting unit for Page have the highest mean life without any failure.

vii. Mean life estimation for dragging units are; 200 hours for Marion and 211 hours for Page.

viii. Mean life estimation for hoisting units are; 448 hours for Marion and 582 hours for Page

ix. Mean life estimation for rigging units are; 267 hours for Marion and 329 hours for Page

x. Mean life estimation for bucket units are; 152 hours for Marion and 139 hours for Page

xi. Mean life estimation for movement units are; 452 hours for Marion and 302 hours for Page

xii. Mean life estimation for machinery house units are; 250 hours for Marion and 315 hours for Page

xiii. At different times, different components have higher importance values meaning those components may require special attention to prevent failure.

xiv. Having a good understanding of the system at hand and proper classification of failure data accordingly are important for reliability analysis.

The items that can be recommended for the future studies can be listed as follows:

i. Results of reliability analyses should be utilized to prepare a maintenance plan considering the critical components. Preparing an appropriate maintenance plan considering the component reliabilities will increase the machines availability, thus decreasing the direct and indirect costs caused by unplanned down times of the machinery.

ii. Optimum preventive or corrective maintenance intervals should be decided considering maintenance costs, repair efficiencies and losses in revenue due to breakdowns.

iii. There can be units that take time to be repaired in case of failure and may require detailed scheduled maintenance considering the repair and maintenance times.

iv. Since mining is a progressive operation, the physical properties of the overburden can vary and this may affect the intensity of some component specific failures. The correlation between failures and working conditions can be implemented to the analyses.

v. Since reliability only considers the working times, the importance factors don’t include the repair times. Further investigation should be carried out considering the repair times and effects of component failures to the system availability.

vi. In future studies, failure mode and effects analysis can be utilized alternative to fault tree analysis in order to comprehend basic failure causes. This analysis requires the detection of failure modes (bending, wear and tear, fatigue, fracture etc.) for each failure.

vii. Maintenance personnel should be specially trained to keep failure logs precisely in order to prevent inaccurate data. If possible, a practical and detailed maintenance data sheet should be prepared to acquire more information about machine lifetime behavior. Some of the explanations in our data were vague and made it difficult to classify the data.

viii. Sensors should be applied to less reliable components for early failure detection in order to keep system reliability around desired levels.

ix. Similar to this study, technological adaptation between reliability and maintenance should be improved by academical projects in cooperation with industry.

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APPENDIX A

A.1. Component Contributions to Number of Unit Failures and Total Down Times

Figure A.1 Ratio of components' number of failures to total number of failures

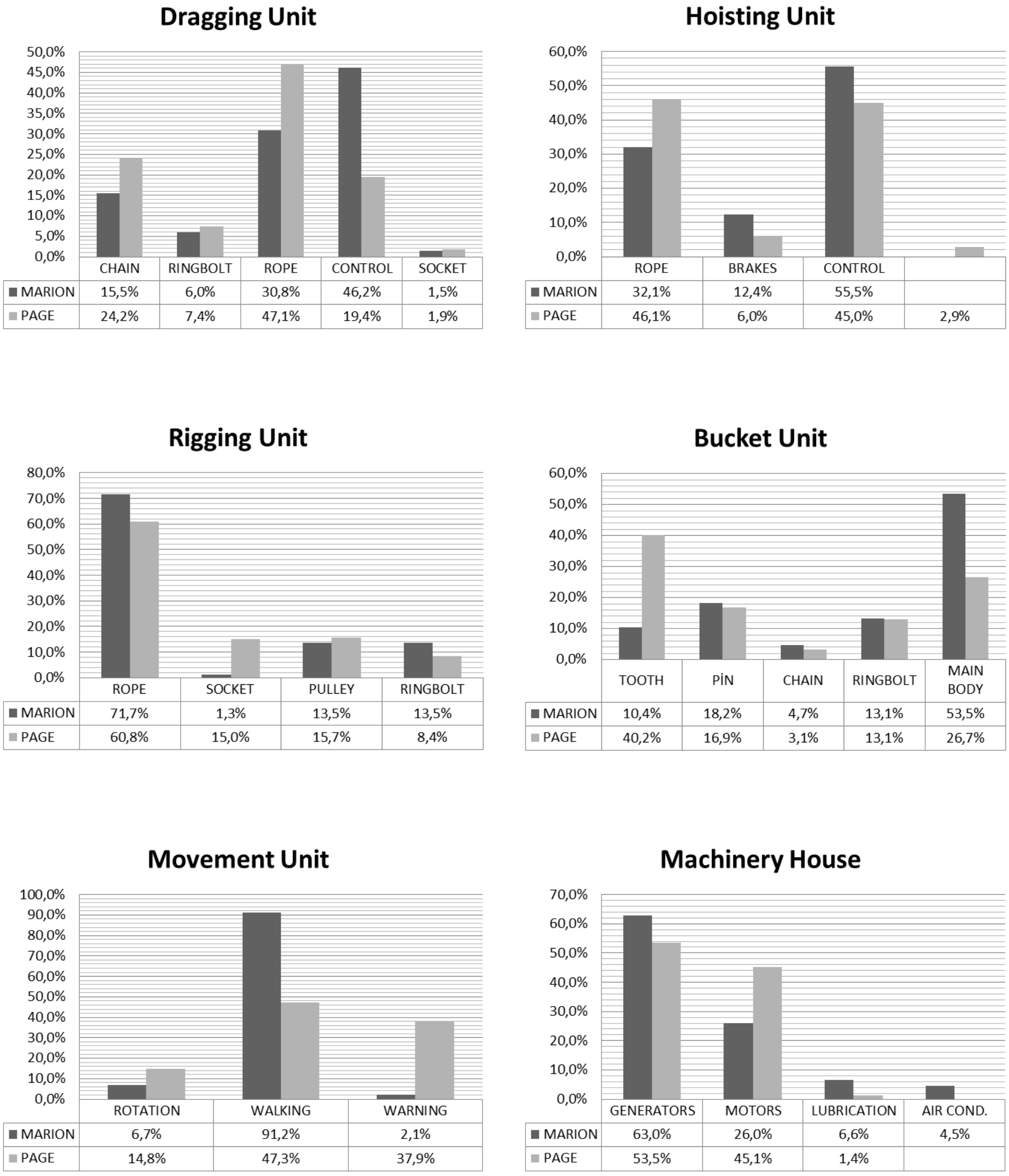

Figure A.2 Ratio of component downtimes to total unit downtimes

A.2. Runs Charts for the Dragline Units

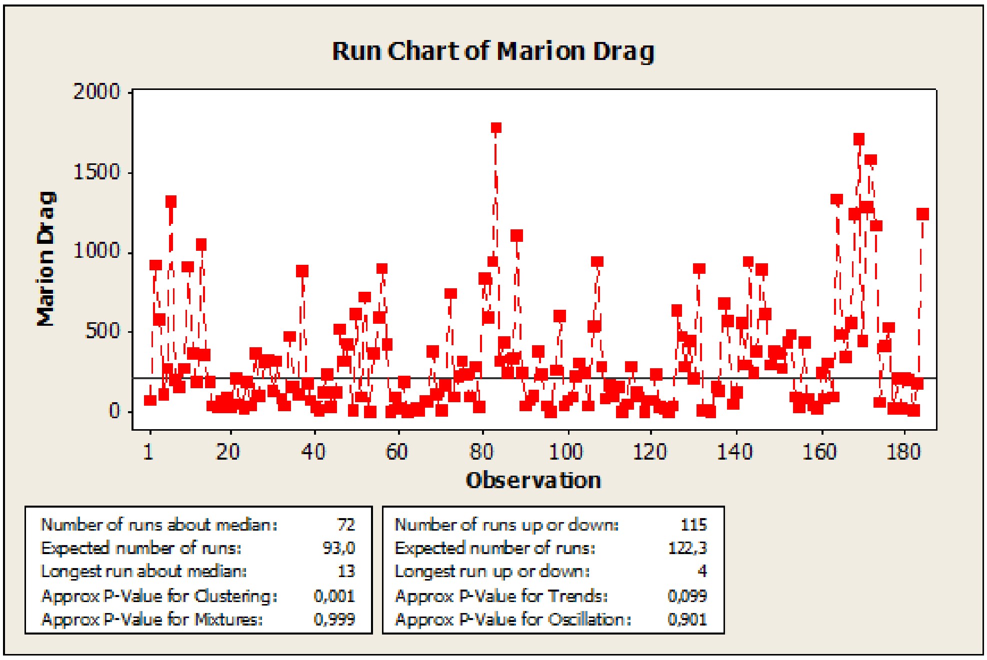

Figure A.3 Runs chart for Marion's dragging unit

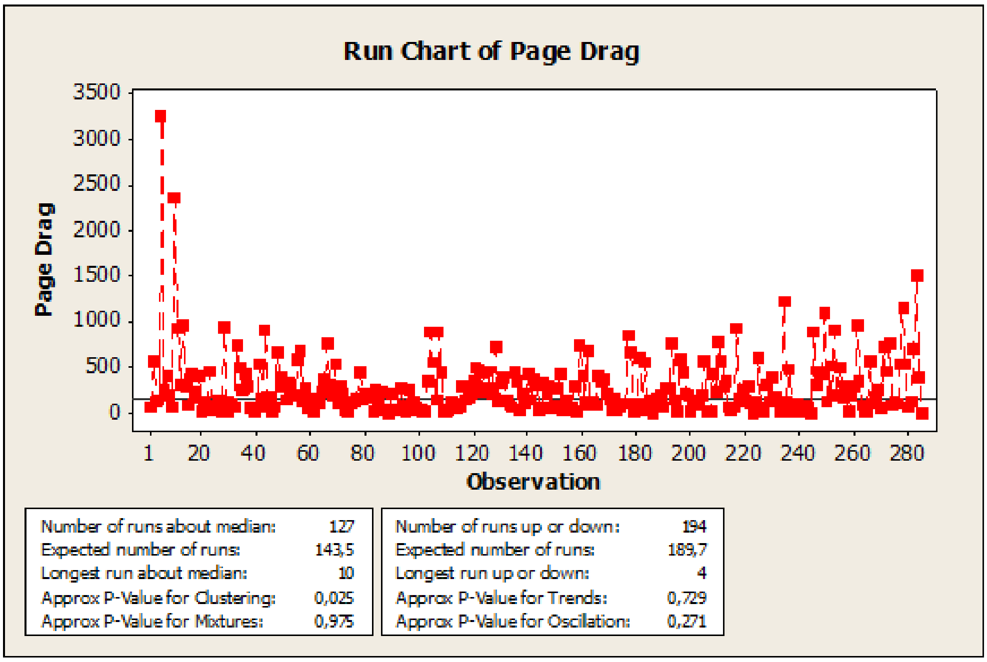

Figure A.4 Runs chart for Page's dragging unit

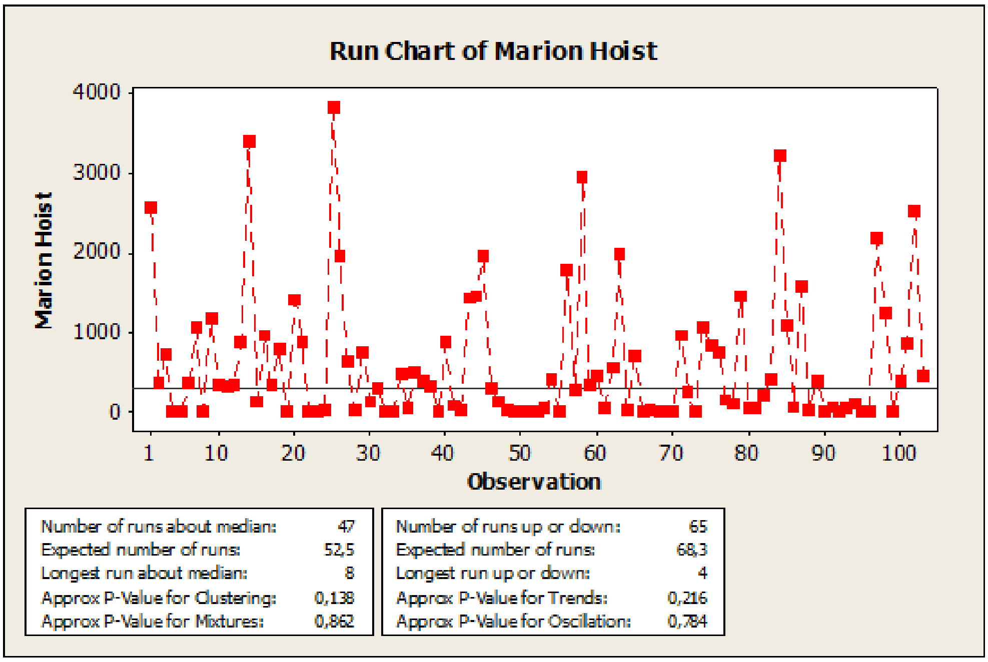

Figure A.5 Runs chart for Marion's hoisting unit

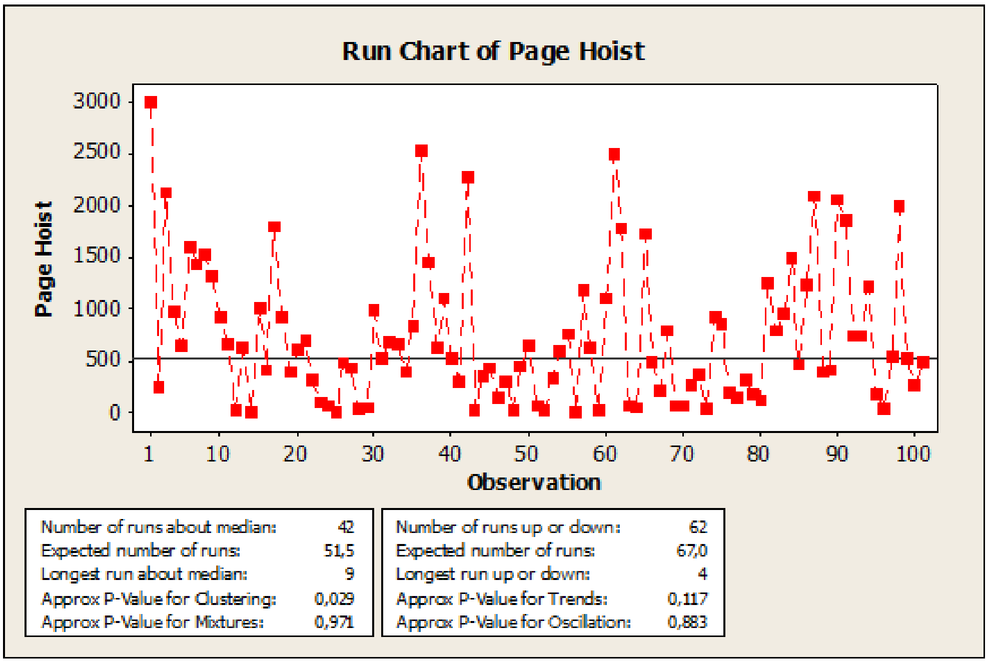

Figure A.6 Runs chart for Page's hoisting unit

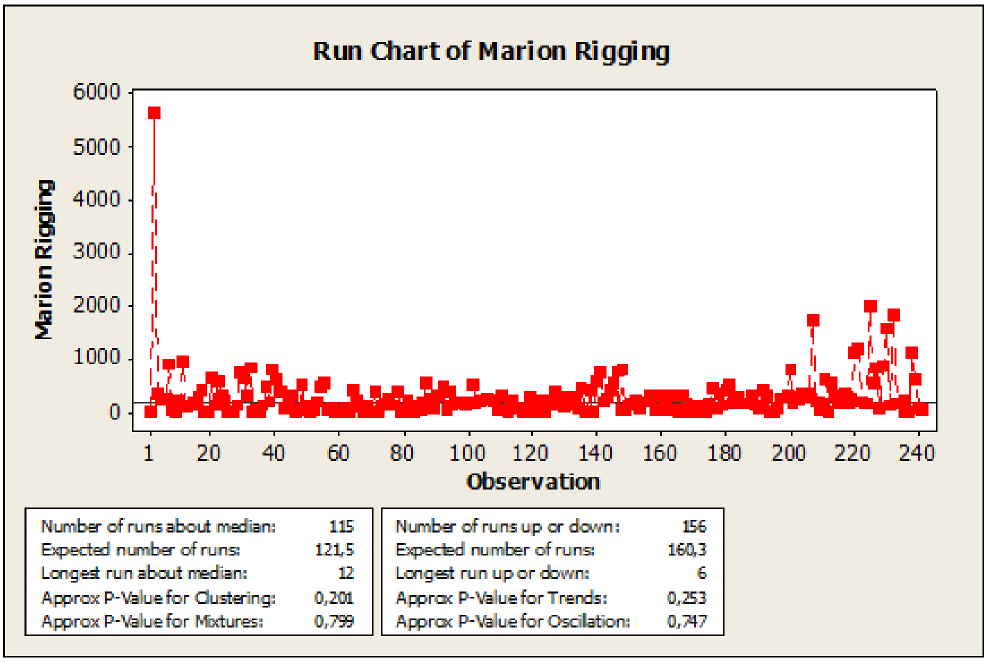

Figure A.7 Runs chart for Marion's rigging unit

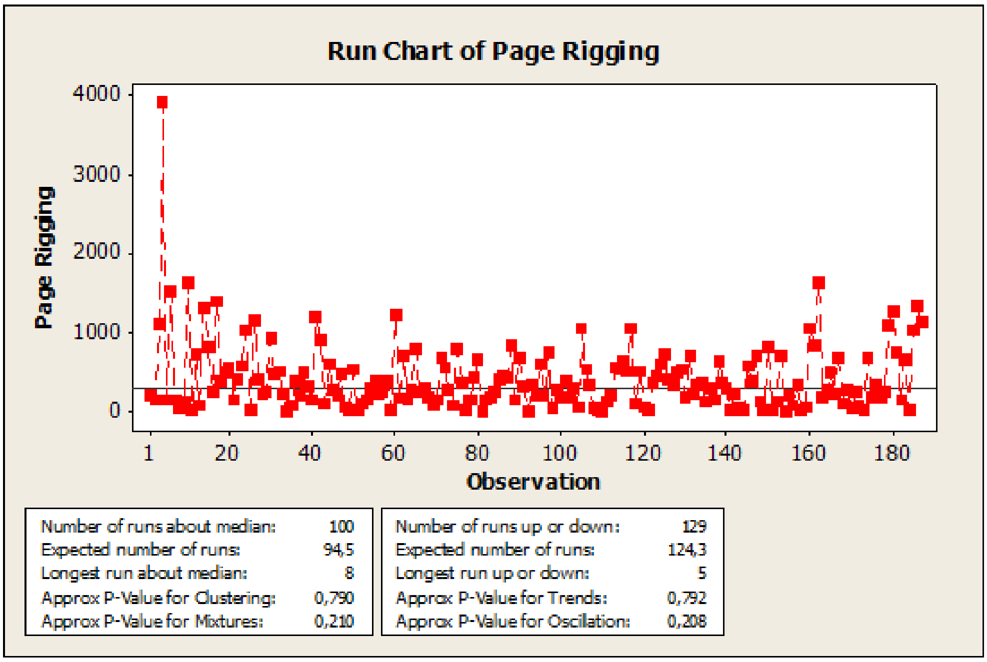

Figure A.8 Runs chart for Page's rigging unit

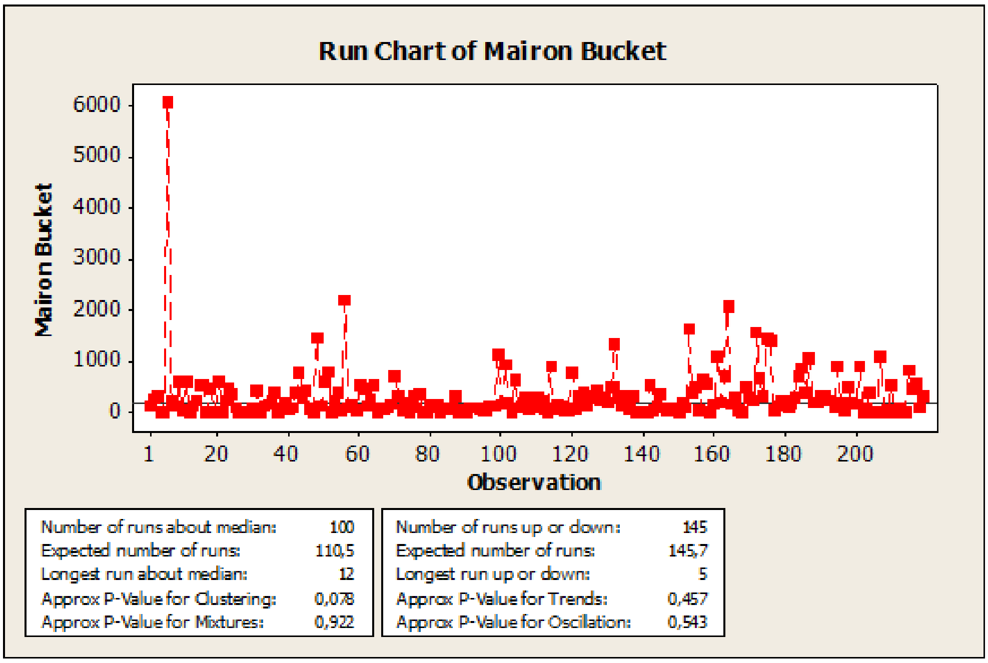

Figure A.9 Runs chart for Marion's bucket unit

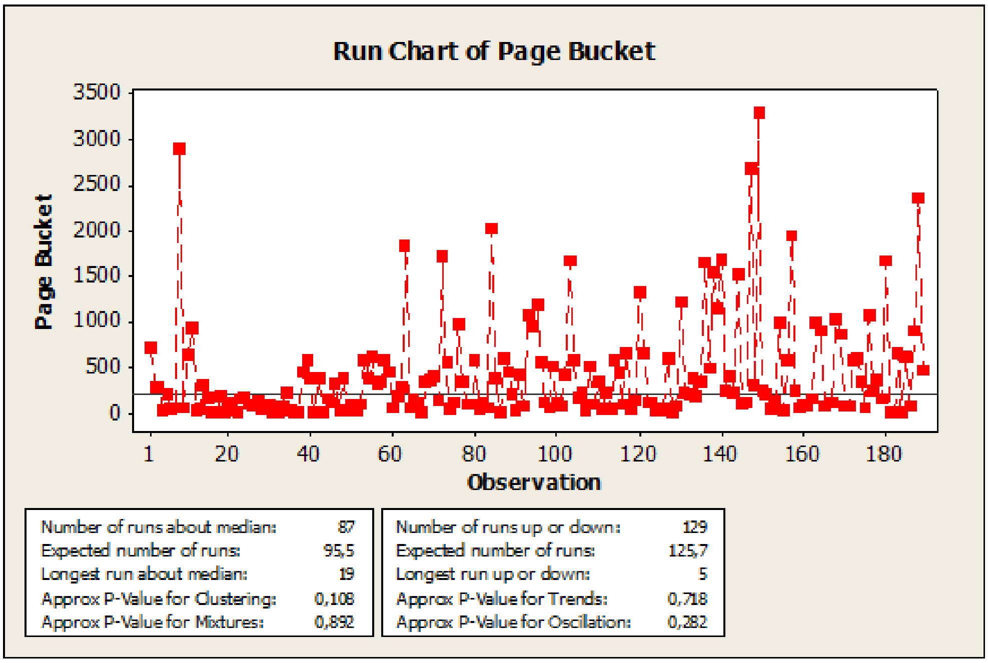

Figure A.10 Runs chart for Page's bucket unit

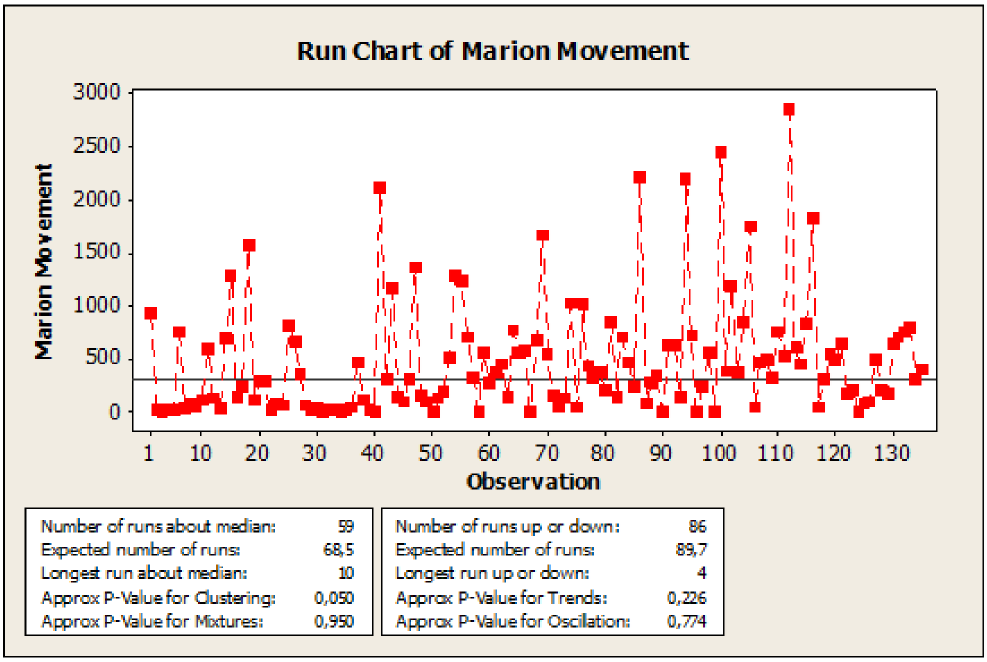

Figure A.11 Runs chart for Marion's movement unit

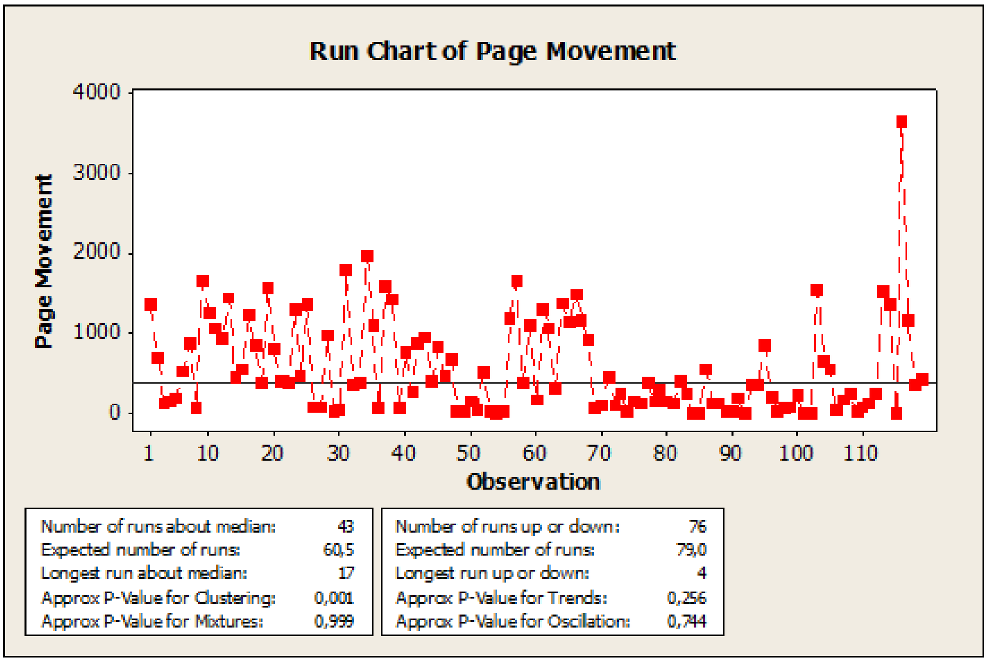

Figure A.12 Runs chart for Page's movement unit

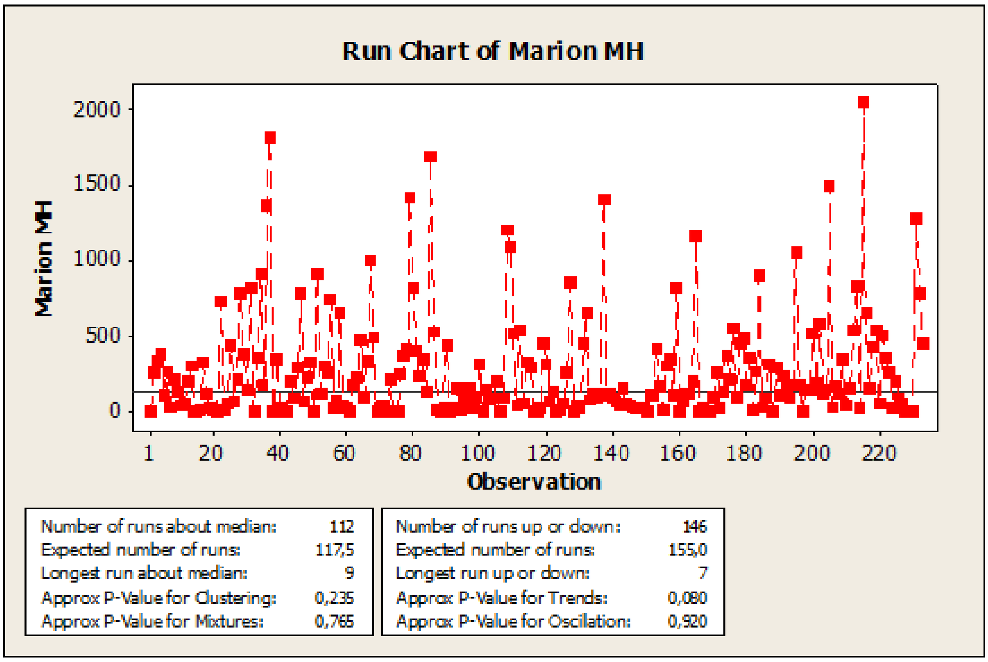

Figure A.13 Runs chart for Marion's machinery house

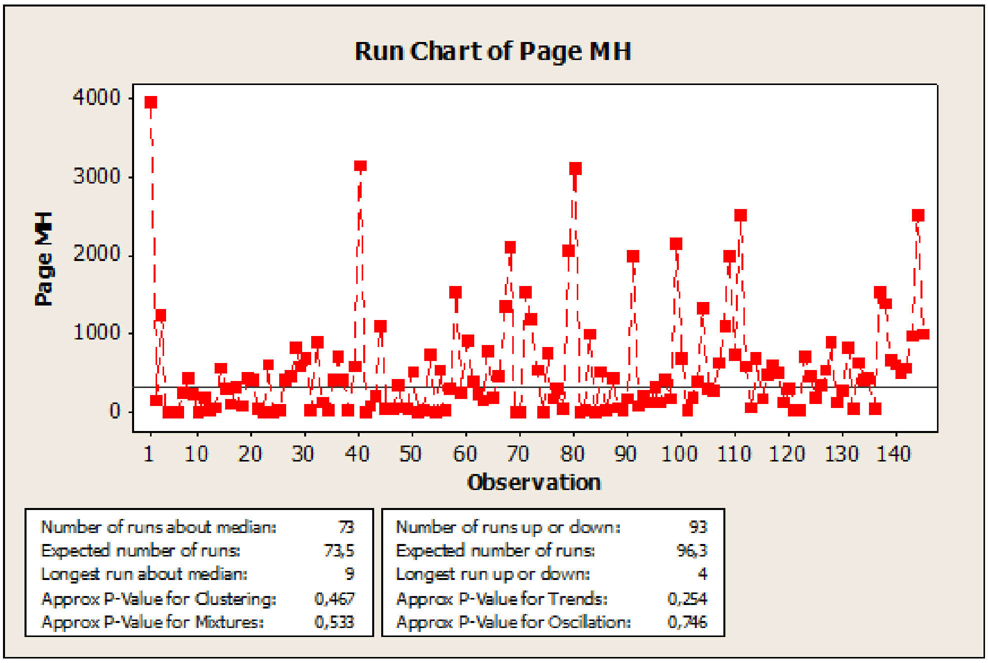

Figure A.14 Runs chart for Page's machinery house

A.3. Probability Density Functions and Reliability Curves of Components

Components of the Dragging Units

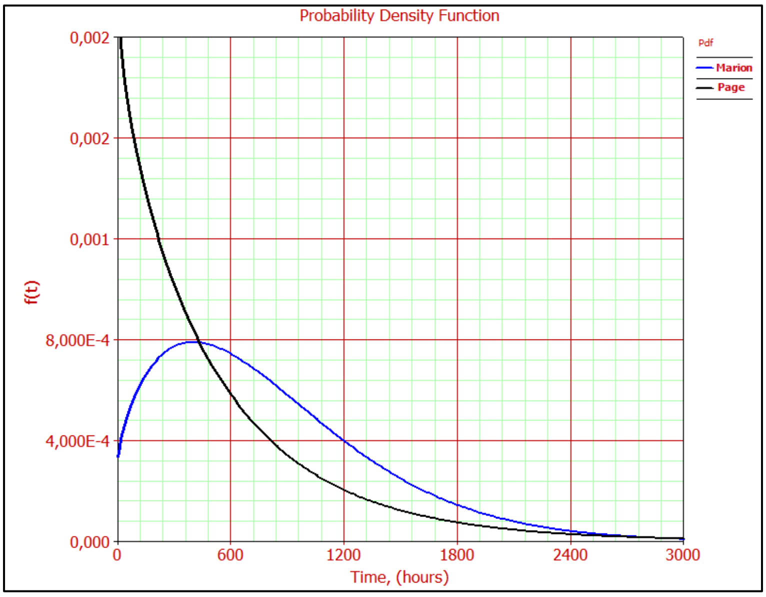

Figure A.15 PDF curves of Dragging - Rope

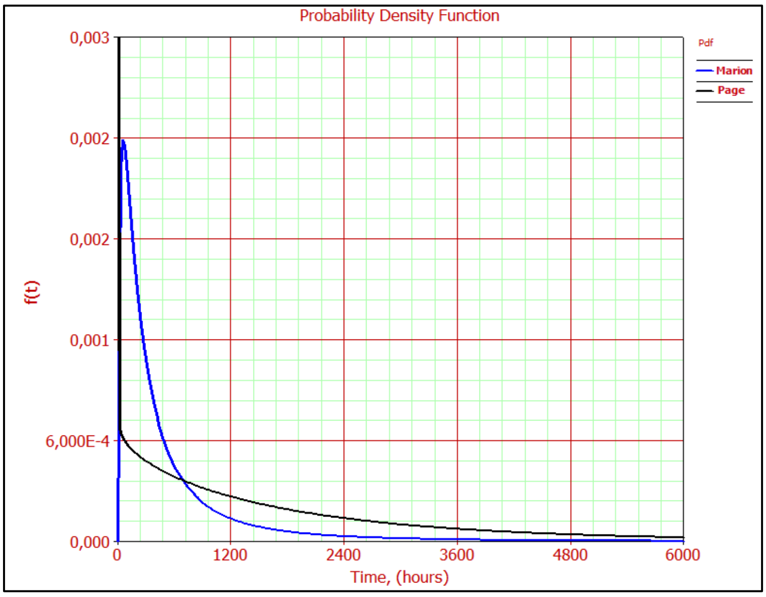

Figure A.16 PDF curves of Dragging - Control

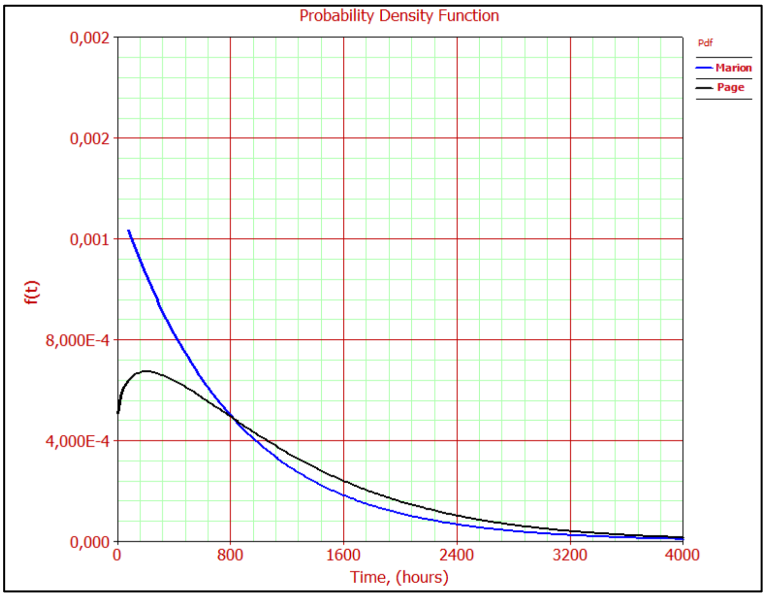

Figure A.17 PDF curves of Dragging – Ringbolt

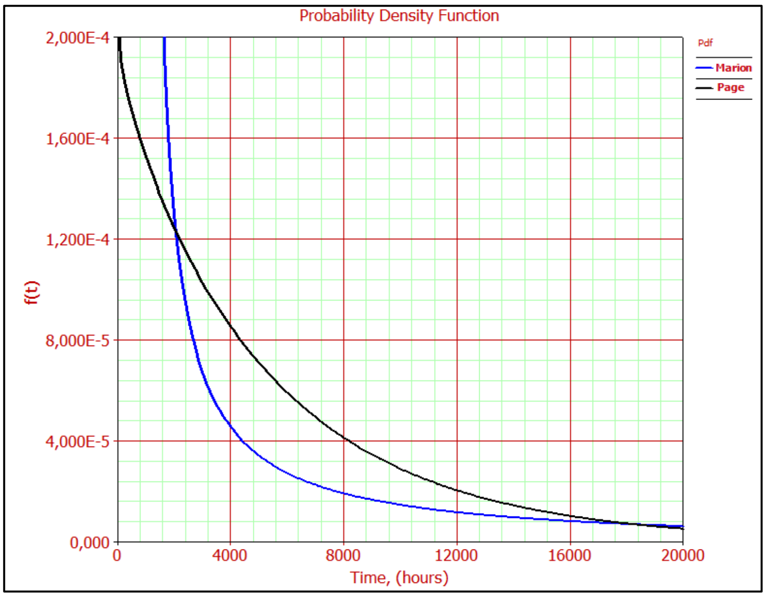

Figure A.18 PDF curves of Dragging – Socket

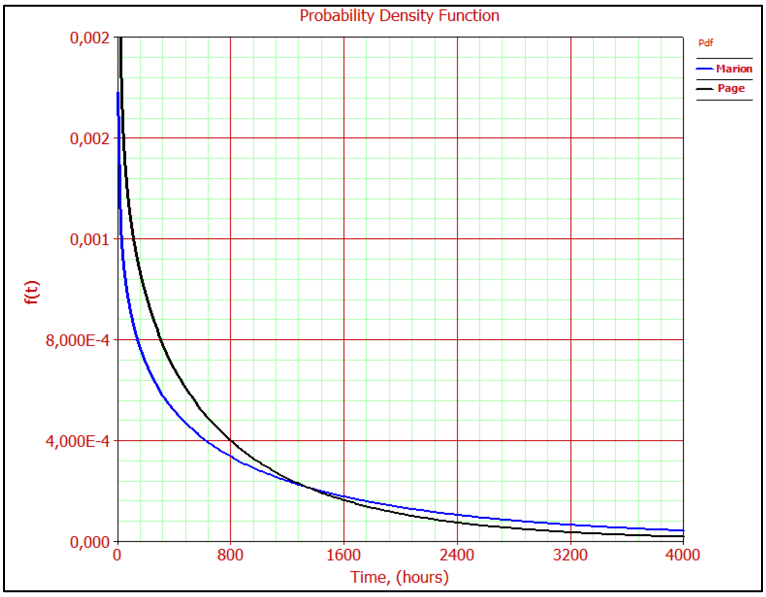

Figure A.19 PDF curves of Dragging – Chain

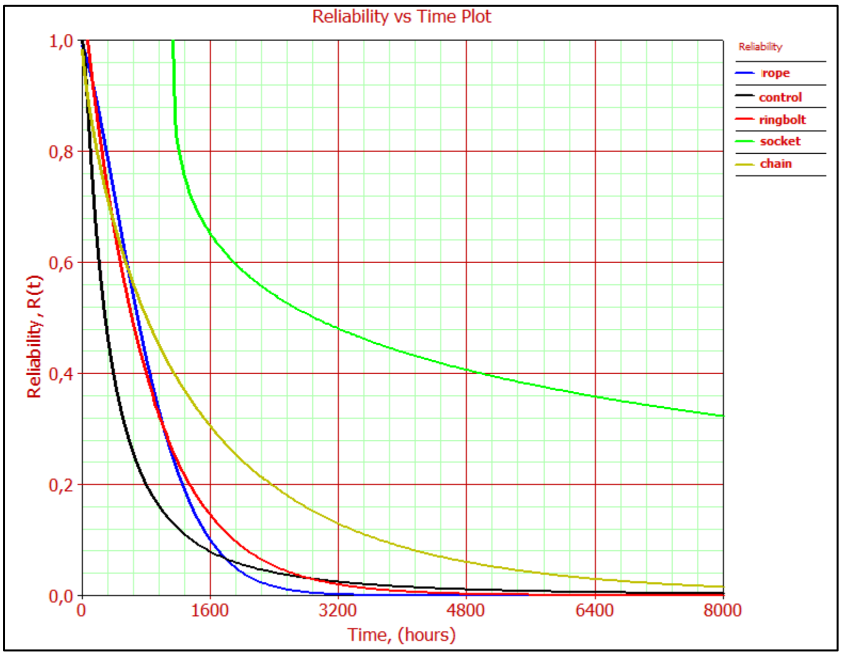

Figure A.20 Reliability curves of components (Marion-Dragging)

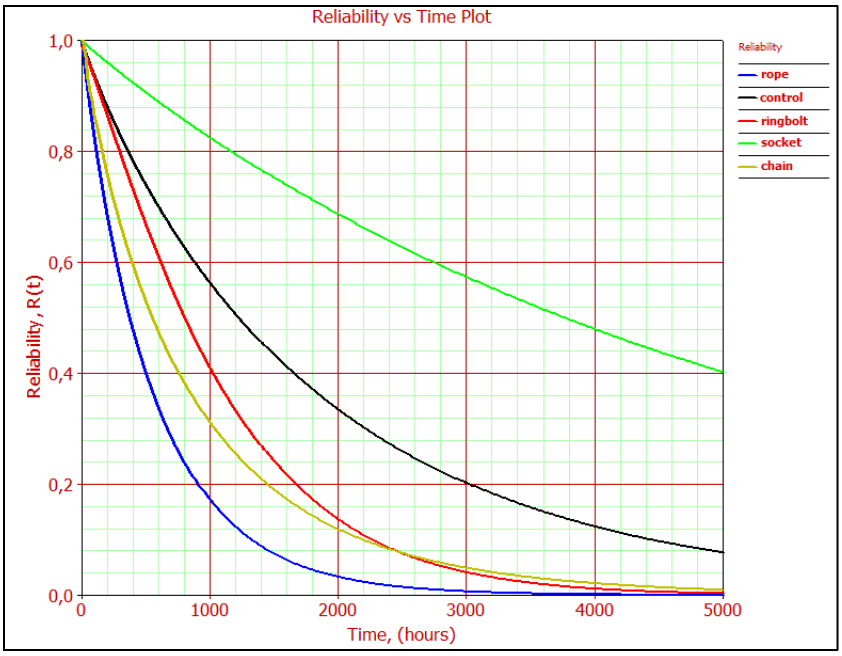

Figure A.21 Reliability curves of components (Page-Dragging)

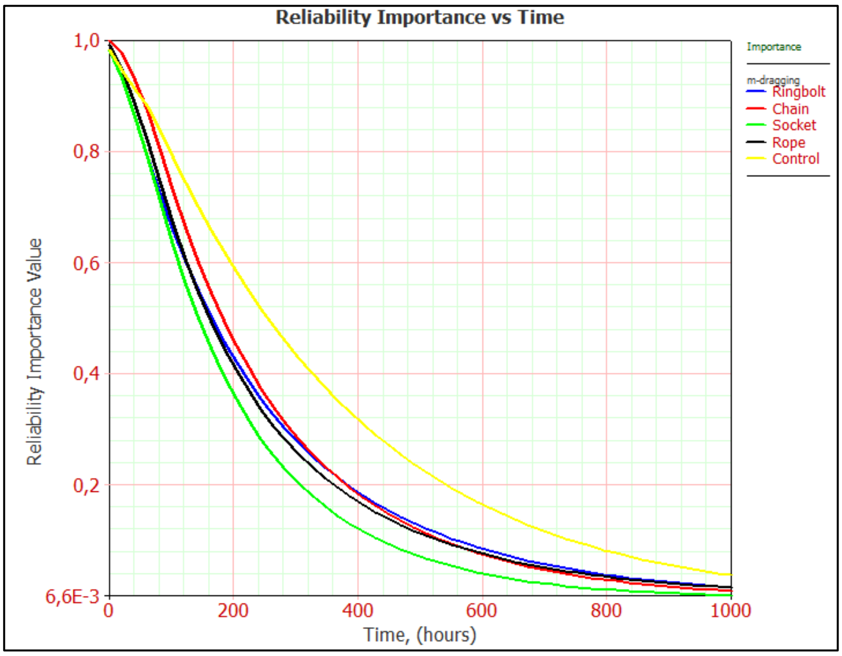

Figure A.22 Changes in importance values with time (Marion-Dragging)

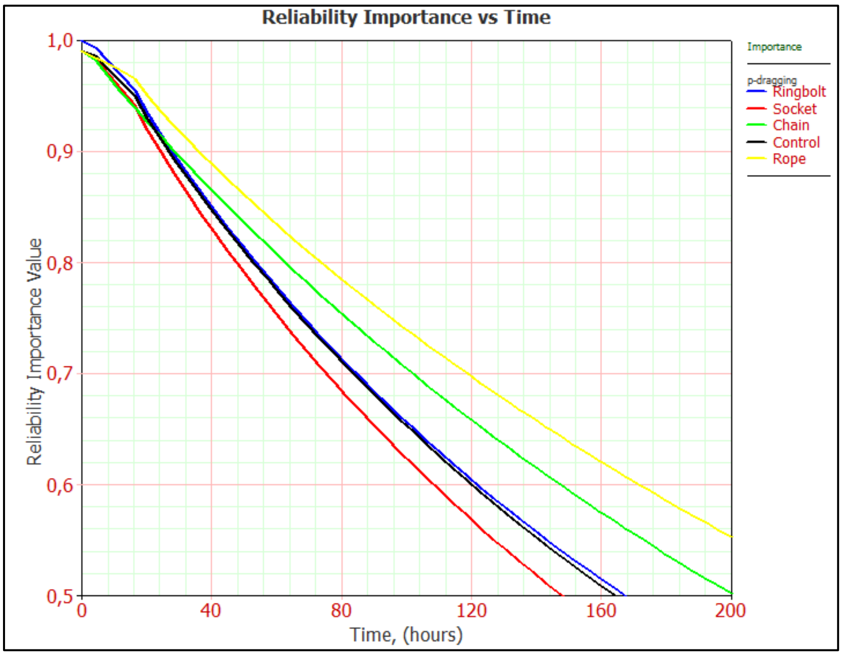

Figure A.23 Changes in importance values with time (Page-Dragging)

Components of the Hoisting Units

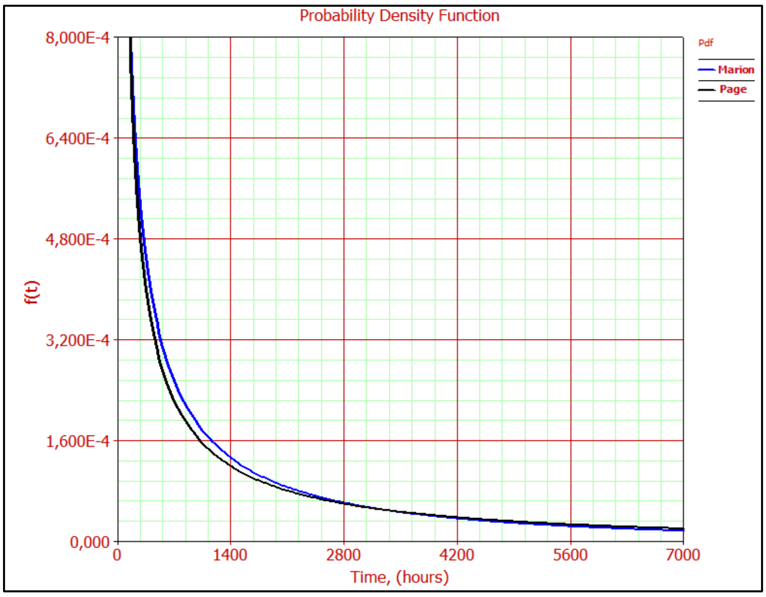

Figure A.24 PDF curves of Hoisting - Brakes

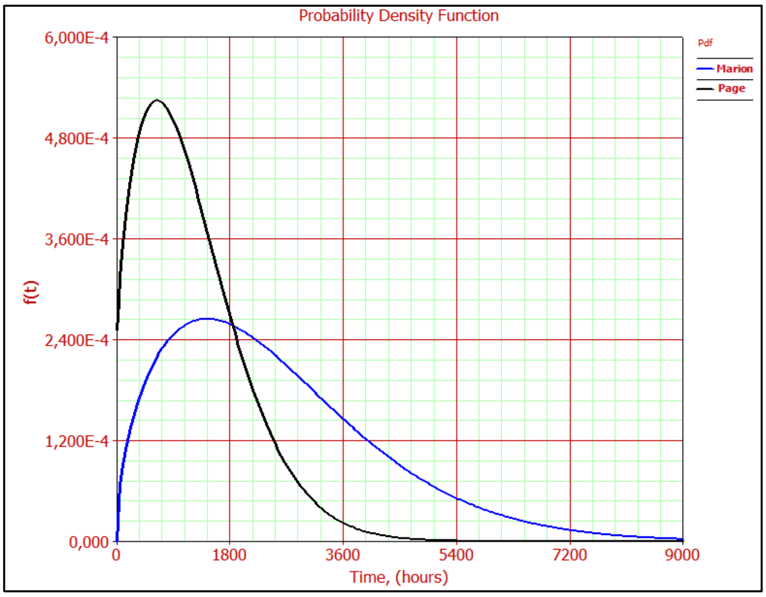

Figure A.25 PDF curves of Hoisting - Rope

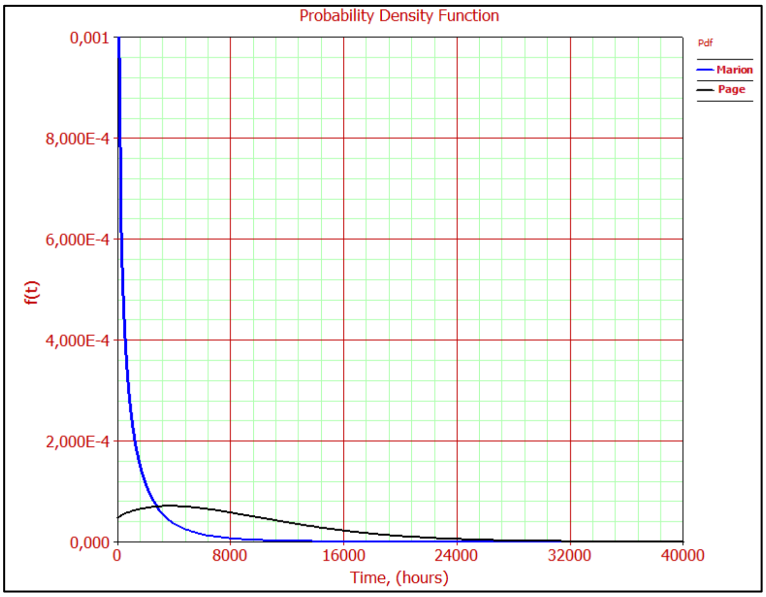

Figure A.26 PDF curves of Hoisting - Control

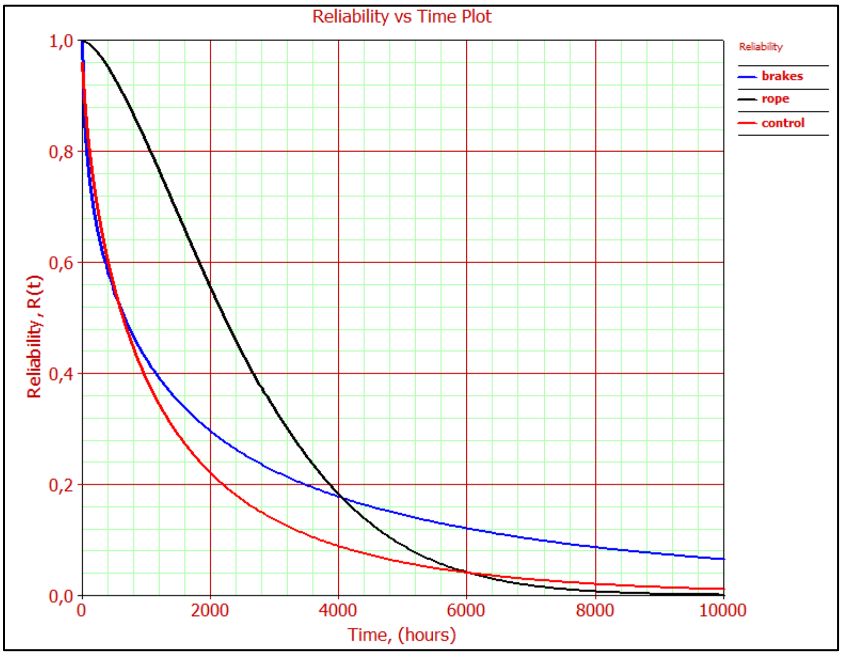

Figure A.27 Reliability curves of components (Marion-Hoisting)

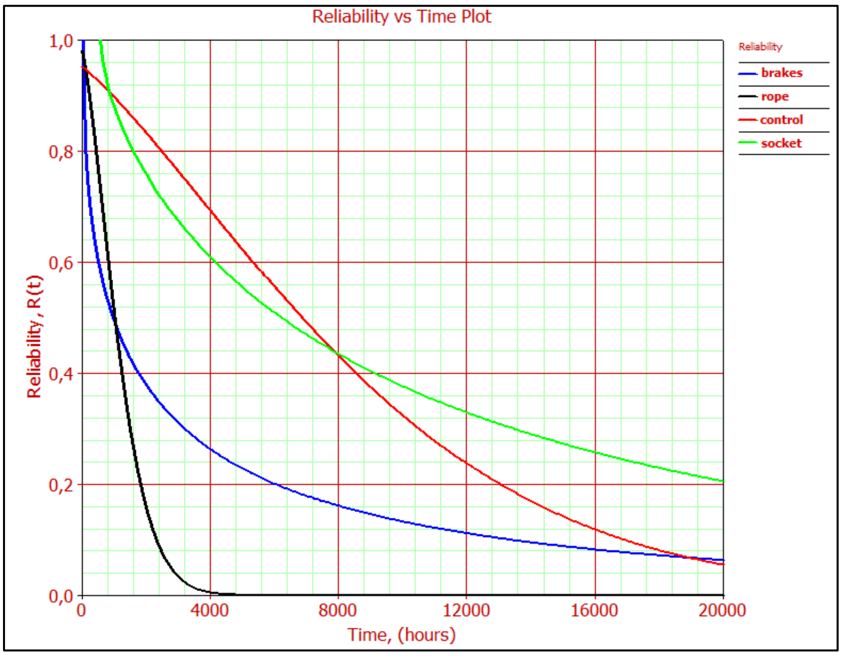

Figure A.28 Reliability curves of components (Page-Hoisting)

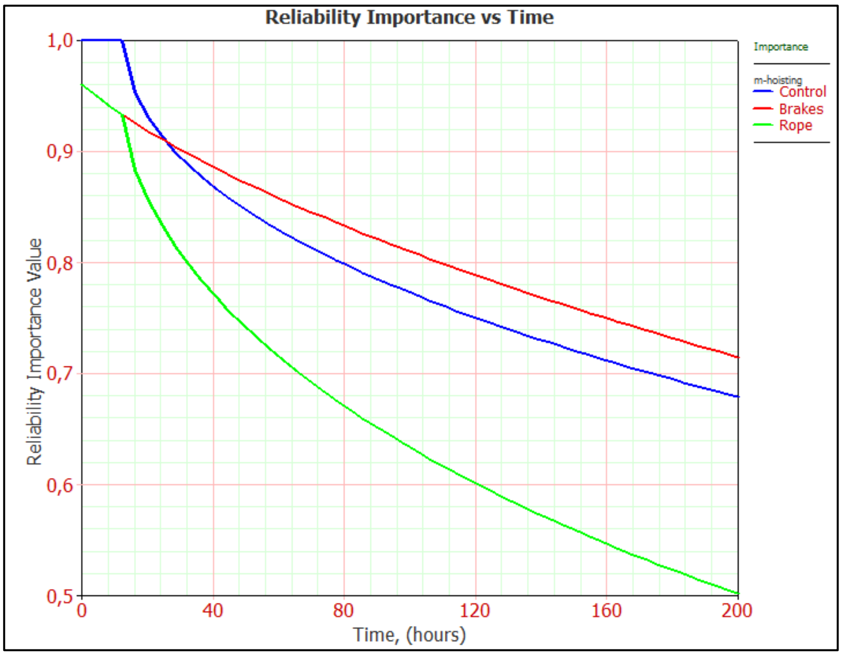

Figure A.29 Changes in importance values with time (Marion-Hoisting)

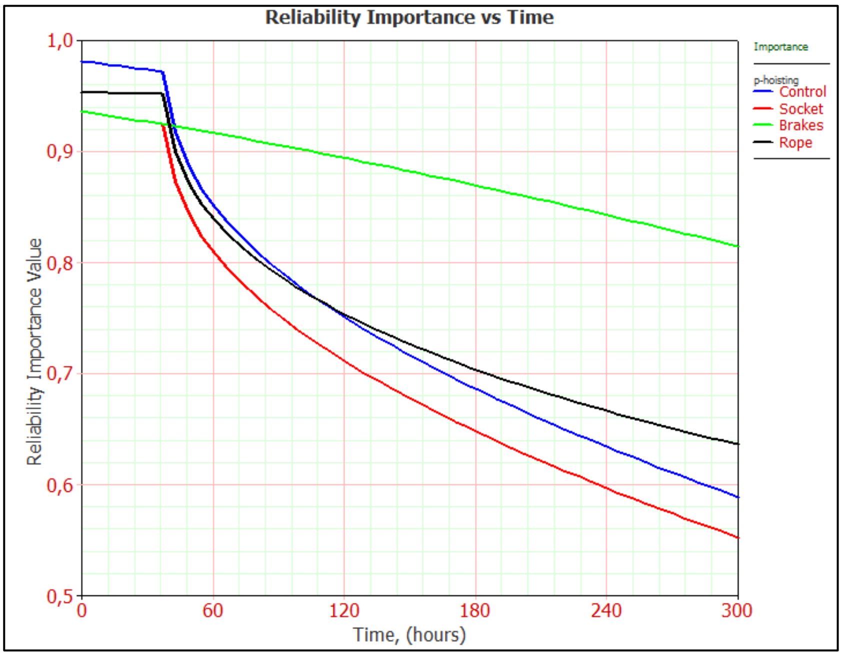

Figure A.30 Changes in importance values with time (Page-Hoisting)

Components of the Rigging Units

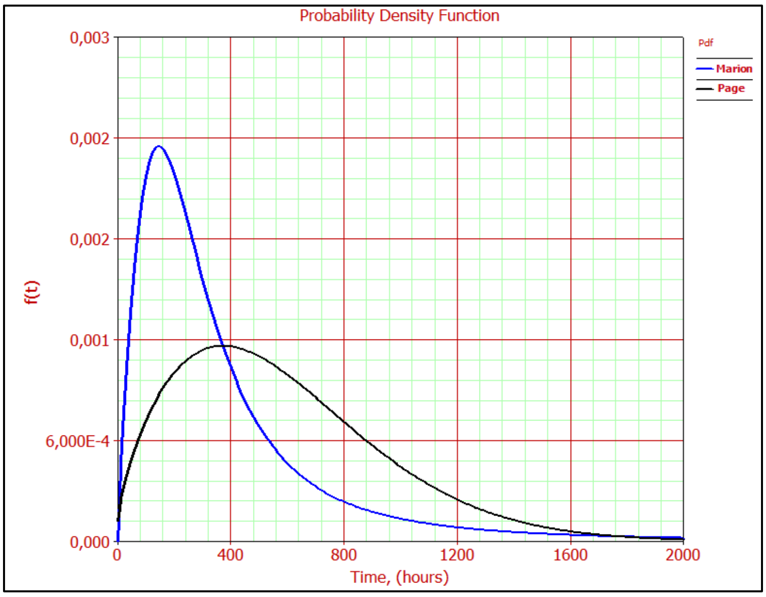

Figure A.31 PDF curves of Rigging - Rope

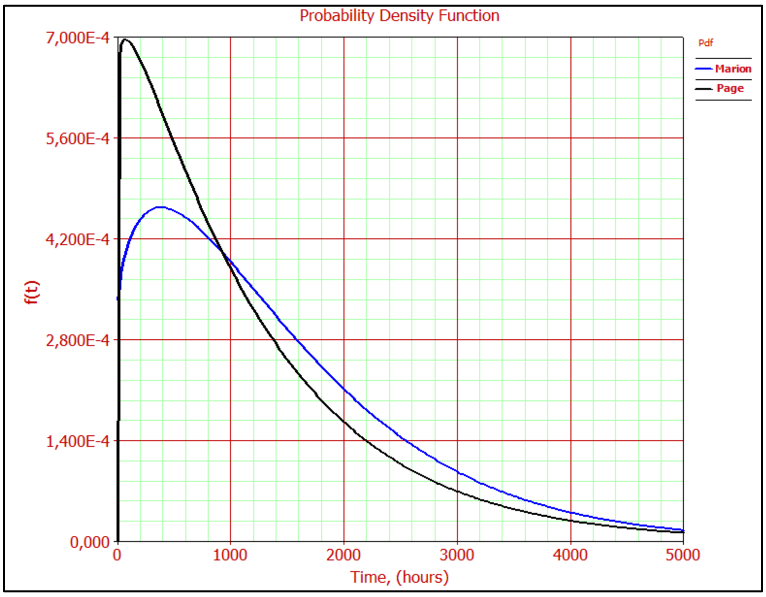

Figure A.32 PDF curves of Rigging - Pulley

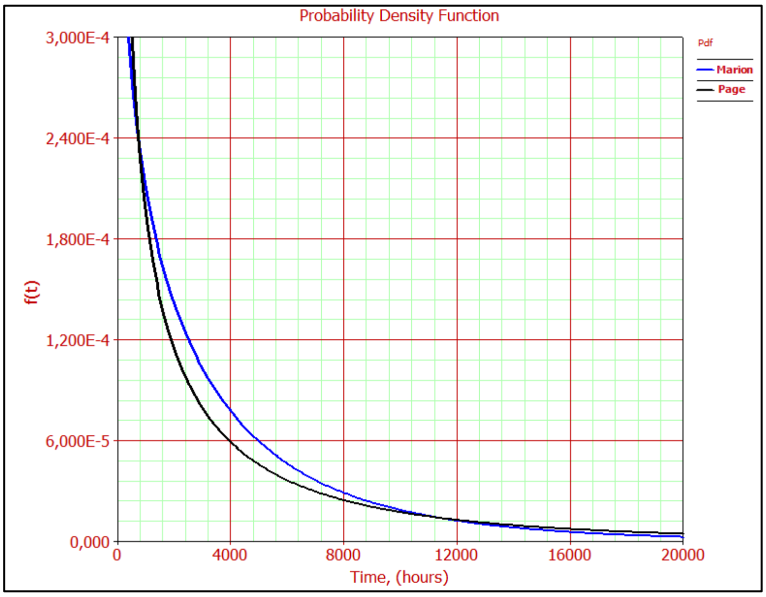

Figure A.33 PDF curves of Rigging – Ringbolt

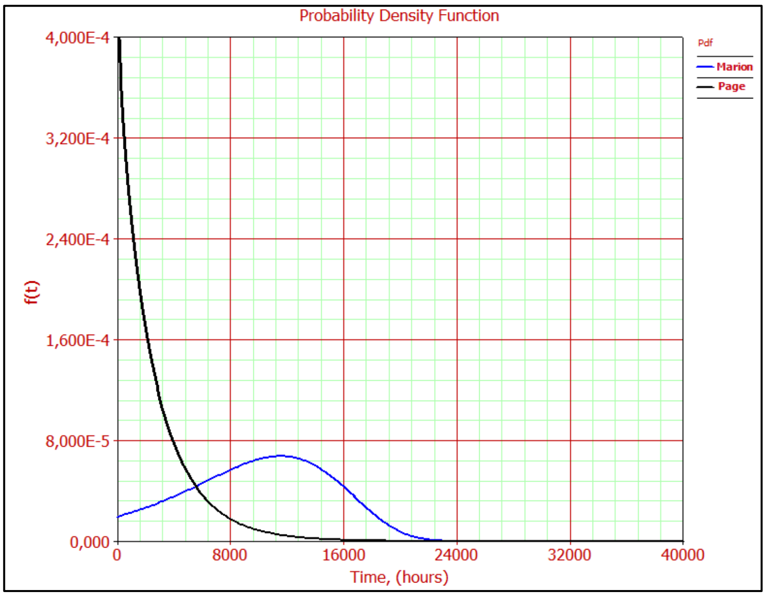

Figure A.34 PDF curves of Rigging - Socket

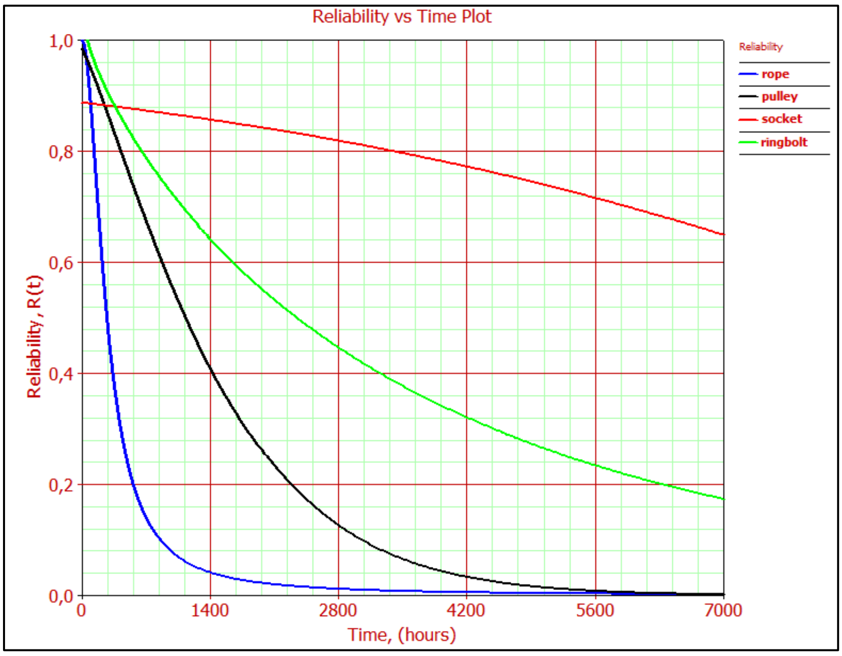

Figure A.35 Reliability curves of components (Marion-Rigging)

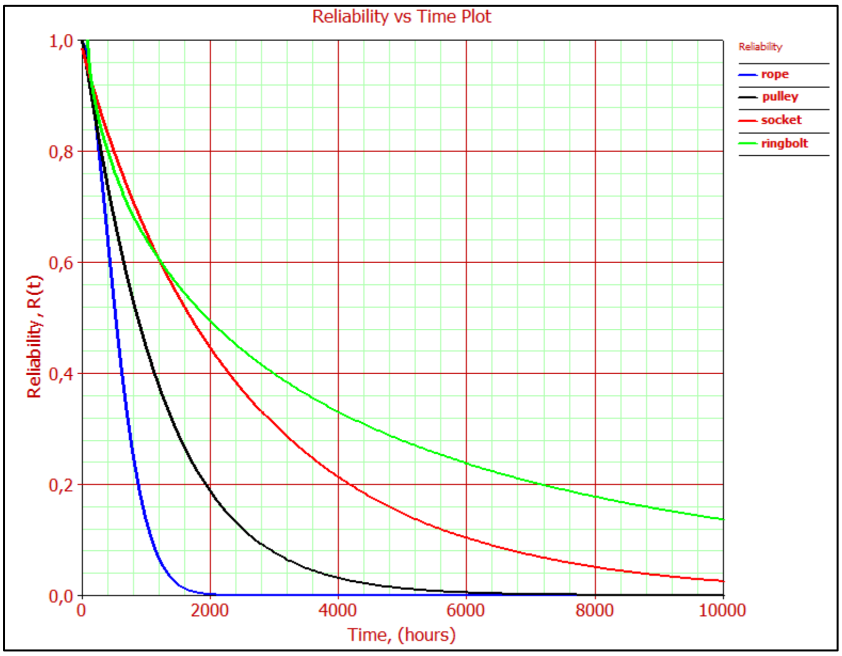

Figure A.36 Reliability curves of components (Page-Rigging)

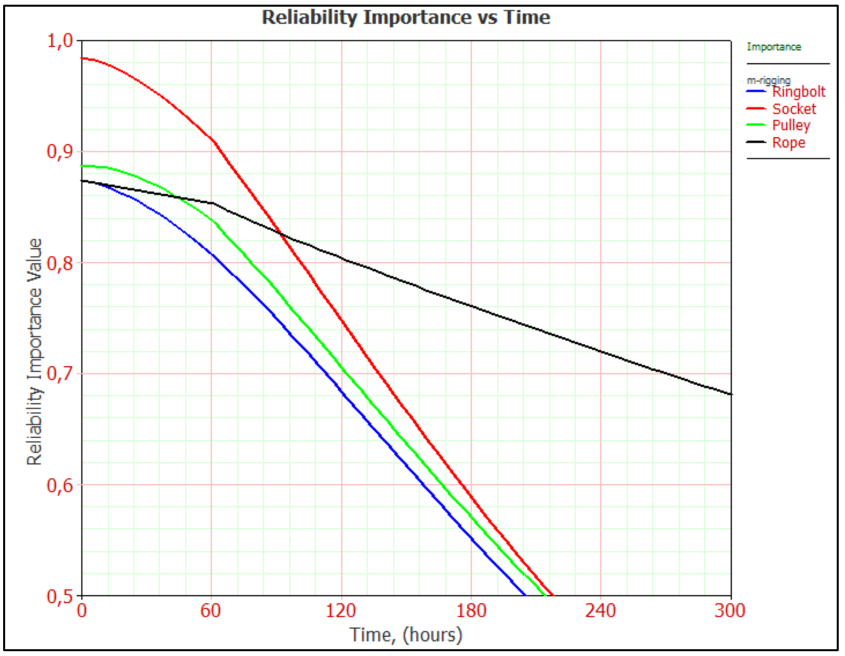

Figure A.37 Changes in importance values with time (Marion-Rigging)

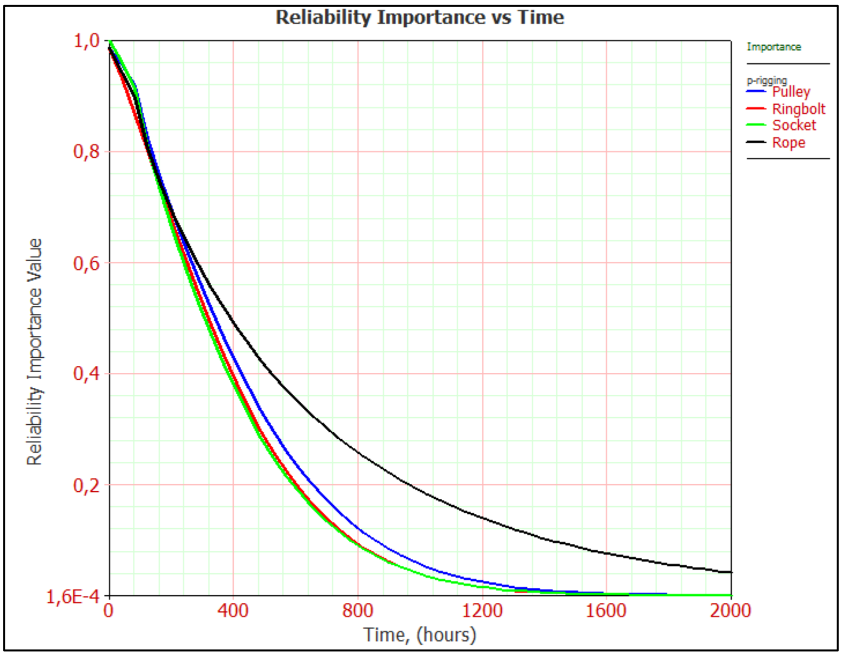

Figure A.38 Changes in importance values with time (Page-Rigging)

Components of the Bucket Units

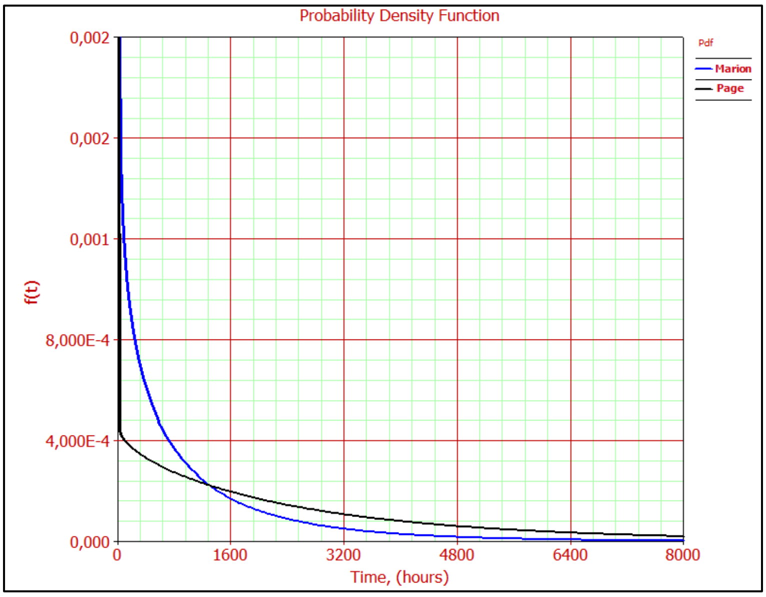

Figure A.39 PDF curves of Bucket – Main Body

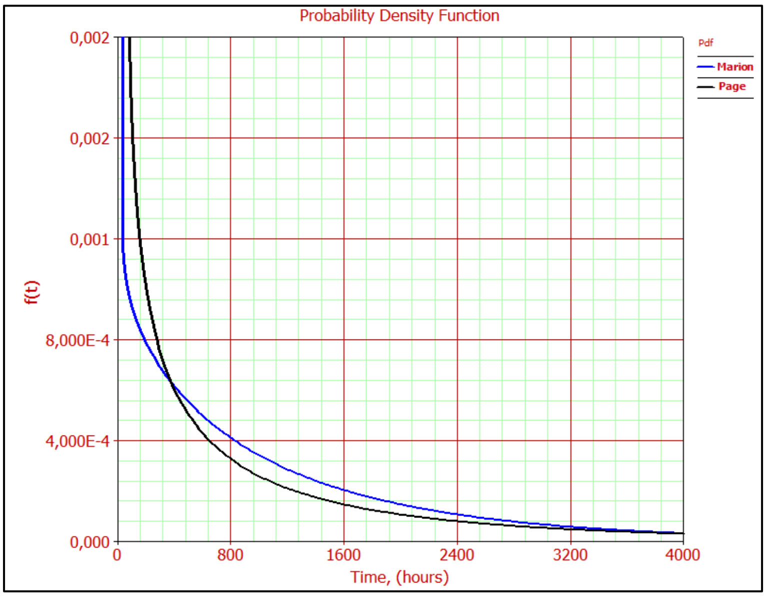

Figure A.40 PDF curves of Bucket – Ringbolt

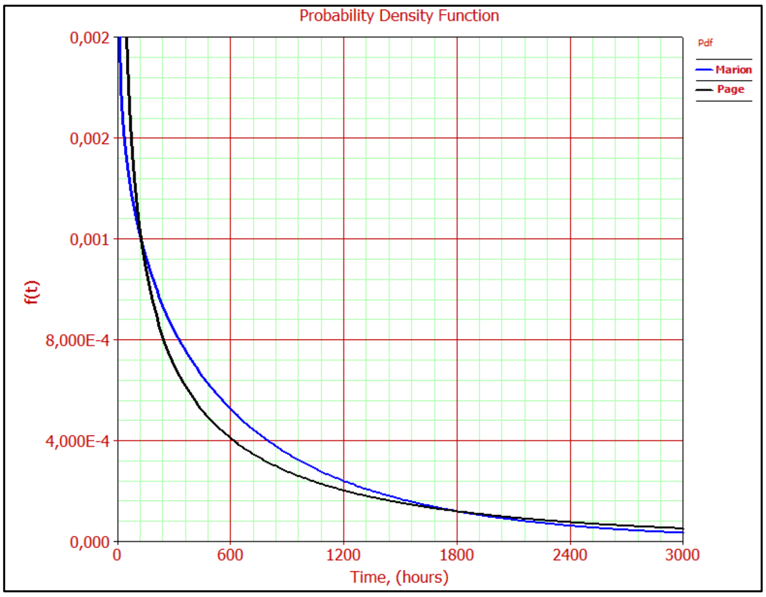

Figure A.41 PDF curves of Bucket – Teeth

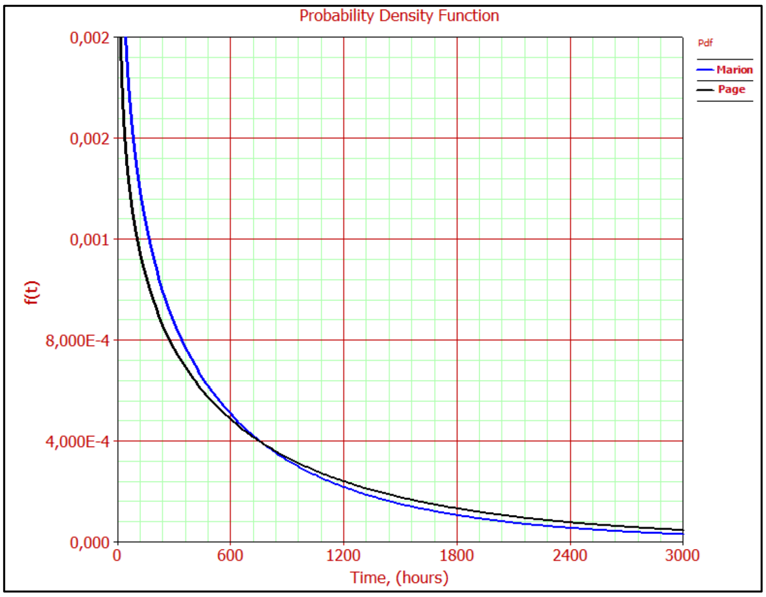

Figure A.42 PDF curves of Bucket – Pins

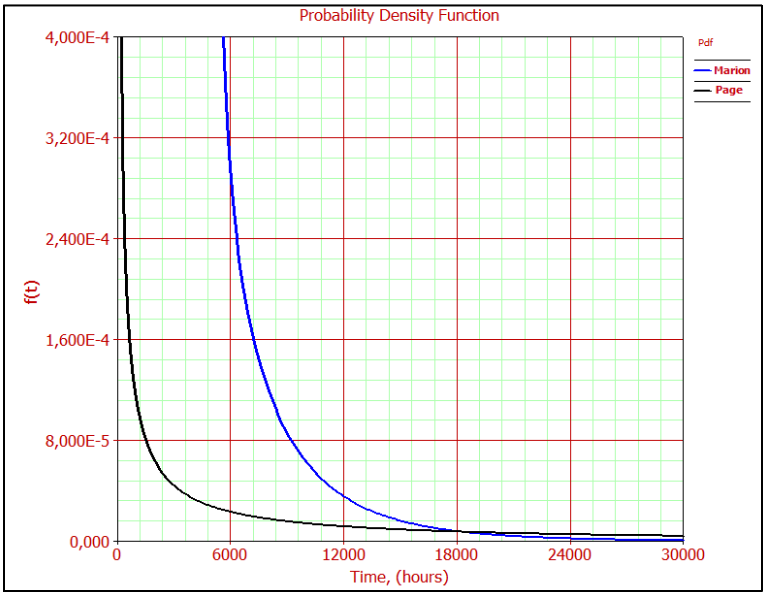

Figure A.43 PDF curves of Bucket – Chains

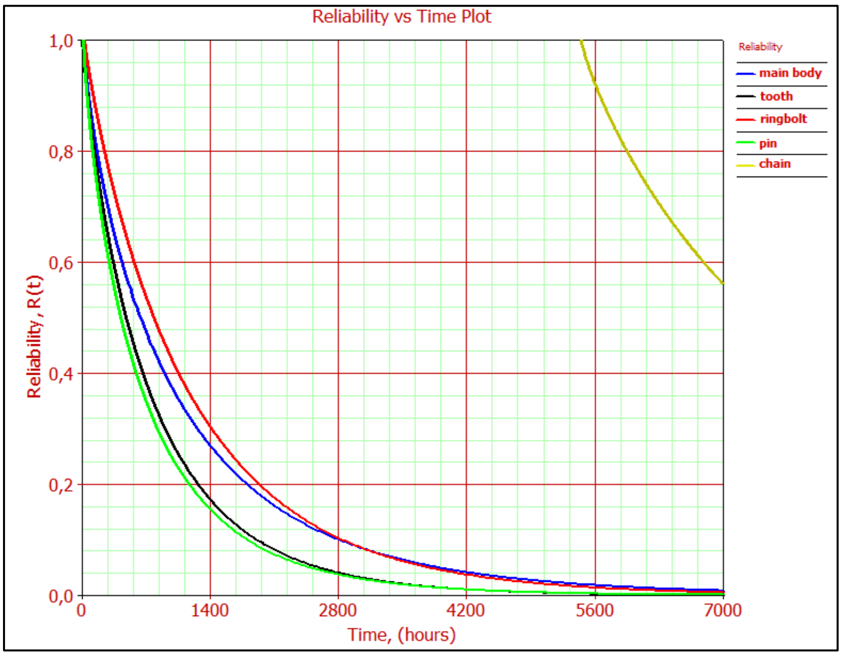

Figure A.44 Reliability curves of components (Marion-Bucket)

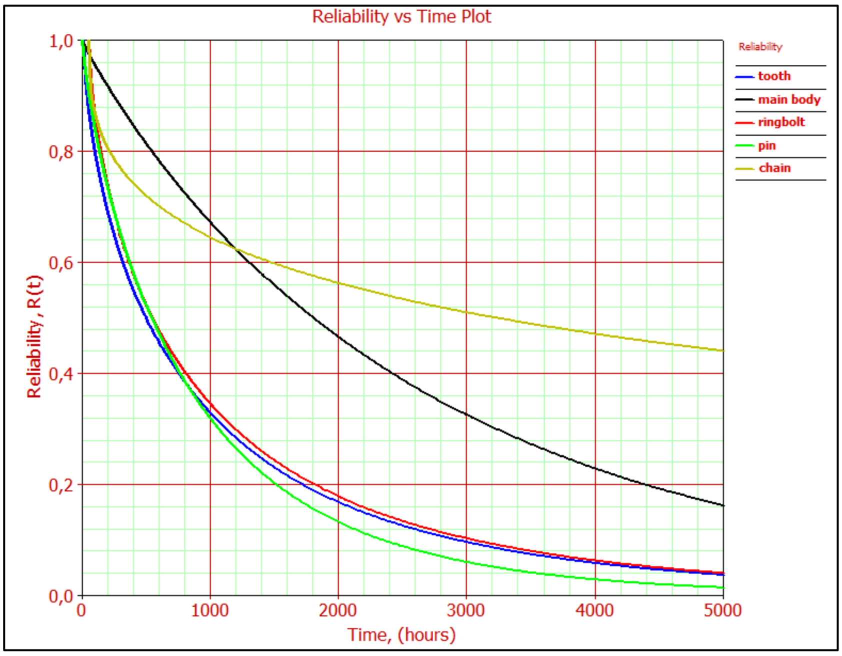

Figure A.45 Reliability curves of components (Page-Bucket)

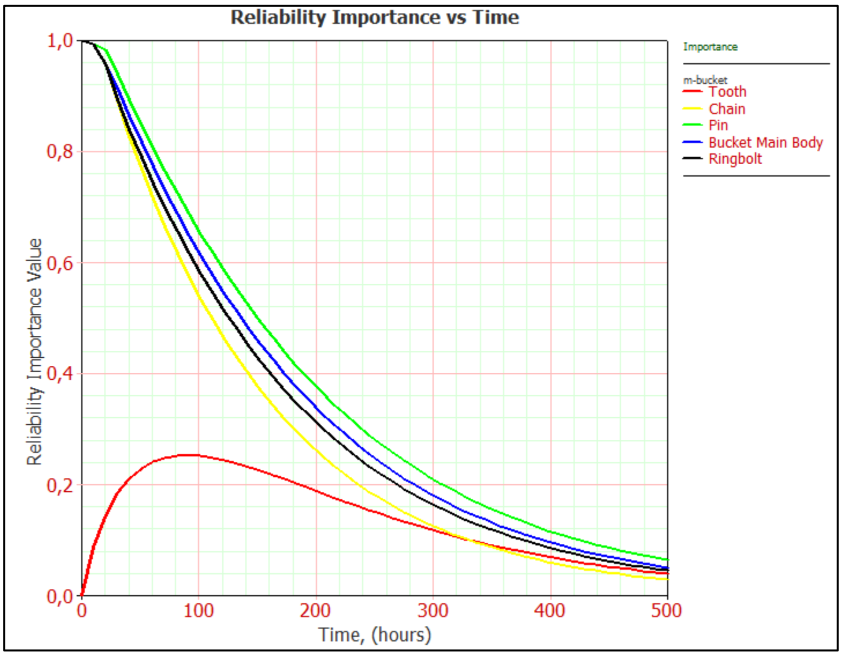

Figure A.46 Changes in importance values with time (Marion-Bucket)

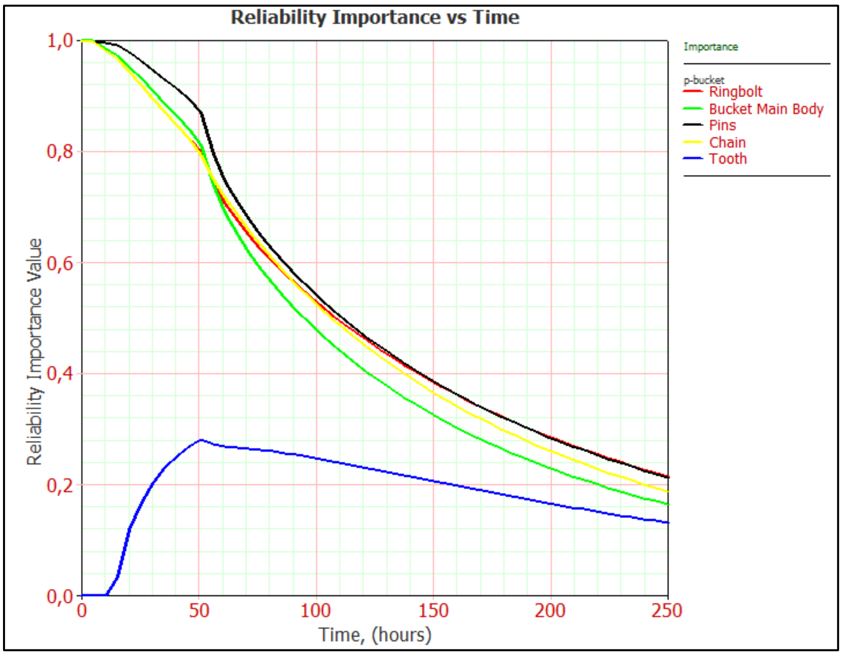

Figure A.47 Changes in importance values with time (Page-Bucket)

Components of the Movement Units

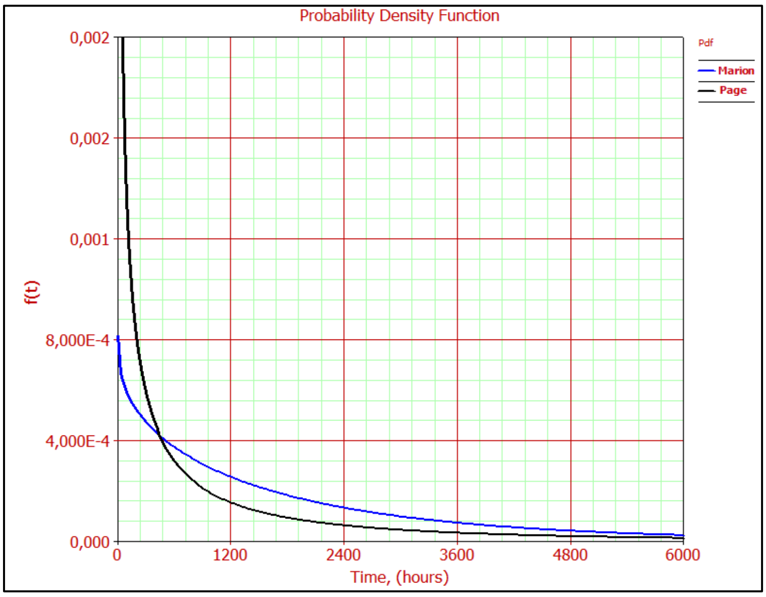

Figure A.48 PDF curves of Movement – Rotation

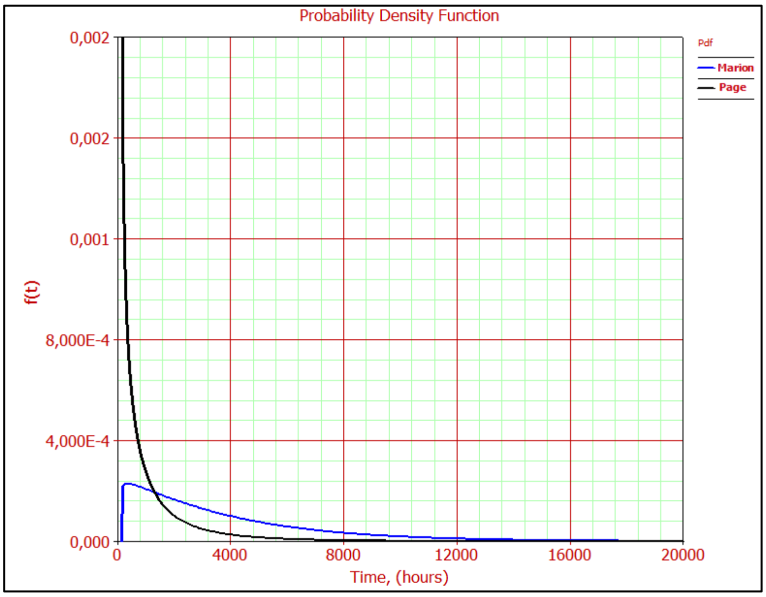

Figure A.49 PDF curves of Movement – Warning

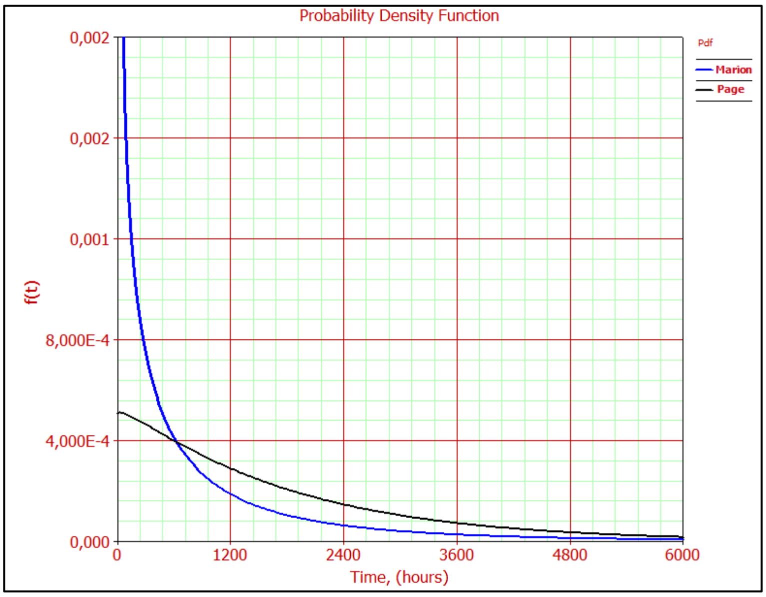

Figure A.50 PDF curves of Movement – Walking

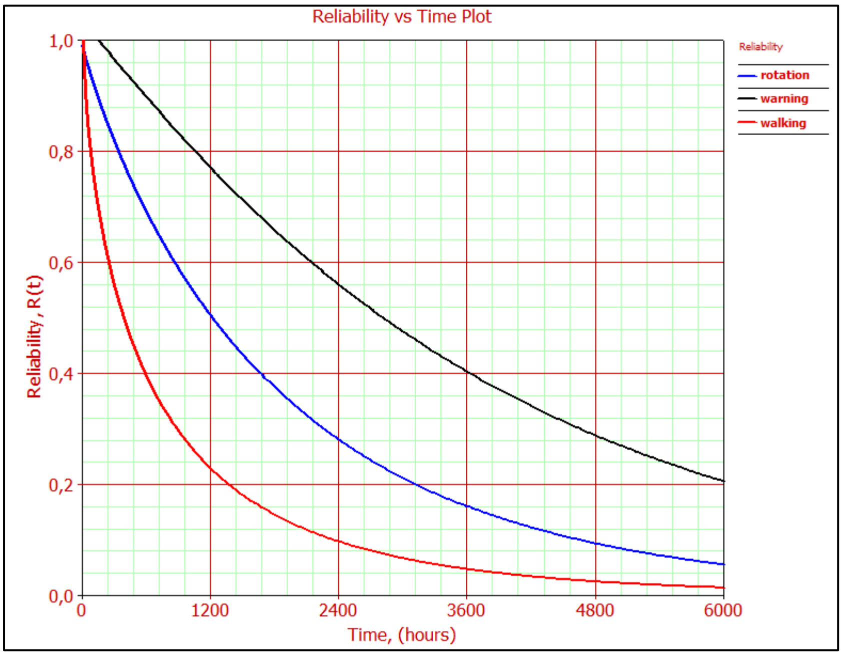

Figure A.51 Reliability curves of components (Marion-Movement)

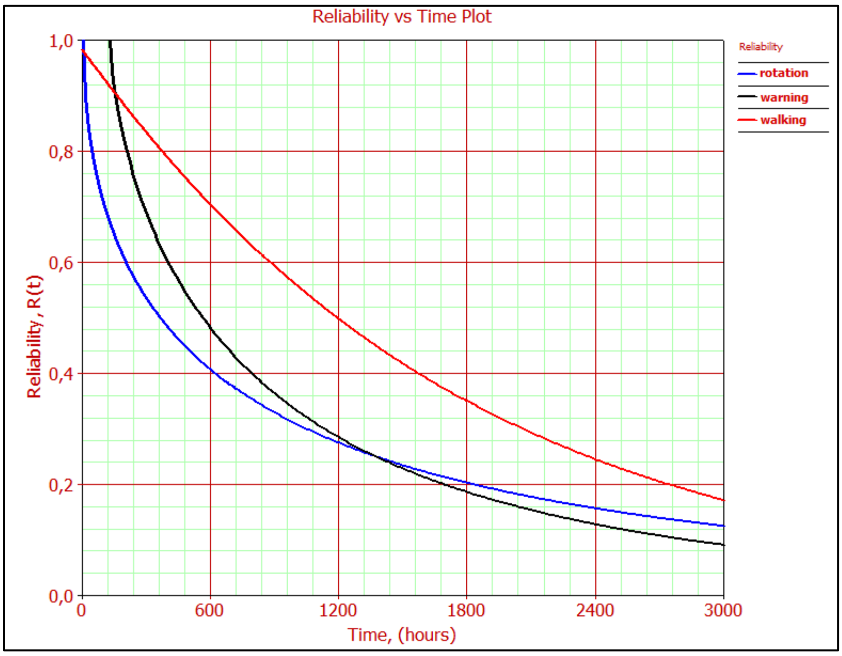

Figure A.52 Reliability curves of components (Page-Movement)

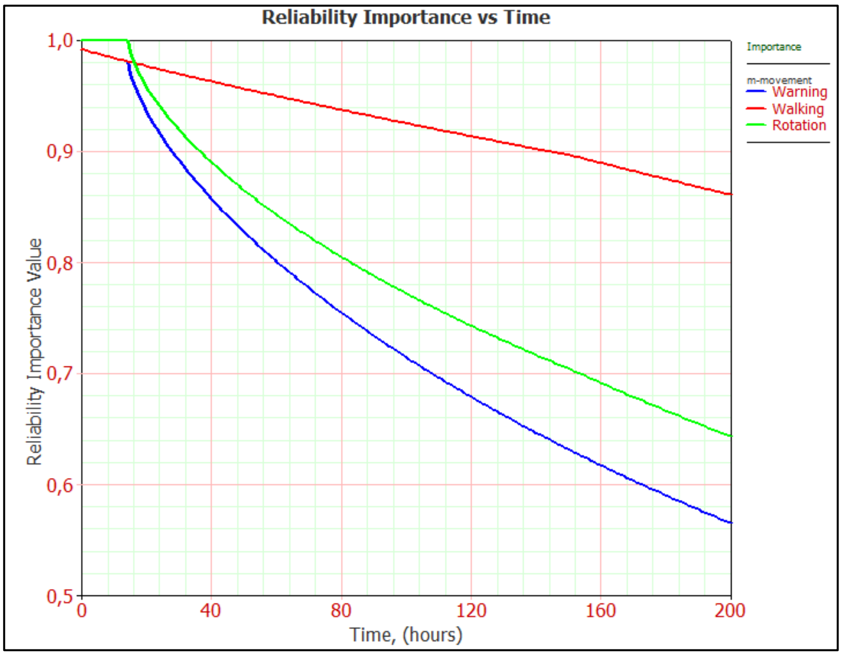

Figure A.53 Changes in importance values with time (Marion-Movement)

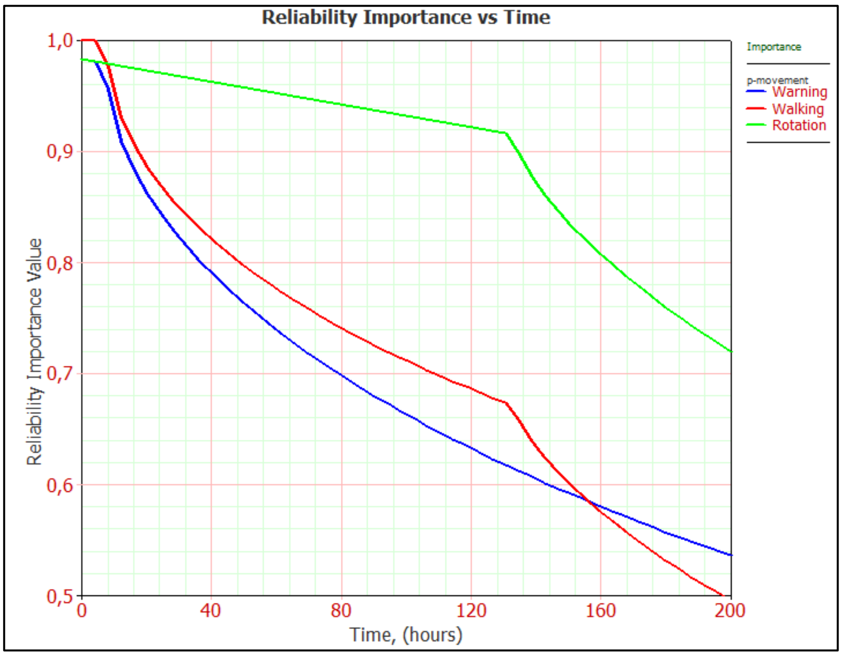

Figure A.54 Changes in importance values with time (Page-Movement)

Components of the Machinery Houses

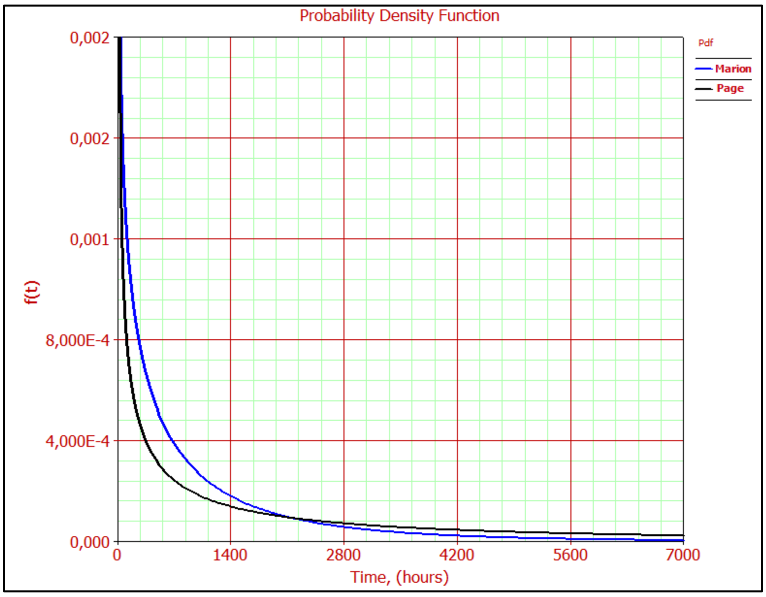

Figure A.55 PDF curves of Machinery House – Generators

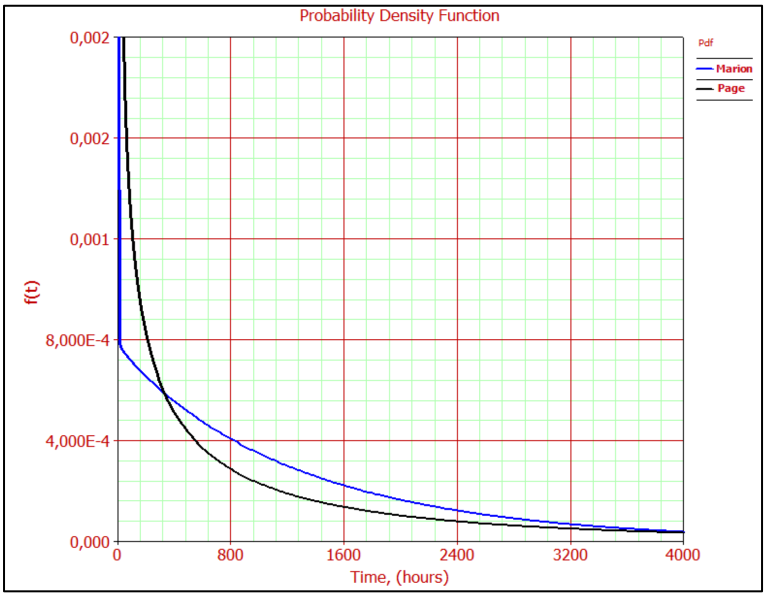

Figure A.56 PDF curves of Machinery House – Motors

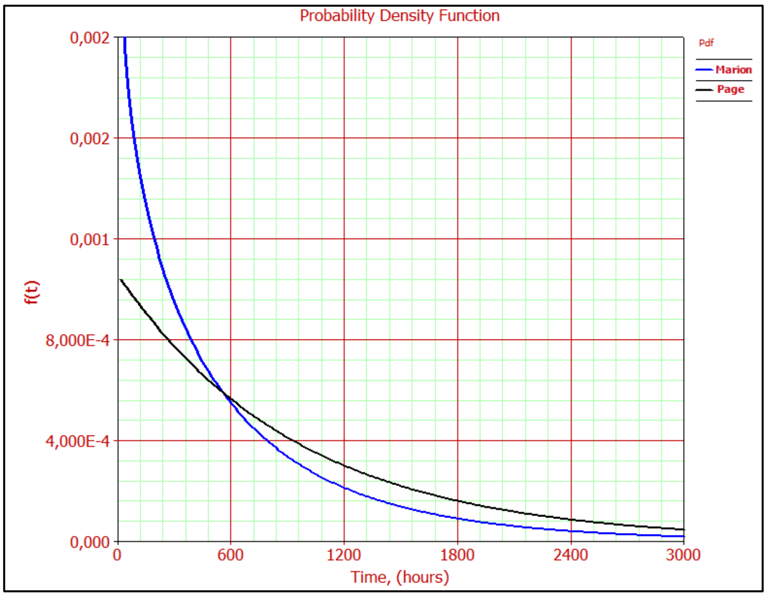

Figure A.57 PDF curves of Machinery House – Lubrication

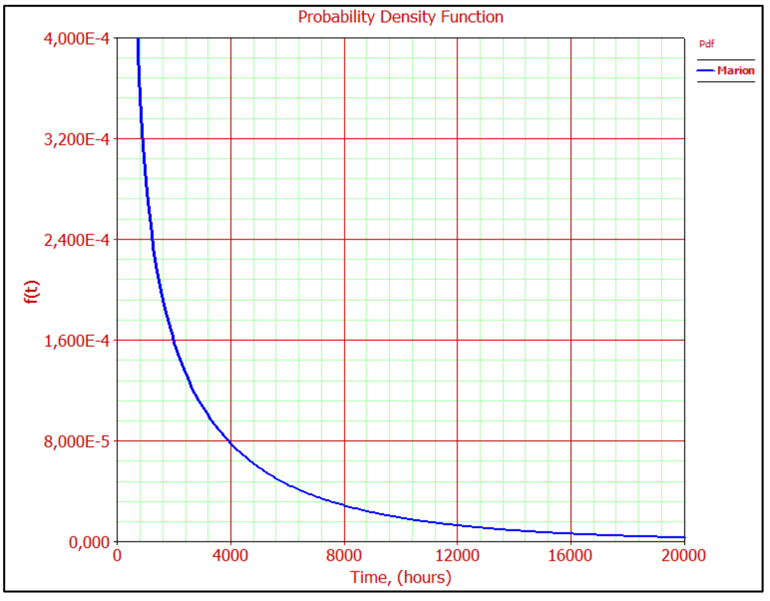

Figure A.58 PDF curves of Machinery House – Air Conditioning

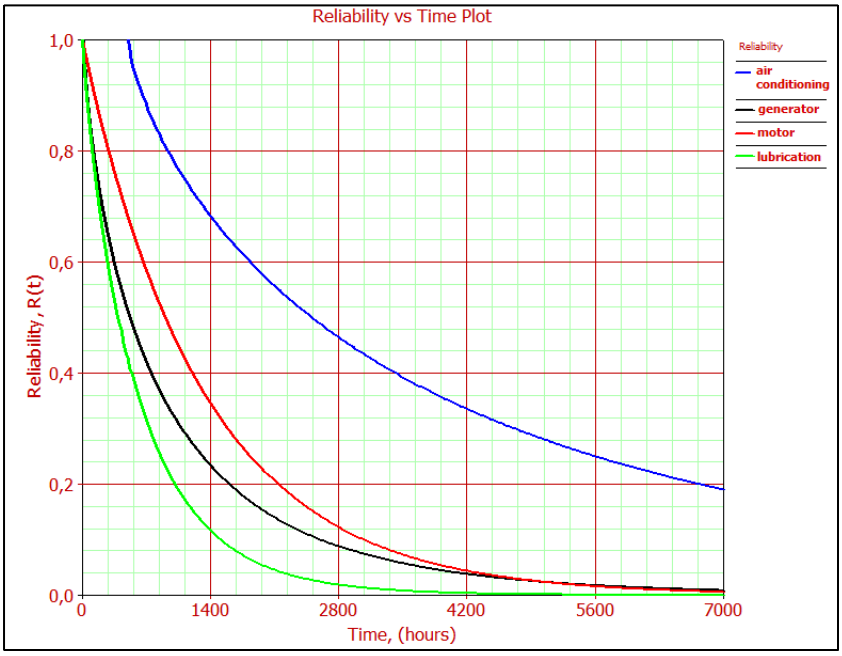

Figure A.59 Reliability curves of components (Marion-Machinery House)

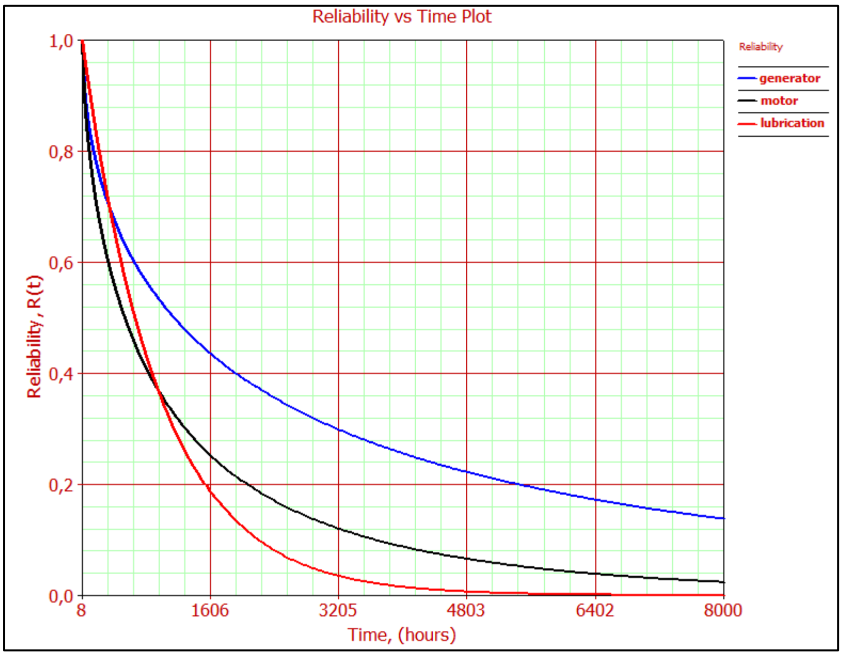

Figure A.60 Reliability curves of components (Page-Machinery House)

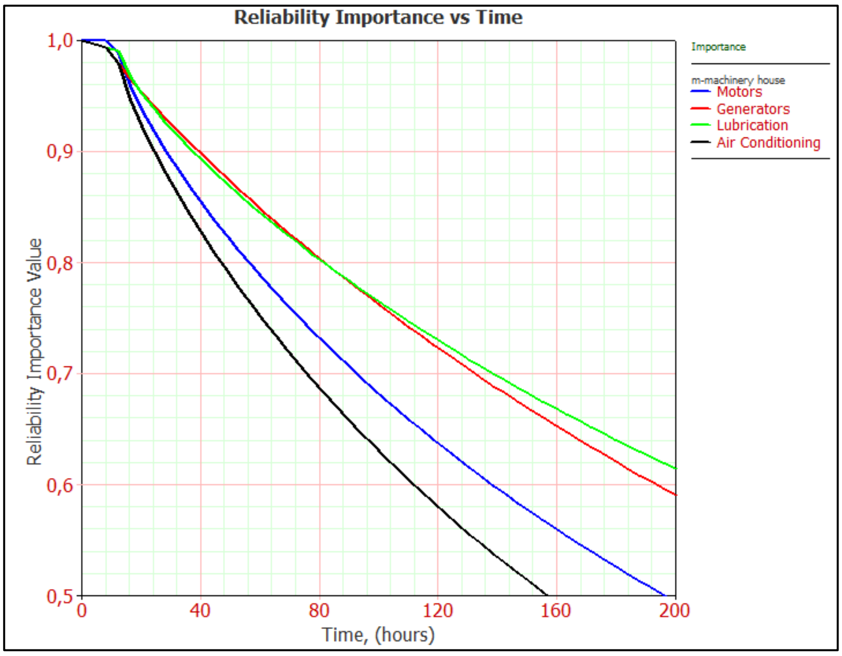

Figure A.61 Changes in importance values with time (Marion-Machinery House)

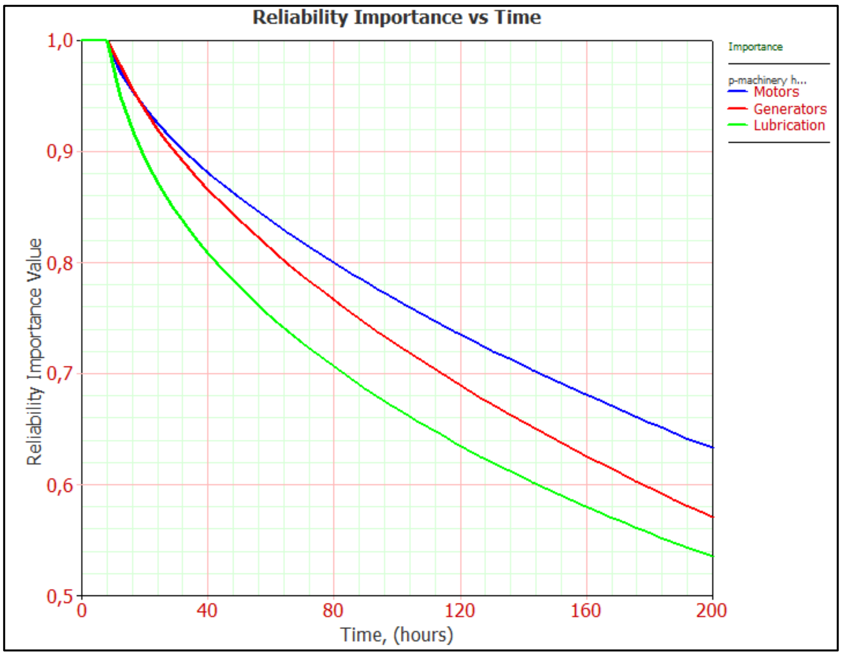

Figure A.62 Changes in importance values with time (Page-Machinery House)