Predicting Failures for Repairable System Subjected to Imperfect Maintenance

by

Nurul Akma Binti Brahim

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

JANUARY 2009

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Predicting Failures for Repairable System Subjected to Imperfect Maintenance

by

Nurul Akma Binti Brahim

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

____
(Assoc. Prof. Ir. Dr. Mohd. Amin Bin. Abd. Majid)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____
NURUL AKMA BINTI BRAHIM

ABSTRACT

The purpose of this project is to develop a reliability model which results from reliability analysis conducted on repairable system subjected to imperfect maintenance. Hence, in order to perform the reliability analysis, field data from actual equipment failure were gathered and analyzed. In this project, the equipment selected was the centrifugal pump used in one of the petrochemical plants. Various stages had been conducted in order to achieve the objectives of the project. This includes data screening and analysis, determination of failure distribution as well as the maintenance effectiveness which denoted by q. All of these phases were performed by using the reliability software, Weibull ++7. The data analysis showed that the failure data displayed Weibull distribution while q value indicated the Generalized Renewal Process (GRP) is the most applicable probabilistic models that characterized the failure data. Thus, the reliability model was developed by using GRP model of Type I and Type II. The comparison between both models was conducted to select the suitable model to be used in developing the reliability model. Based on the likelihood value (LV), GRP model Type I was selected as it possessed higher LV and this model was used to predict the future failures of the system. Evaluation phase was conducted to verify that GRP model Type I was the most suitable model which fits best the failure data. In this phase, the reliability model was developed by using other probabilistic models such as Renewal Process (RP) and Non-Homogeneous Poisson Process (NHPP). The LV were compared which resulted in GRP model Type I produced the highest LV. Finally, the model was validated by using reliability models developed based on the different duration of operation days which were 1500 and 2000 operation days, respectively. The expected cumulative numbers of failures calculated by both models were then compared with the actual cumulative number of failures obtained from the model developed using 3000 operation days. Based on the comparison, both models produced similar values with the actual failure data. Hence, the developed reliability model could be used to predict the next failure of the system. It is hoped that this project and report could be used as a reference for further research and study.

ACKNOWLEDGEMENTS

The author wishes to take the opportunity to express her utmost gratitude to the individual that have taken the time and effort to assist the author in completing the project. Without the cooperation of these individuals, no doubt the author would have faced some minor complications through out the course.

First and foremost the author’s utmost gratitude goes to the author’s supervisor, Assoc. Prof. Ir. Dr. Mohd. Amin Abd. Majid. Without his guidance and advice, the author would not be succeeded to complete the project. The high appreciation also goes to Mr. Masdi Muhammad, co-supervisor, who always providing information needed and giving continuous guidance all the way through the project. During the progress of the project, Dr. Mohd Amin and Mr. Masdi had provided lots of feedback which were related to the project as well as shared their expertise and knowledge on the subject. Throughout the project, the author had obtained valuable knowledge on reliability field which was very new to her with the most help from both of them.

The next acknowledgement would be conveyed towards the staffs in reliability department from PETRONAS Penapisan Terengganu Sdn. Bhd. (PPTSB) for their kind assistance in helping the author to comprehend more on the reliability concept and maintenance data. Their expertise in this particular field had contributed the biggest part in helping the author to develop a more realistic reliability model. Kind consideration and generosity from the department’s staffs had been really helpful to the author in order to complete this project. Therefore the author highly appreciated the cooperation given by PPTSB.

Last but not least, to all individuals that has helped the author in any way, but whose name is not mentioned here, the author thank you all.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In most industries, reliability of equipments is essential in order to optimize the companies' efficiency and productivity. Therefore, these equipments will undergo maintenance activities either scheduled or nonscheduled after they have been installed and commissioned. Scheduled maintenance is performed on timely basis such as monthly, six-monthly, or annually which falls under Preventive Maintenance (PM). On the other hand, unscheduled maintenance is referred to maintenance activities which carried out when failure occurs. This action is called Corrective Maintenance (CM). As these equipments undergo PM and CM activities which will restore their operating conditions, they can be referred as repairable systems.

Generally, the condition of the repairable systems after maintenance activities can be divided into three main conditions, namely 'as good as new' for perfect repair, 'as bad as old' for minimal repair and the intermediate stage, 'better-than-old-but-worse-than-new' for imperfect repair or imperfect maintenance. Apart from these three conditions, the repairable system may also end up in another two conditions after a repair; 'better than new' and 'worse than old' [1]. However, the two latter conditions do not have practical approach due to difficulties in developing the mathematical analysis thus not taken into consideration. Among the three conditions, systems are more likely included in the intermediate stage between perfect repair and minimal repair after maintenance action. In this project, the author is intended to develop a reliability model to predict the future failures of the repairable system. Once the failure predicted, the maintenance activities could be planned at optimum level and at the same time the maintenance cost could be reduced.

1.2 Problem Statement

According to Beebe [2], maintenance activities are carried out with the aim of contributing to the production and profit objectives of the organisation by keeping plant reliability at the optimum level, consistent with safety of people and plant. However, the condition of repairable systems after maintenance activities are often found in the imperfect maintenance state which is better than old system but worse than the new one. For example, only one component of the pump is replaced during the maintenance activities to restore the pump operation to its normal condition. The pump then will functioning at satisfactory level; it neither operates like a new pump nor functions badly like the old one. After a certain period of time, the pump will fail again due to various causes. Somehow, the future failure of the pump is unknown which results in unscheduled maintenance. This situation is not only affects the reliability of the systems, but also affects the maintenance cost. Hence in order to ensure the optimized operation of system, the failure prediction of the repairable system is essential and it could be achieved by developing a reliability model.

1.3 Significance of the Project

Upon completion of this project, a reliability model will be established to predict more accurate time of the system's next failure. Once the time predicted, more effective preventive maintenance activities could be planned. As a result, the unscheduled maintenance could be reduced and subsequently the system's availability could be increased. At the same time, the maintenance cost could be reduced.

1.4 Objectives

The objectives of this project are:

1. To determine the failure distribution for pumps used in a petrochemical plant based on the historical maintenance data.
2. To calculate the effectiveness of maintenance activities (q) for the pumps.
3. To develop a reliability model for prediction of the pumps' future failure.

1.5 Scope of Study

The project on the development of reliability model for repairable system is to be completed within approximately one year time frame (two semesters). The scope for the first phase of the project had been completed in the first semester. The first phase of this project was started by the analysis of historical maintenance data of selected repairable system which is the pumps. The pumps' maintenance data used in this project were obtained from a petrochemical plant. Besides that, the tasks which had been completed in the first phase include determination of failure distribution, calculation of effectiveness of maintenance activities and development of conceptual stage of the reliability model. In this project, the reliability model of the pump was developed by using a reliability software, Weibull ++7. In the second semester, the project was continued with the second and final phase. In this phase, the evaluation of the model and validation of the reliability model had been done as a continuation of the reliability model developed earlier. The establishment of the reliability model was performed after the validation stage had been completed.

1.6 Relevancy of Project

This project is relevant to the study of reliability and assessment engineering under manufacturing cluster. The outcome of this project is the reliability model for repairable system to be used in business operations which deals with a wide variety of repairable systems. For example, the outcome of this project could be implemented in the plant operations where people are paying great attention to three primary concerns which are economics, safety and project viability [3].

1.7 Feasibility of the Project

The project is feasible as it utilized a software called Weibull ++7 and analyzed the life data obtained from a petrochemical plant in Malaysia. The data were collected from the historical maintenance activities on the pumps used in the plant. In the aspect of scope of study, the resources such as the data and software used had been obtained from the authorized parties while in the time frame perspective; this project had been completed within the stipulated time which is in two semesters. Hence, this project is highly feasible.

CHAPTER 2

LITERATURE REVIEW

This chapter summarized the information obtained from literature study which consists of reliability, types of failure distributions, probabilistic models and also a brief description on the selected system which is pump.

2.1 Reliability Concept

Mechanical reliability is defined as the probability that a component, device, or system will perform its prescribed duty without failure for a given time when operated in a specified environment. [3] In mathematical terms, probability is the chance of some event happening, such as kicker valves will likely fails to operate due to leakage at its tubing and fitting. If 100 units of valves are taken during the test, the numbers of failed valves at specified time interval could be counted and illustrated in a histogram. A histogram is the best way to show the density of failure distribution of the system whereby in this case, valves. The observation could be made hence prediction of the probability of a failure for a certain batch could be produced.

Another concern in reliability is the failure. Failure is usually associates with three aspects namely modes, causes and effects [3]. Mode of failure is the way of manifestation of the failure. For example in pump, the failure modes could be mechanical seal leaking, motor burnt out and pump shaft corroded. The causes for the failures then will be examined from different levels. The examination of the causes is normally conducted in details to obtain precise information. Finally, the effects of the failure are highlighted so that the rectification on the device or the equipment can be performed.

2.2 Reliability System

A reliability system can be categorized as non-repairable and repairable. Non-repairable system can only failed once which means it will produce single event failure data while repairable system possesses a sequence of repeated failures whereby producing recurrent event failure data [4]. There are two major classification of maintenance under repairable systems namely corrective maintenance (CM) and preventive maintenance (PM). Corrective maintenance (CM) is generally carried out in order to repair the components which are already failed. When failure occurs, CM offers two method of maintenance; whether the equipment shall be repaired or be replaced. In contrast, preventive maintenance (PM) is performed in order to prevent failures from occurring thus it reduces the risk of system failure. Preventive Maintenance can be performed whether on timely basis or cycle basis. In timely basis, the system will undergo maintenance under the specified duration of operation time such as every six months while for cycle basis, the system will undergo maintenance after the sequence of operation of the system is periodically repeated such as every 10,000 kilo standard cubic meter per day (kscmd) of the flow supplied to the customer.

2.3 Failure Analysis Theory

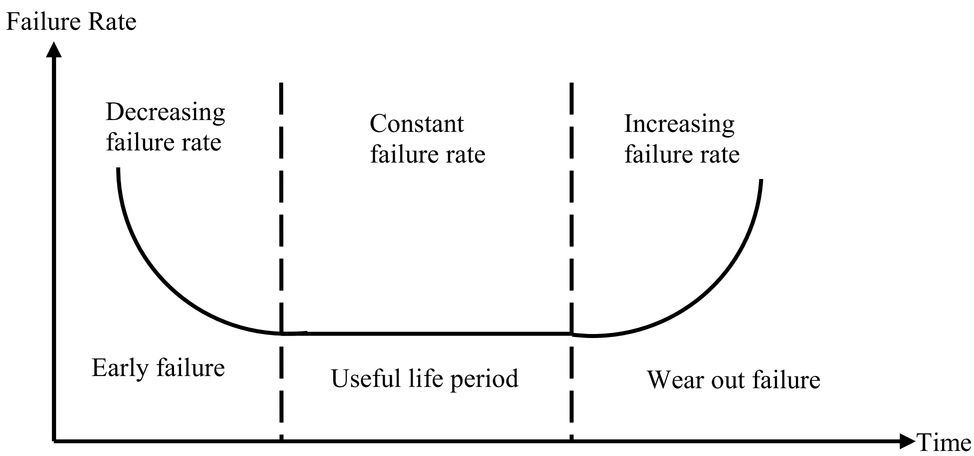


Figure 2.1: "Bathtub" Curve

Figure 2.1 shows the 'bathtub" curve which represents the patterns in failure rate. This curve is applicable for most products as the plot of the failure rate often exhibit the curve similar to bathtub [5]. The first region is known as early failure period, often referred as infant mortality period characterized by decreasing failure rate with time. The trend occurs at the initial phase of product usage due to many reasons such as design faults, manufacturing and shipping faults, poor quality components and installation error. The failure rate somehow will decrease rapidly with time and the trend will lasts for several weeks or time [5]. The product or components will then experience the useful life period in which the failure rate would be constant. Sometimes the useful life period is called as intrinsic failure period [5]. Most of the products or components possess long time of useful life period which indicated by the flat portion of the curve. Soon after several years, the products would likely to experience problems with its function or operation. The condition can be explained as wear-out failure period as shown at the third region in 'bathtub' curve. The materials started to wear out, degradation started to occur and failure rate will increase rapidly.

2.4 Types of Failure Distributions

In evaluating the reliability of the system design, the type of failure distributions plays an important role. Generally, it depends on the component's failure mechanisms and other factors associated with component repairs. The common types of failure distributions include normal distribution, lognormal distribution, exponential distribution and Weibull distribution.

Normal distribution is most widely-used for modeling strengths of material and the lifetimes of consumables. It frequently used to describe equipment failure behavior that has increasing failure rates with time [6]. Commonly normal distribution is defined by two parameters, which are the mean (average, μ) as the location parameter and scale parameter represented by variance (standard deviation squared, σ^2) [7].

The lognormal distributions are often used to model the lives of units whose failure modes are of a fatigue-stress nature such as metal fatigue testing and crack propagation [7]. This type of distribution has similar characteristics with normal distribution in the sense that the usage of two parameters, mean (μ) and standard deviation (σ). However, lognormal distribution uses the logarithms of the values of random variables-rather than the values themselves [6].

The exponential distributions describe the process or failure which occurs in constant rate [8, 9]. The constant failure rate is obtained by assuming that the component failure behavior is memoryless. The term memoryless refers to the independency of a component's remaining life of its current age [8]. Even though the memoryless property may not applicable for all components, it does assisting in exponential distribution by assuming successful operation of a component does not degrade the component.

Weibull distribution is a continuous probability distribution which is one of the most widely used lifetime distributions in reliability engineering. There are three paramaters in Weibull distributions, location parameter (γ), scale parameter (η) and shape parameter (β) [10]. Scale parameter defines the shape of the distribution. As the value of η increases, the shape of the distribution stretches out and its height decreases while at the same time maintaining the shape and location of the curve. The shape parameter is used to describe the shape of the curve and sometimes refers the slope of the curve. The different value of β will indicate different characteristics which shows other types of distributions. Figure 2.2 below is an example of Weibull distributions.

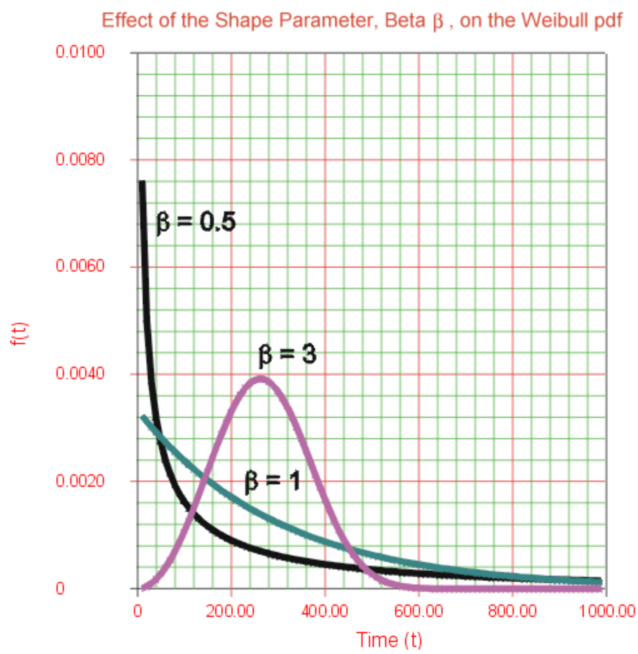


Figure 2.2: Weibull Distribution [10]

Figure 2.2 shows that when the value of $\beta = 1$, the curve will exhibit the exponential distribution while value of $\beta = 3$ indicates the normal distribution. Therefore, this type of distribution will be preferable in this project due to its unique characteristic.

Specifically, the mathematical distribution is defined by its probability distribution function (pdf) equation is used. In Weibull distribution, the pdf is given by equation (1) below:

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \tag{1}$$

Where :

β is the shape parameter,

γ is the location parameter,

η is the scale parameter

T indicates the time

In most cases, the location parameter is not used hence the value becomes zero and subsequently the distribution is reduced to two parameter Weibull distribution.

The reliability funtion is used to determine the reliability of the system and is given by equation 2:

$$R(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \tag{2}$$

In order to obtain the failure rate of the system, one can obtain the equation by dividing the pdf equation with the reliability equation. Thus by dividing equation (1) and (2) will give equation 3 and the failure rate is given by parameter λ [11].

$$\lambda(T) = \frac{f(T)}{R(T)} = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} \tag{3}$$

2.5 Types of Probabilistic Models

The most commonly used models to characterize failure process of a repairable system are renewal processes (RP), corresponding to perfect repairs, non-homogeneous Poisson processes (NHPP), corresponding to minimal repairs, and general renewal processes (GRP), corresponding to imperfect repairs [12] .

2.5.1 Renewal Process (RP)

Ordinary Renewal Process or Renewal Process (RP) described the situation where a repairable system can be stored to as good as new condition, and the time between failures of a component or system are distributed independently and identically.[8] This process assumes that the system will be restored to its original condition or renew itself upon completion of the repair action. Basically, renewal process is a special case of Homogeneous Poisson Process which characterized by parameter $\lambda>0$ meet the following conditions:

- The cumulative number of failures during initial condition is zero, $N(0)=0$
- The process has independent increments
- The distribution of the number of failures in any interval of time t is featured by Poisson distribution with parameter λt

For renewal process, the failure occurence in a time interval t can be obtained from the equation below:

$$\Lambda(t) = \lambda t \tag{4}$$

Where λ is referred to the failure intensity or rate of occurence of failure (ROCOF) [4]. Somehow the model has very limited application and sometimes becomes nonpractical as it represents ideal situation.

2.5.2 Non-homogeneous Poisson process (NHPP)

Non-homogeneous Poisson process (NHPP) is a Poisson process with a simple parametric model used to represent events with a non-constant failure recurrence rate. This type of model is often used to model failure process with certain trends, namely reliability growth and the reliability of repairable units.[8] NHPP describes the cumulative number of failures up to time t, N(t) and it follows a Poisson distribution with parameter $\lambda(t)$ for a counting process $\{N(t), t \geq 0\}$. Parameter $\lambda(t)$ is the rate of the process and is a function of time.

NHPP exists when the occurrence rate is time-dependent. Assuming that the failures are governed by NHPP and that $\mathbf{N}(\mathbf{t})$ denotes the cumulative number of failures observed during the time interval (0, $\mathbf{t}$]. Usually, $\{\mathbf{N}(\mathbf{t}), \mathbf{t} \geq 0\}$ can be modelled by an NHPP, with intensity function $\lambda(\mathbf{t})$, if the following conditions are met [9]:

- $\mathbf{N}(0) = 0$.
- The number of failure that occur in disjoint time intervals are independent
- $P\{\mathbf{N}(\mathbf{t} + \Delta t) - \mathbf{N}(\mathbf{t}) \geq 2\} = o(\Delta t)$. This means the system will never experience more than one failure at the same time
- $P\{\mathbf{N}(\mathbf{t} + \Delta t) - \mathbf{N}(\mathbf{t}) = 1\} = \lambda(\mathbf{t})$. Probability of exactly one failure occurs at a time equal the failure rate.

The advantage of the NHPP model over the renewal process model is that there are no more requirements of stationary increments therefore it is possible that some events are more likely to occur during certain times of the day than other time periods. This situation is more realistic as, after a failure, the system performance is likely to be changed. It can be improved if proper maintenance actions are taken and worsened if only minimum efforts are put into restoring the system to its functional states.

2.5.3 Generalized Renewal Process (GRP)

Generalized Renewal Process (GRP) offers a general approach to modeling repairable systems. Krivtsov [6] has introduced the Monte Carlo approach to GRP with several advantages and disadvantages produced from the model. The Monte Carlo approach is initiated with the assumption that the time to first failure (TTFF) distribution is known and can be estimated from the available data. Besides, he also assumed that repair time is negligible and the failures can be viewed as point process. The approach offers a solution for all kinds of distributions, including empirical ones, which is unbiased and consistent. However, the approach is extremely time consuming apart from the need of large amount of data. Thus, the approach outside of automotive industry such as nuclear, petrochemical and chemical would be limited due to small amount of equipment used in those industries as stated by Yañez et. al. [1].

In his Monte Carlo approach, Krivtsov [6] also has introduced the concept of virtual age (v_i) for GRP model. The virtual age indicates the age of the system after the *i*-th repair occurs. This concept then further used to develop two types of GRP models, which are Type I and Type II [13]. Type I GRP model assumes that the repair can only removed the damage from the last repair. This type of model governs by equation

$$v_i = v_{i-1} + qx_i \tag{5}$$

In the other hand, Type II model assumes that the repair can remove all cumulative damages, which means the condition of the system will be stored to its original condition. Thus the equation which governs this type of GRP model is

$$v_i = q(v_{i-1} + x_i) \tag{6}$$

Where in both type of models,

v_i =virtual age of the system immediately after *i*-th repair, i =1, 2,…

x_i = failure times

q = maintenance effectiveness

According to Type I model, when $q = 0$ is assumed, the result will show the characteristic of renewal process which is the perfect repair. Meanwhile, when $q = 1$ is assumed, the condition of as-bad-as-old will occur which describes the NHPP. However, when the value of q is in interval $0 < q < 1$, the results lead to the state where the condition is in intermediate stage, better than old but worse than new [1]. Subsequently, these have indicated that RP and NHPP are the specific cases of GRP as shown by Kaminsky and Krivtsov in their study.

2.6 Maximum Likelihood Estimation (MLE)

Parameter estimation is the main procedure used in order to determine the goodness of fit of the selected data. There are many techniques in estimating the parameters including probability plotting, linear least-squares, orthogonal least-squares, gradient-weighted least-squares and robust techniques. However, in this section, only two techniques will be discussed further, namely least-square estimation (LSE) and maximum likelihood estimation (MLE).

LSE is widely used in many statistical concepts such as linear regression, sum of squares error and root mean squared deviation. The main advantage of LSE is that it requires minimal or no distributional assumptions; hence it is favorable in obtaining a descriptive measure for the observed data.

In the other hand MLE serves as a standard approach to parameter estimation in statistics. This has been proven when MLE is a prerequisite for the chi-square test, the G-square test, Bayesian methods and other model selection criteria [14]. Initially, this method will be started with a mathematical expression which known as the likelihood function of the collected data. In this expression, unknown model parameters are included. All of these parameters' value which maximizes the data likelihood refers to Maximum Likelihood Estimates or MLE's.

To put it roughly, the main purpose of MLE is to determine the parameters that maximize the probability (likelihood) of the sample data. Thus, the method of maximum likelihood is considered versatile as it yields estimators with good statistical properties apart from applicable to most models and different types of data. The methodology of this method may seem quite simple yet the implementation of this method is much more anticipated in mathematical field.

Even though MLE is not widely used in mathematical models compared to LSE, it does possess its own advantages that always taken into consideration. This is due to the very desirable large sample properties such as [15]:

- When the sample size increases MLE and likelihood function become unbiased minimum variance estimators
- Confidence bounds can be generated as a result of the calculated sample variances approximation and normal distribution approximations
- Likelihood functions can be used to test hypotheses about models and parameters

However, there are also limitations of the MLE. The only two drawbacks yet important ones including:

- MLE can be heavily biased if small numbers of failures data exists (less than 5 or even less than 10 can also be considered as small). If this occurs, the large sample optimality properties do not apply
- Specialized software for solving complex non-linear equations is often required to calculate MLE. Somehow this drawback is negligible as the statistical software is being upgraded to increase its capability as time goes by.

The basic understanding of MLE is started with the random variable with probability density function (pdf). In this case, if *x* is a continuous random variable with pdf, the function would be [16]:

$$f(x;\theta_1,\theta_2,...\theta_k) \quad (7)$$

Where $\theta_1,\theta_2,...\theta_k$ are *k* unknown constant parameters and need to be estimated. In order to achieve that, an experiment is conducted to obtain *N* independent observations, $x_1, x_2, ..., x_N$. The likelihood function will be given as:

$$L(x_1,x_2,...,x_N \mid \theta_1,\theta_2,...\theta_k) = L = \prod_{i=1}^{N} f(x_i;\theta_1,\theta_2,...,\theta_k) \quad (8)$$

With $i = 1, 2, \dots, N$

Hence the logarithmic likelihood function will be given by the following equation:

$$\Lambda = \ln L = \sum_{i=1}^{N} \ln f(x_i;\theta_1,\theta_2,...,\theta_k) \quad (9)$$

By maximizing L or Λ, the value of MLE for $\theta_1, \theta_2, ...\theta_k$ can be obtained. The equations will then be,

$$\frac{\partial(\Lambda)}{\partial\theta_j} = 0, \quad j = 1,2,...,k \tag{10}$$

Besides, to understand better, an example of likelihood function for exponential distribution would be really helpful. The basic equation which is the likelihood function for exponential distribution is given by [16]:

$$L(\lambda|t_1, t_2, ..., t_n) = \prod_{i=1}^{n} f(t_i) \tag{11}$$

$$= \prod_{i=1}^{n} \lambda e^{-\lambda t_i} \tag{12}$$

$$= \lambda^n \cdot e^{-\lambda \sum_{i=1}^{N} t_i} \tag{13}$$

whereby in this equation, lambda (λ) value going to be estimated. Compared to this equation, the log-likelihood function seems to be easier to be manipulated mathematically. Hence, the derivative is done by taking the natural logarithm of the likelihood function. The log-likelihood function then will become:

$$\Lambda = \ln(L) = n \ \ln(\lambda) - \lambda \sum_{i=1}^{n} t_i \tag{14}$$

This method is aiming on the maximizing the value of likelihood, thus the derivative of both sides in equation (14) is performed which has results in the equation (15) below:

$$\frac{\partial\Lambda}{\partial\lambda} = \frac{n}{\lambda} - \sum_{i=1}^{n} t_i = 0 \tag{15}$$

The equation is set to be equal to zero in order to maximize the value of lambda (λ). As the analysis goes on, it reach the final step which the rearrangements of the terms in the equation. After the rearrangement, the value of lambda (λ) can be estimated by using equation (16) below:

$$\hat{\lambda} = \frac{n}{\sum_{i=1}^{n} t_i} \tag{16}$$

2.6.1 Maximum Likelihood Estimation in GRP

According to M. Yañez et. al.,[1] in the case of reasonably enough data available, it is possible to use the directly the maximum likelihood estimation. The minimum requirement for data analysis is three failures data; somehow the availability of additional data would reduce the risk of uncertainties in the analysis. The likelihood function can be described with the equation:

$$L = \prod_{i=1}^{n} f(t_i) = f(t_1)\prod_{i=2}^{n} f(t_i) \tag{17}$$

In GRP, the probability of component or system failure at the respective time t is given by:

$$F(t_i) = 1 - \exp\left[\left(\frac{q}{\alpha}\sum_{j=1}^{i-1} t_j\right)^{\beta} - \left(\frac{t_i + q\sum_{j=1}^{i-1} t_j}{\alpha}\right)^{\beta}\right] \tag{18}$$

Where q is the maintenance effectiveness meanwhile β is shape parameters. The derivation of this function will result in conditional Weibull density function which will be used in estimating the maximum likelihood later. The function is as below

$$f(t_i) = \left(\frac{\beta}{\alpha^{\beta}}\right)\left[t_i + q\sum_{j=1}^{i-1} t_j\right]^{\beta-1} \times \exp\left[\left(\frac{q}{\alpha}\sum_{j=1}^{i-1} t_j\right)^{\beta} - \left(\frac{t_i + q\sum_{j=1}^{i-1} t_j}{\alpha}\right)^{\beta}\right] \tag{19}$$

In GRP, the first failure is determined by equation:

$$f(t) = \frac{\beta}{\alpha}\left(\frac{\beta}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{20}$$

Hence, the likelihood function for GRP parameters would be:

$$L = \left\{ \frac{\beta}{\alpha}\left(\frac{t_1}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t_1}{\alpha}\right)^{\beta}\right]\right\}$$

$$\times \left\{ \prod_{i=2}^{n}\left(\frac{\beta}{\alpha^{\beta}}\right)\left[t_i + q\sum_{j=1}^{i-1} t_j\right]^{\beta-1} \times \exp\left[\left(\frac{q}{\alpha}\sum_{j=1}^{i-1} t_j\right)^{\beta} - \left(\frac{t_i + q\sum_{j=1}^{i-1} t_j}{\alpha}\right)^{\beta}\right]\right\} \tag{21}$$

In order to determine the values of all three parameters, the logarithm of the likelihood function need to be differentiated which will results in three simultaneous equations with three variables. These equations can only be solved by computer software since they are extremely complicated. The equations for the three parameters are:

$$\frac{\partial[\ln(L)]}{\partial\alpha} = \frac{\beta}{\alpha^{\beta+1}}\left[\sum_{i=2}^{n}\left[\left(t_i + q\sum_{j=1}^{i-1} t_j\right)^{\beta} - \left(q\sum_{j=1}^{i-1} t_j\right)^{\beta}\right]\right] + \frac{\beta}{\alpha}\left[\left(\frac{t_1}{\alpha}\right)^{\beta} - (n)\right] \tag{22}$$

$$\frac{\partial[\ln(L)]}{\partial\beta} = \left[\frac{(n)}{\beta} + \ln(t_1) - (n)\ln(\alpha) - \left(\frac{t_1}{\alpha}\right)^{\beta}\ln\left(\frac{t_1}{\alpha}\right)\right] + \sum_{i=2}^{n}\left[\ln\left(t_i + q\sum_{j=1}^{i-1} t_j\right)\right]$$

$$-\left(\frac{t_i + q\sum_{j=1}^{i-1} t_j}{\alpha}\right)^{\beta}\ln\left(\frac{t_i + q\sum_{j=1}^{i-1} t_j}{\alpha}\right) + \left(\frac{q\sum_{j=1}^{i-1} t_j}{\alpha}\right)^{\beta}\ln\left(\frac{q\sum_{j=1}^{i-1} t_j}{\alpha}\right) \tag{23}$$

$$\frac{\partial[\ln(L)]}{\partial q} = (\beta - 1)\sum_{i=2}^{n}\left(\frac{\sum_{j=1}^{i-1} t_j}{t_i + q\sum_{j=1}^{i-1} t_j}\right) + \frac{\beta q^{(\beta-1)}}{\alpha^{\beta}}\sum_{i=2}^{n}\left(\sum_{j=1}^{i-1} t_j\right)^{\beta}$$

$$-\frac{\beta}{\alpha^{\beta}}\sum_{i=2}^{n}\left(t_i + \sum_{j=1}^{i-1} t_j\right)^{\beta-1}\left(\sum_{j=1}^{i-1} t_j\right) \tag{24}$$

2.7 Repairable System: Centrifugal Pump

The fundamental function of a pump is to keep the fluid moving in a useful way by imparting energy to the fluid. By referring to Engineering Pump Handbook [17], a centrifugal pump is a device, which converts driver energy to kinetic energy in a liquid by accelerating it to the outer rim of a revolving device known as an impeller. The impeller, driven by the pump shaft adds the velocity component to the liquid by centrifugally casting the liquid away from the impeller vane tips. This outward flow reduces the pressure inside the impeller thus allowing more liquid to enter. Figure 2.3 below shows the components of centrifugal pump.

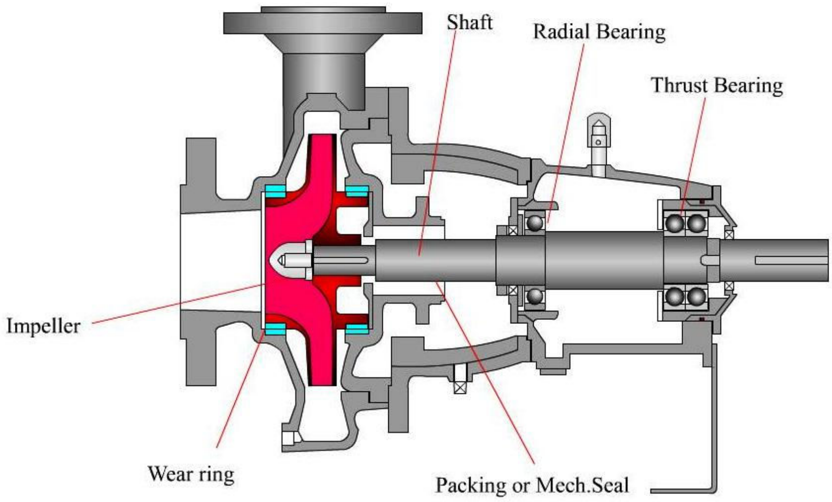


Figure 2.3: Centrifugal Pump Components [17]

Based on Figure 2.3, the components inside the centrifugal pump such as mechanical seal and shaft are always taken into account discreetly due to its tendency to fail. Mechanical seal is one of the most important components in centrifugal pump as it prevents leakage. Thus, the malfunction of mechanical system will lead to centrifugal pumps' failure. This is explained further by Sahdev [18], in which the most problems encountered by centrifugal pumps are due to design errors, poor operation and poor maintenance activities as well. Consequently, these three reasons will cause the system's failure and appropriate repair and maintenance action shall be taken.

Centrifugal pumps are widely used in oil and gas industries due to the usage of the fluid as the main component. For example, in PETRONAS Penapisan Terengganu Sdn Bhd (PPTSB), centrifugal pumps are used in processing different fluids such as crude oil, naphtha, aromatics hydrocarbon and other petroleum products [19].

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

In this project, information is very important in order to understand better on the concept and current situation regarding the project. The information was obtained through the books, journals and websites. Beside that, other method used in this project was data analysis by using reliability software, Weibull ++7. The data used in this project life data which is the historical maintenance data of pumps used in petrochemical plant. By using the software, graph was plotted as the main method to determine the failure distribution and models the failure process of the pump. Finally, the reliability model was developed by using the same software.

3.2 Project Activities

The work flow of the project activities for this project could be referred to Figure 3.1.

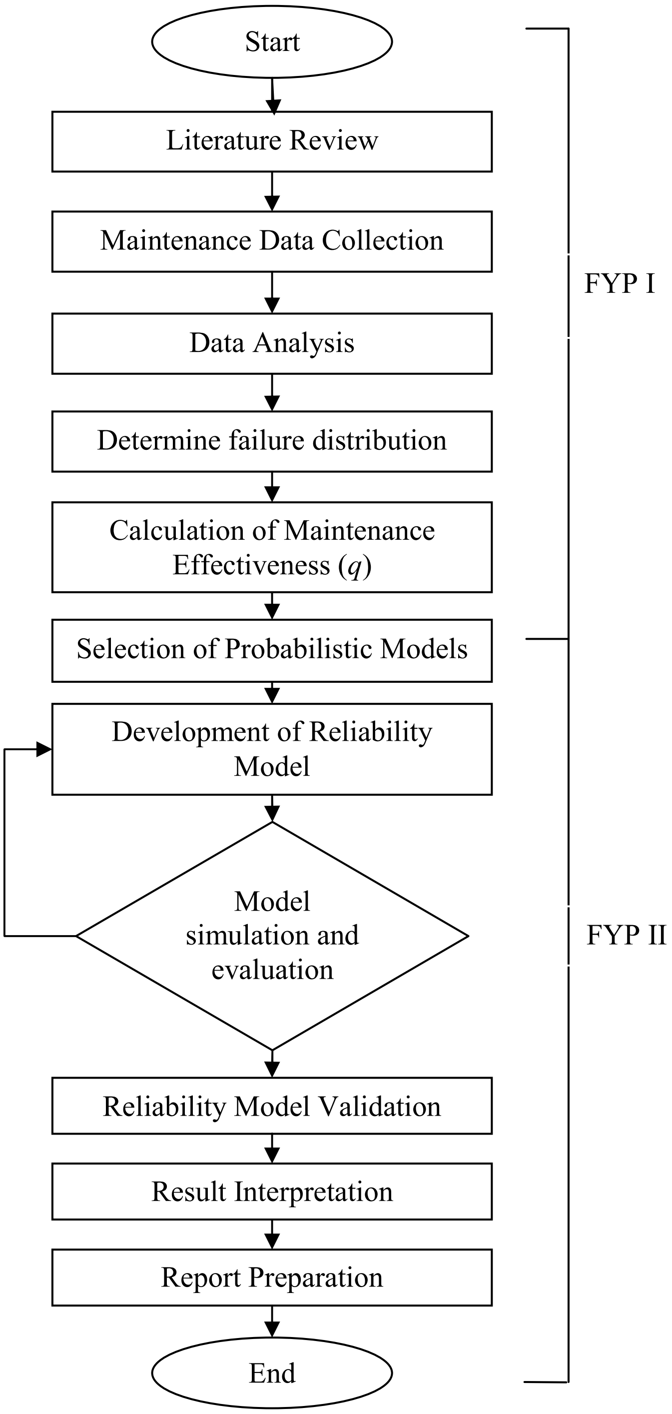


Figure 3.1: Flow Chart of Project Execution

Figure 3.1 shows the flow chart of the project execution whereby the whole project was divided into two major section; FYP I and FYP II. Tasks categorized in FYP I were performed in the first semester of Final Year meanwhile the latter tasks in FYP II groups were conducted during the second semester. The detail information of every stage is explained in this section for further understanding.

3.2.1 Maintenance Data Collection

After literature review was completed in FYP I, the life data which is the historical maintenance data was gathered at the second stage. The data was obtained from the maintenance department of the petrochemical plant which summarized the recorded failure involving many types of process fluids such as aromatics hydrocarbon, naphtha, raw water, sour water and wash water. These data were obtained in raw form and included the historical maintenance and failure data starting from year 2000 until year 2008. However, since this project will only focus on pump with aromatics hydrocarbon as the process fluid, thus only data involving pump failures with aromatics hydrocarbon will be taken into consideration.

3.2.3 Data Analysis

After the collection of the failure data, the segregation of the data was conducted. The purpose of data segregation was to extract failure data of pumps which their process fluid was aromatics hydrocarbon only. The data sorting was done by using Microsoft Excel with several conditions:

- The starting date of recorded data for all of the centrifugal pumps in the plant was on 15th June 2000
- The end date of recorded data for all of the centrifugal pumps in the plant was on 1st September 2008
- All of the centrifugal pumps in the plant were operating with aromatic hydrocarbon as the process fluid.

After the data sorting was completed, the detail data analysis was carried out by using Weibull ++7, a reliability software. This software possesses similar interface with Microsoft Excel hence the data analysis could be conducted easier.

3.2.3.1 Determination of Failure Distribution

The determination of failure distribution was the initial stage of pump failure data analysis. In the analysis tool of Weibull ++7 time to first failure (TTFF) was assumed to possess the characteristic of Weibull distribution. This is because Weibull distribution is a versatile distribution which can exhibit other types of distribution when calculated with different value of shape parameter, β (beta), scale parameter, η (eta) and location parameter, γ (gamma). The calculation of the parameter was done by the analysis tool called 'Distribution Wizard'. After the calculation done, the results indicated the ranked order of suitable type of distributions with the pump data provided. After selecting the most suitable distribution, the graph was displayed which showed the type of failure distribution for pumps in the plant.

3.2.3.2 Calculation of Maintenance Effectiveness (*q*)

The second stage of the data analysis by using Weibull ++7 analysis tool was the calculation of maintenance effectiveness. The maintenance effectiveness was calculated by the analysis tool in Weibull ++7 software. In this study, the maintenance effectiveness was calculated by using GRP model Type I. the Type I model assumes that the repair can only removed the damage from the last repair as discussed earlier in section 2.5.3. The value of q will determine which probabilistic models assumption governs the pumps' failure characteristics; RP, NHPP or GRP. The calculation of q was done by using Weibull ++7 which was the suitable software for reliability calculation. As the author had explained in Section 2.6.1, the value of q could only be determined by using the computer due to very complex simultaneous equation. By using computer software, in this case Weibull ++7, not only q value, but λ and β values could be determined as well.

3.2.3.3 Selection of Probabilistic Model

The probabilistic model selection was conducted after the maintenance effectiveness, q was calculated. Based on the q value, the probabilistic model was selected for the reliability model development. If the value of q calculated to be 0, then the assumption of as good as new condition will govern the maintenance activities performed on the pumps. Hence, the Renewal Process (RP) model will be used to develop the reliability model. Meanwhile, if $q = 1$, Non-Homogeneous Poisson Process (NHPP) model which follows the assumption of as bad as old condition will be used to develop the reliability model. However, if the value of q obtained is between 0 and 1, which is the intermediate stage, then the reliability model will be developed by using Generalized Renewal Process (GRP) model.

3.2.3.4 Development of Reliability Model

The development of reliability model which was the conceptual stage has been completed in Final Year Project I (FYP I). The further development of model was then continued in Final Year Project II (FYP II). The model was developed based on the selected probabilistic models and the maintenance effectiveness value obtained in the earlier stage. The reliability model refers to the conditional reliability versus time graph which was obtained during the earlier stage of data analysis. From this model, the next failure of the pump for a certain period of time, for example, five and ten years can be predicted.

3.2.4 Model Simulation and Evaluation

After the model was developed, the simulation and evaluation of the model need to be conducted so that it could function properly. The model was tested repeatedly using different time intervals and the consistency of the results produced will be observed. Besides that, the pump data will also be analyzed by using the other two probabilistic models which are RP and NHPP. The reliability model was developed by using the same software, Weibull ++7 which was used for GRP model. The number of likelihood value (LV) produced by each reliability model was compared with the value produced by GRP model to determine the best fit data with the determined failure distribution earlier. This stage was repeated in order to obtain the consistency in results for every reliability model.

3.2.5 Reliability Model Validation

In this phase, the reliability model was developed by using different time duration. In actual data analysis, 3000 days of operation had been taken into consideration. Hence, in order to validate the model developed, two different days of operation; which were 1500 days and 2000 days were considered. This means that only half of the data were used. These two durations were used to develop another reliability models to predict the next failure within the time duration of 3000 operation days. The values obtained from both model were then compared to the actual failure data. The validity of the model was determined based on the accuracy of the models to produce similar cumulative number of failures with the actual failure data.

3.2.6 Result Interpretation

Result interpretation stage was carried out upon completion of model evaluation and validation. In this stage, the model was used to predict the next failure of the system for a certain period of time. The results produced by the reliability model was interpreted in such a way whether the results produced was in the reasonable interval and value.

3.2.7 Report Preparation

This stage was performed in order to complete the whole project which summarizes all the activities which had been conducted throughout the semesters. This documentation will provide information to the reader on the whole project and can be used for future references and ideas. In addition, the report will also assist the companies who are interested with the proposed model in predicting the future failure of the equipments in their company.

3.3 Gantt Chart

The Gantt Chart of the project in second semester can be referred in the Appendix A.

3.4 Tools and Equipments Required

The tools and equipment required in this Final Year Project are a Windows based personal computer (PC) together with the programs such as Microsoft Office and Weibull ++7 software which was used to analyze the data obtained from the field. Weibull ++7 software is a reliability software which performs the reliability analysis and develops the reliability model for the repairable system.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Failure Distribution

Based on the data analysis performed by analysis tool of Weibull ++7 software, the failure distribution for the pumps can be obtained from the Figure 4.1 below.

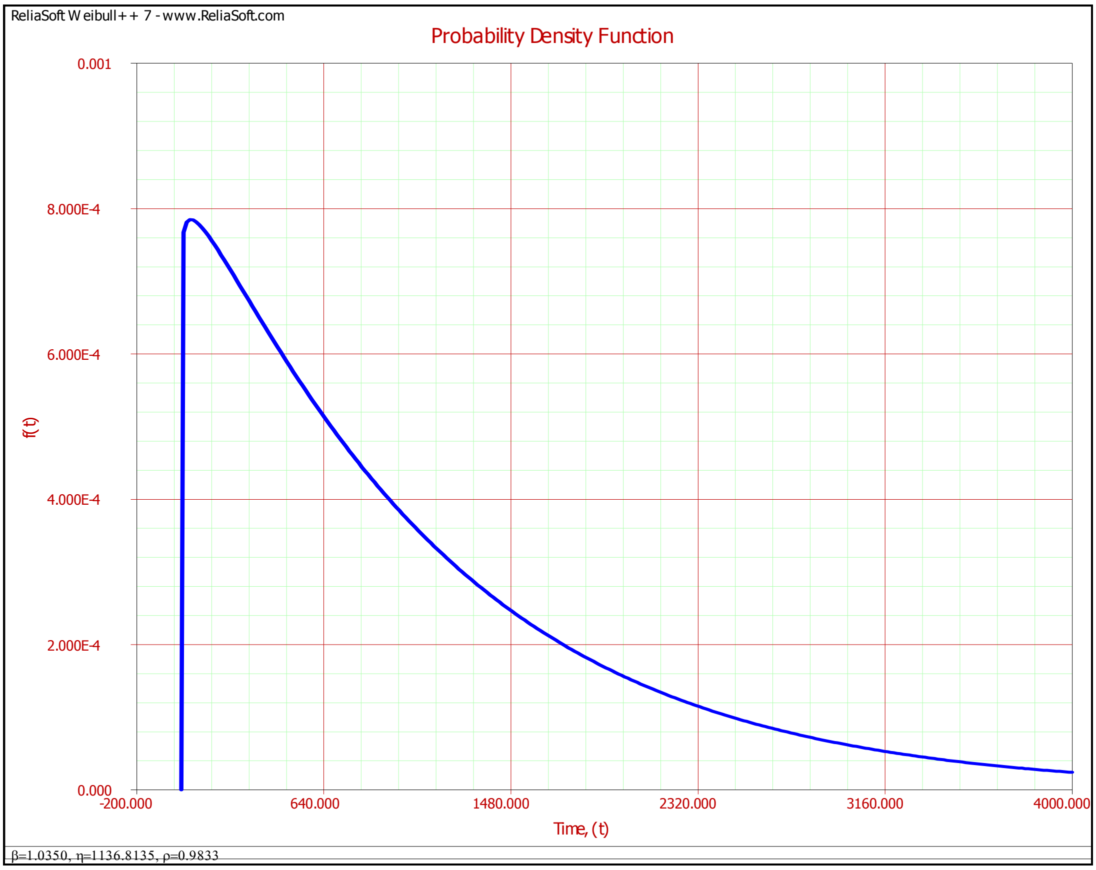


Figure 4.1: Probability Density Function versus Time Graph for the Pumps

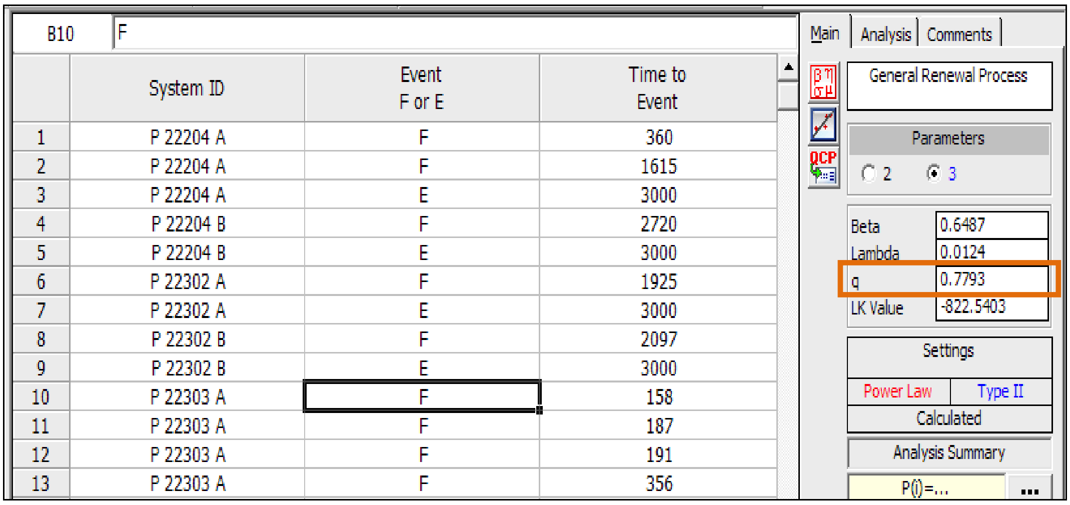
Figure 4.1 shows the probability density function versus time graph for the pumps. Based on the plotted graph in Figure 4.1, it indicates the characteristics of Weibull distribution with two parameters which are:

- Shape (β) parameter = 1.0350
- Scale (η) parameter = 1136.8135

The value of β = 1.0350 exhibits the characteristics of exponential distributions which shows that the pump failures in the plant occurred at a constant rate. The scale parameter (η) is an indicator of the statistical dispersion. The larger value of η will causes the distribution spread out wider while the smaller value will make the distribution become more concentrated. In reliability field, scale parameter refers to mean time between failures (MTBF). Based on Figure 4.1, the large values of scale parameter indicate that the pump failures occur quite often within the recorded time.

4.2 Calculation of Maintenance Effectiveness

Figure 4.2 shows the calculated maintenance effectiveness, *q* for the pumps in Weibull ++7 software. System ID indicates the tag number for the pump while the for the Event column, F indicates the failure while E indicates the event. The term event here refers to the last date of the maintenance data of pumps' operation recorded which is on September 1st, 2008. The last column which is time to event refers to the time of the failure occurs for each pump. The value is determined by calculating the days of operation from the first day of recorded data on June 15th, 2000 up until the failure occurs. The total operation days for the pumps are 3000 days as per shown in the figure. Based on Figure 4.2, the value of q = 0.7793 is obtained. This value indicates that the system followed the Generalized Renewal Process (GRP) model which indicates imperfect maintenance.



	System ID	Event F or E	Time to Event
1	P 22204 A	F	360
2	P 22204 A	F	1615
3	P 22204 A	E	3000
4	P 22204 B	F	2720
5	P 22204 B	E	3000
6	P 22302 A	F	1925
7	P 22302 A	E	3000
8	P 22302 B	F	2097
9	P 22302 B	E	3000
10	P 22303 A	F	158
11	P 22303 A	F	187
12	P 22303 A	F	191
13	P 22303 A	F	356

Figure 4.2: Calculated *q* for the Pumps

4.3 Selection of Probabilistic Models

Based on the q value obtained earlier, the failure data shows that it is governed by GRP model assumption. Therefore, the reliability model is developed by using the GRP assumptions. Since there are two types of GRP models which are Type I and Type II, the model for both types is developed and compared to determine the most suitable one to be used in this project. The graphs of conditional reliability versus time for both models are shown below in Figure 4.3 and Figure 4.4.

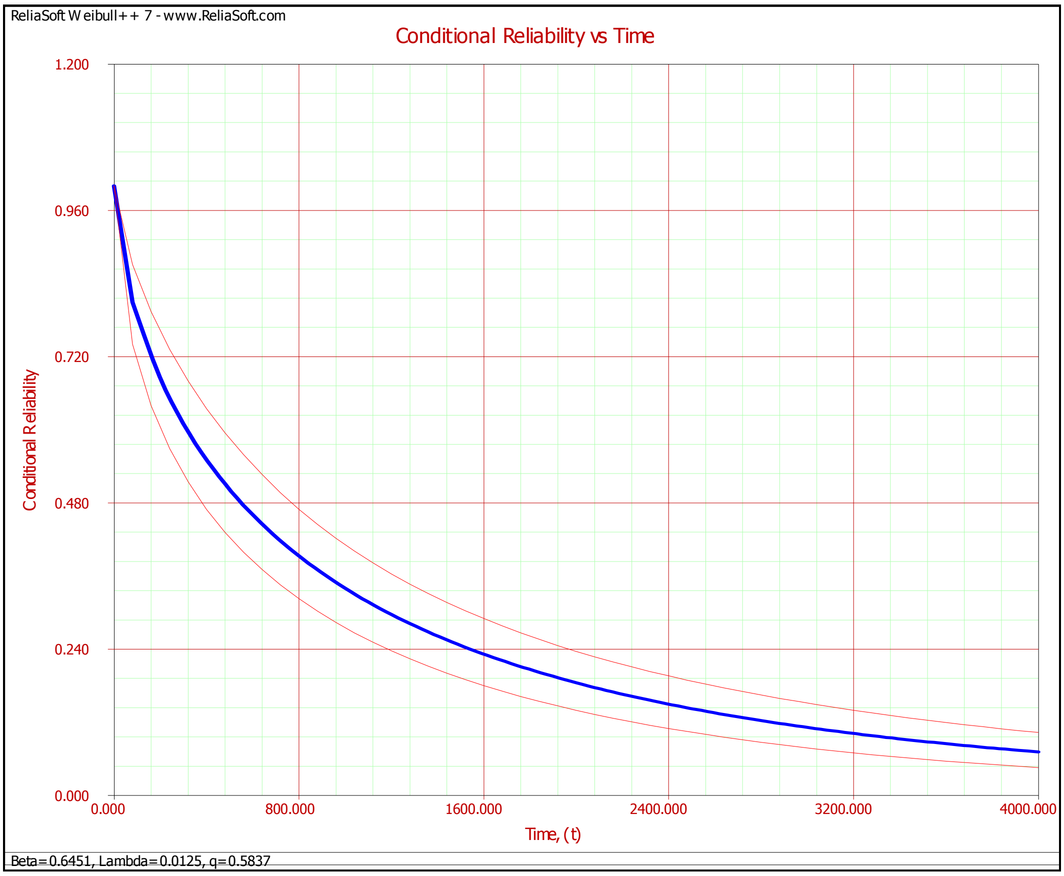


Figure 4.3: Conditional Reliability versus Time Graph for GRP Type I

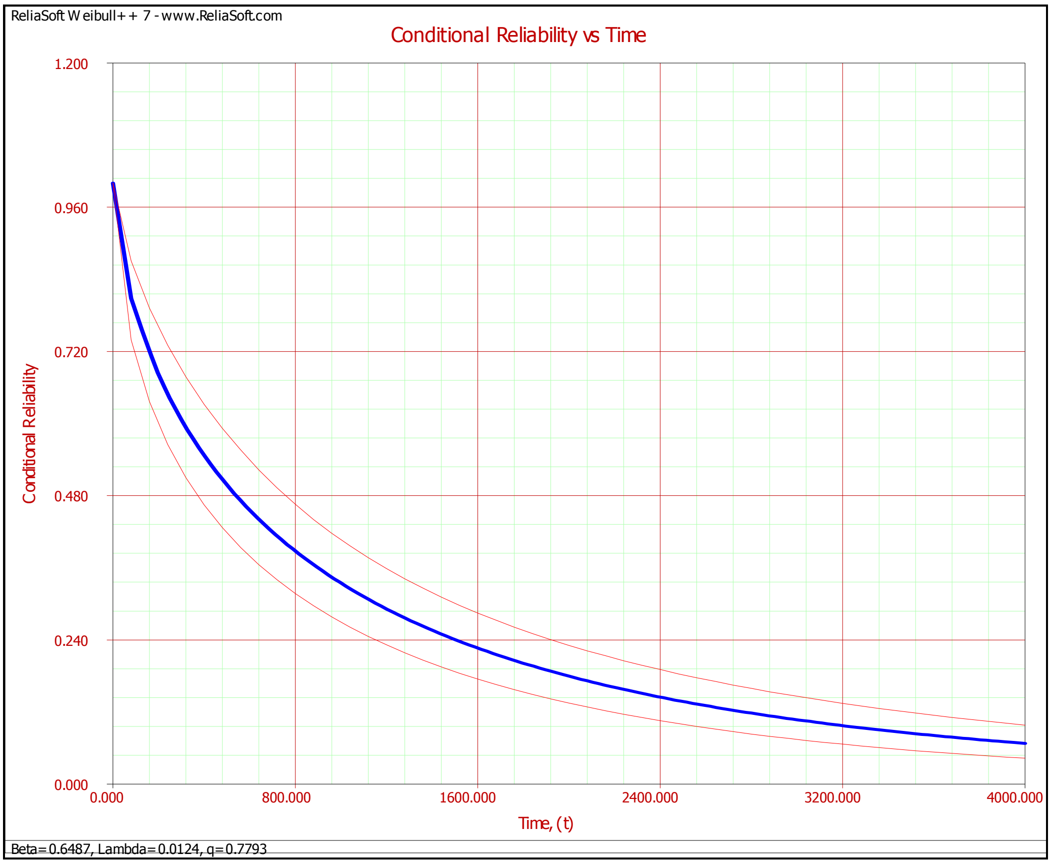


Figure 4.4: Conditional Reliability versus Time Graph for GRP Type II

Referring to the graphs visually, there is no significant difference between both models thus the current conditional reliability for the models are calculated and compared. The results are shown in Figure 4.5 below:

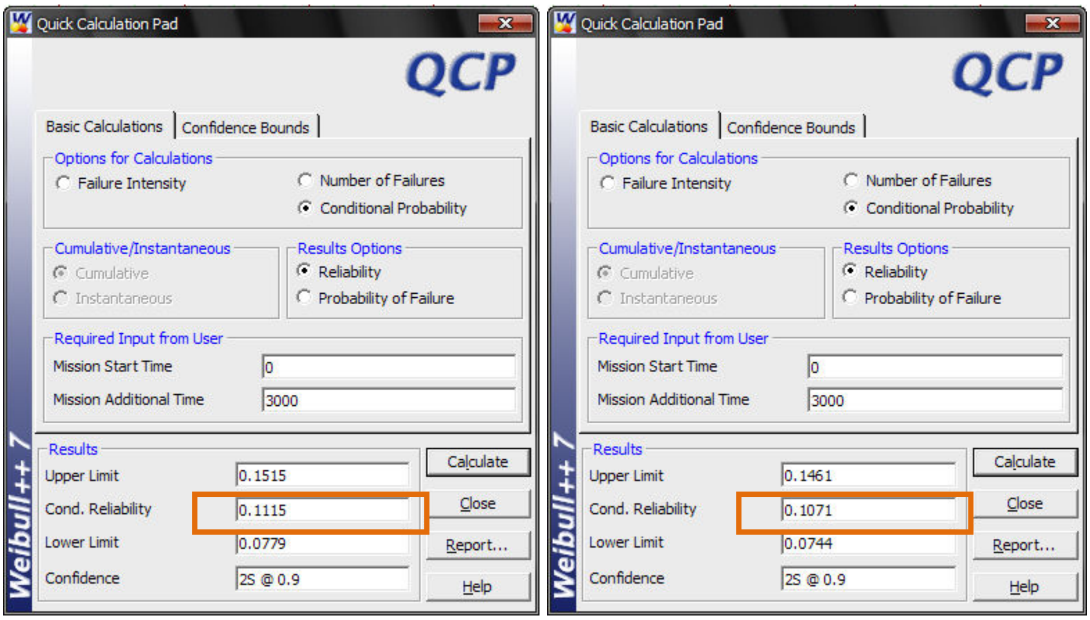


Figure 4.5: Current Conditional Reliability for GRP Type I (left) and GRP Type II models (right)

Figure 4.5 shows the current conditional reliability of the system determined by the models developed by using GRP assumption models Type I and Type II. GRP model Type I indicates 0.1115 or 11.15% reliability; higher than GRP model Type II which produces 0.1071 or only 10.71% reliability. These values indicate that GRP model Type I will produce higher reliability of the system. Somehow this feature could not determine the most suitable model which best fit the data. Thus the likelihood value (LV) for both types of models is compared to select the most suitable model for the failure data. The calculation made by Weibull ++7 and the results are displayed below in Figure 4.6.

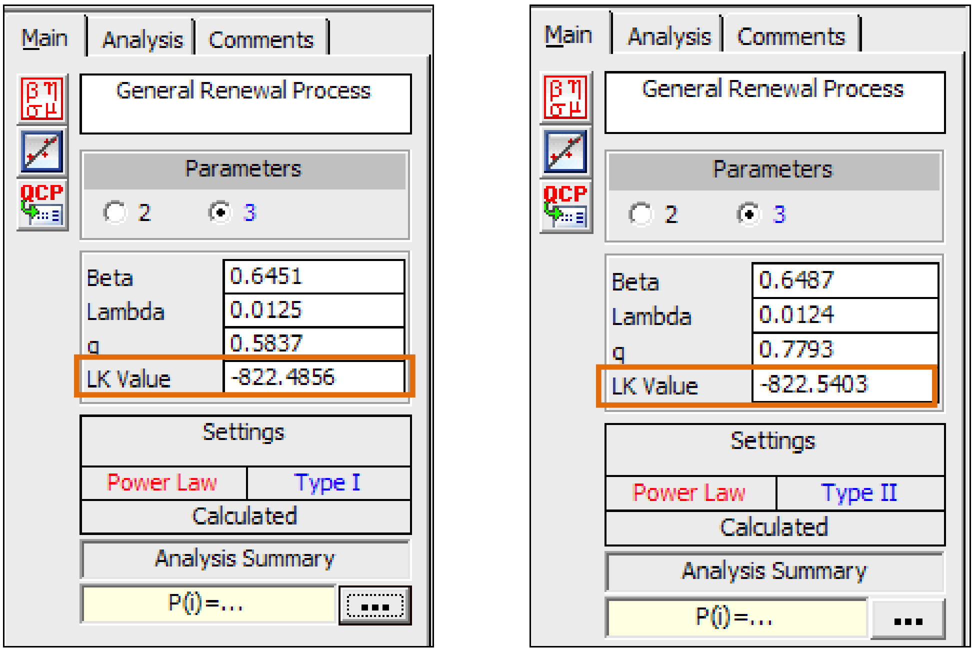


Figure 4.6: Likelihood Value (LV) for GRP Type I (left) and GRP Type II models (right)

Figure 4.6 shows the likelihood value for GRP Type I and GRP Type II models, respectively. Based on the calculation done by the software, GRP Type I model produces higher likelihood value (LV) which is -822.4856 as compared to GRP Type II models which produces -822.5403. Higher likelihood value indicates that the model fits best the data provided. Hence in this project, GRP model Type I is the most suitable model to be used to develop the reliability model.

4.4 Prediction of Next Failure

Basically, the reliability model has been developed once the graphs are plotted. The model for pumps in each plant can be referred to the graphs of conditional reliability versus time, respectively. The graph is plotted with 90% of confidence interval, and from the graph, the cumulative of failures can be calculated. In statistical perspective, confidence interval refers to an interval in which a measurement or trial falls corresponding to a given probability. The percentage value of the confidence interval is depends on the user of the model. The greater value of the confidence interval, the larger range of data could be obtained. In this project, 90% value is selected so that it will provide larger range of output data.

Figure 4.7 shows the conditional reliability versus time graph and while Figure 4.8 and 4.9 show the estimation of cumulative number of failures for pumps in the plant within five and ten years, respectively.

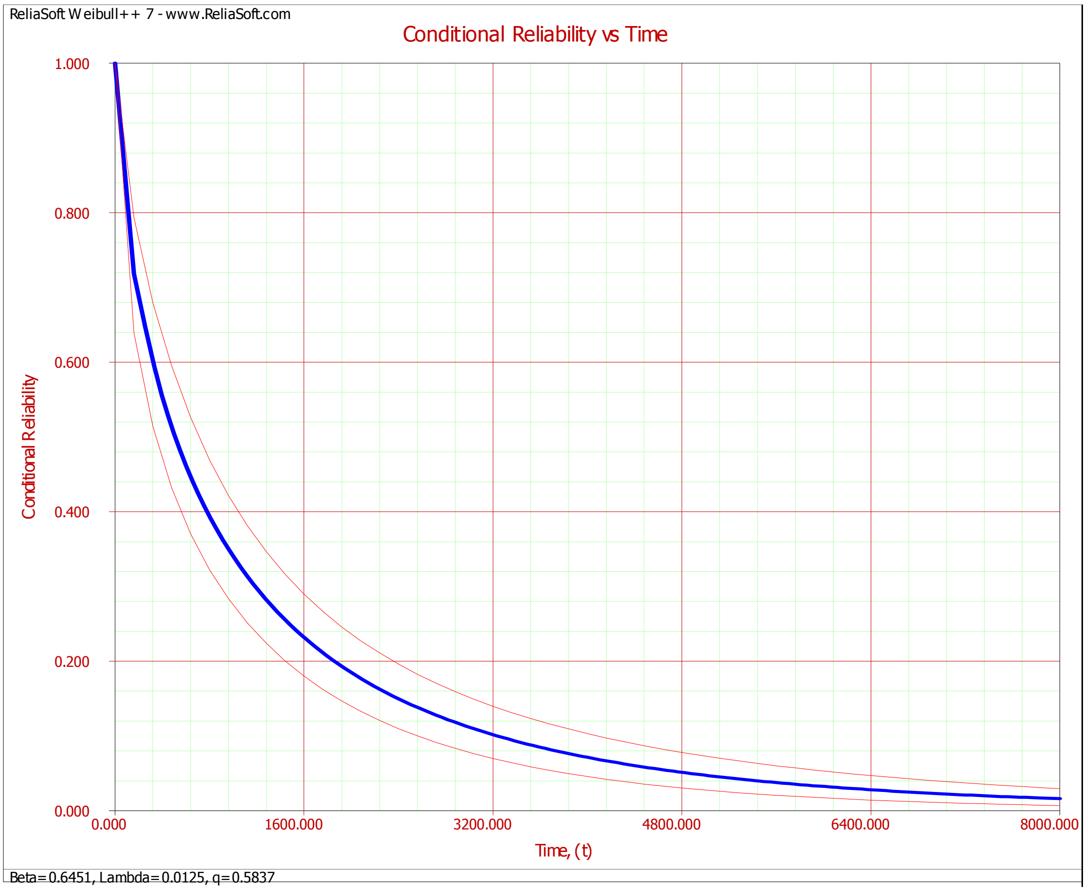


Figure 4.7: Conditional Reliability versus Time Graph for the Pumps

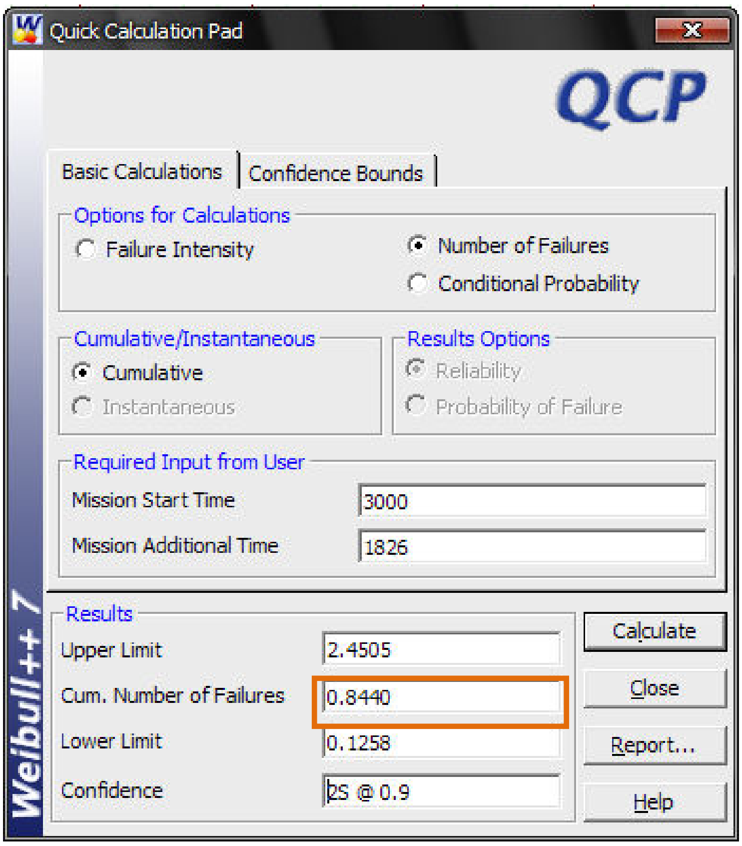


Figure 4.8: Estimation of Cumulative Number of Failures within 5 years

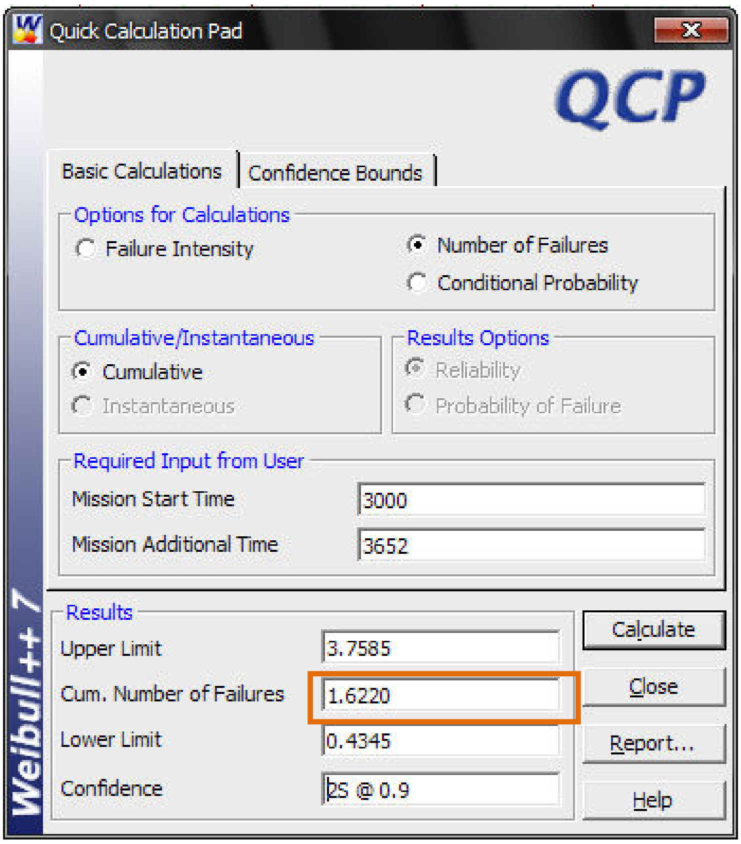


Figure 4.9: Estimation of Cumulative Number of Failures within 10 years

Based on the figures, approximately one failure will occur within five years. The estimation is displayed in Figure 4.8 which 0.8440 is the cumulative number of failures and the upper and lower limits are 2.4505 and 0.1258, respectively. As for prediction of failures within ten years time, the number of pump failures in the plant which likely to occur is 1.622 of 90% confidence interval which the upper limit is 3.7585 and the lower limit is 0.4345. This data indicates that within 10 years of operation, there are most likely two (2) pump failures will occur. The upper limit and lower limit are produced by using 90% of confidence interval. This means that the model has predicted the maximum number of pump failures would be four (4) meanwhile the minimum number of probability of pump failures is one (1). Even though this prediction may not be exactly accurate, in one way it has produced a good prediction for the pump operating life. At the same time, the maintenance department could plan their maintenance activity effectively since approximately 2 pump failures will most likely to occur within 10 years.

4.5 Evaluation of Reliability Model

In order to evaluate the reliability model developed earlier, the likelihood value (LV) of other models such as RP and NHPP also taken into account. The likelihood value is compared in order to evaluate the suitability of the model to fit the failure data. The calculation is done by using Weibull ++7 and the results are shown in Figure 4.10 below. Figure 4.10 shows the likelihood values and others for RP model and NHPP models respectively.

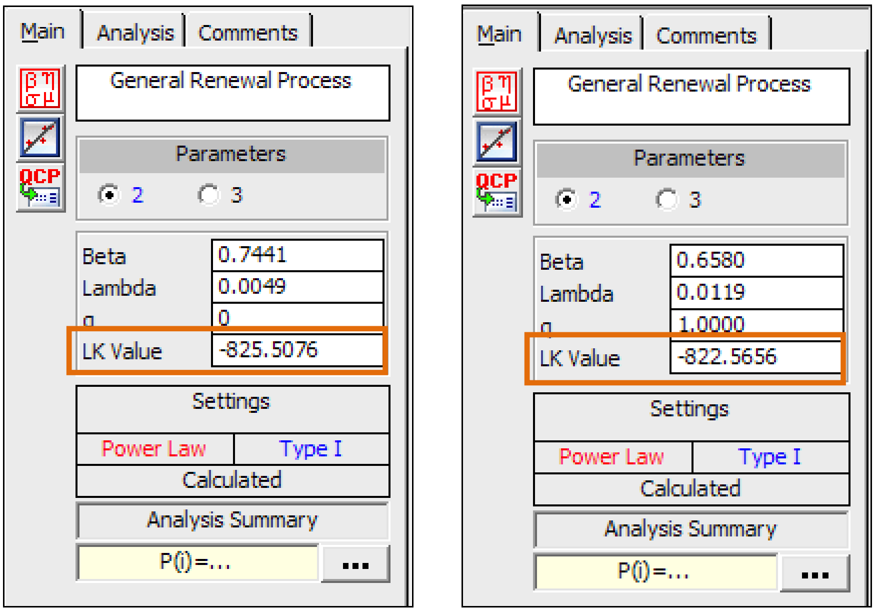


Figure 4.10: Likelihood Value (LV) for RP model (left) and NHPP model (right)

In order to calculate the likelihood value (LV) for RP model, the value of q is set to be equal to 0 as the model requirement and condition this results in likelihood value equal to -825.5076. As for NHPP model, the input value for q is set to be 1 for the same purpose and the likelihood value for NHPP model is calculated as -822.5656. Based on the Figure 4.10, value of beta and lambda can also be obtained apart from the likelihood value. All of these results are tabulated in Table 4.1 below.

Table 4.1: Analysis Result Comparison

Probabilistic Model	β (beta)	q	λ (lambda)	LV
GRP Type I	0.6451	0.5837	1.25E-02	-822.4856
GRP Type II	0.6487	0.7793	1.24E-02	-822.5403
RP	0.7441	0	4.90E-03	-825.5076
NHPP	0.6579	1	1.19E-02	-822.5656

By referring to Table 4.1, GRP Type I produce the largest value of likelihood value (LV) at -822.4856. This result shows that GRP Type I fit best the maintenance data used in this project as compared to GRP Type II, PRP and NHPP models. At value of q = 0.5837, it clearly shows that the intermediate stage assumption which proves the imperfect maintenance of the system. Hence, GRP model Type I is the best choice for the reliability model.

4.6 Validation of Reliability Model

By taking 1500 and 2000 operation days into consideration, the reliability models are developed and the expected cumulative numbers of failures within 3000 days of operation are predicted by using the models. The results can be referred to Figure 4.11 below.

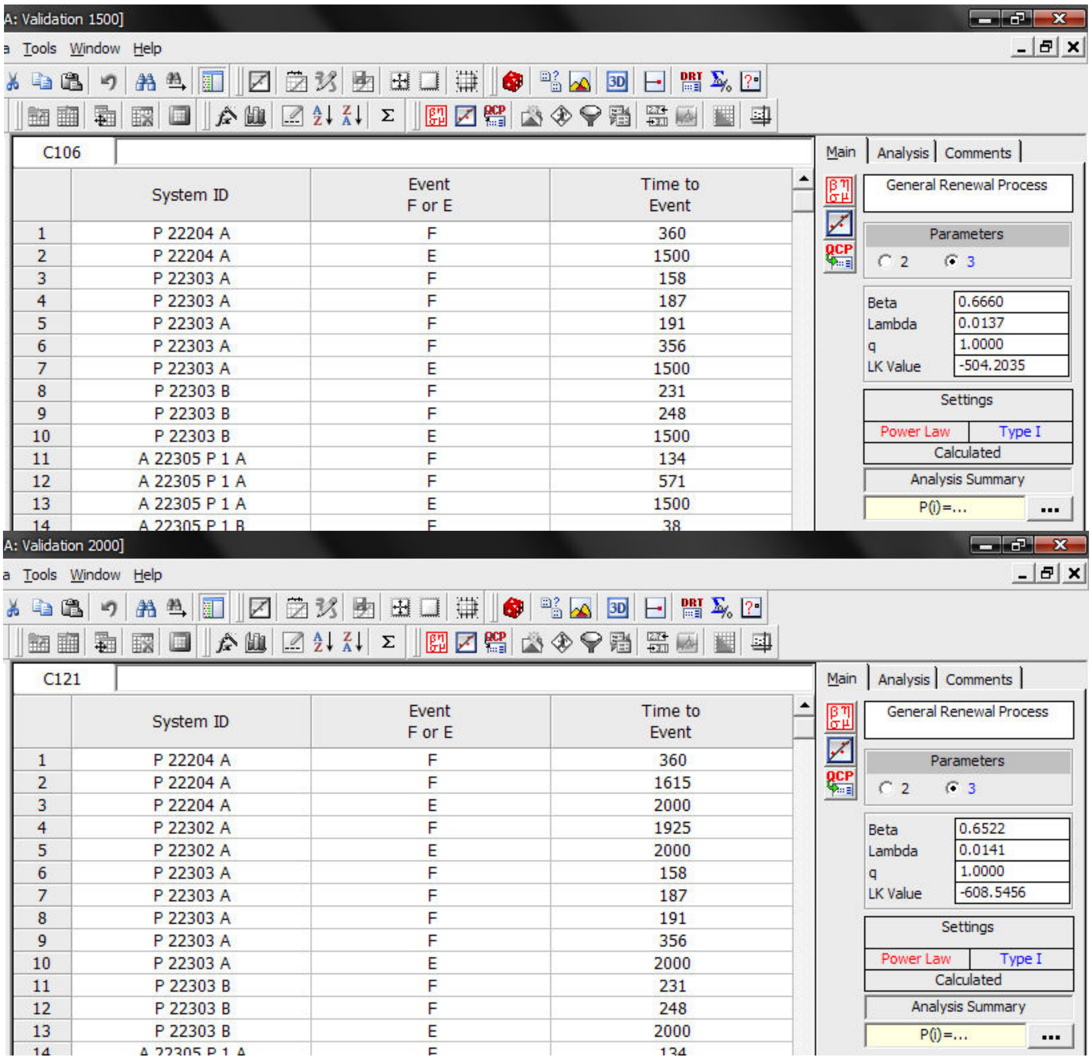


Figure 4.11: Data Analysis of 1500 Operation Days (top) and 2000 Operation Days (bottom)

Figure 4.12 shows the data analysis of the pumps historical maintenance data by using taking 1500 and 2000 operation days into consideration. Based on the both table, it is clearly shown that 1500 and 2000 were selected as the time to event which refers to the end date of recorded data. The data analysis performed also shows variables due to different operation days. In analysis for 1500 operation days, q value calculated to be 1 which exhibits the characteristic of NHPP meanwhile for 2000 operation days, the GRP assumption governs the failure data which has the value of q equal to 0.9894. However, both of these values could not be used to validate the reliability model developed earlier. Hence, the conditional reliability versus time graph is plotted for both 1500 and 2000 operation days.

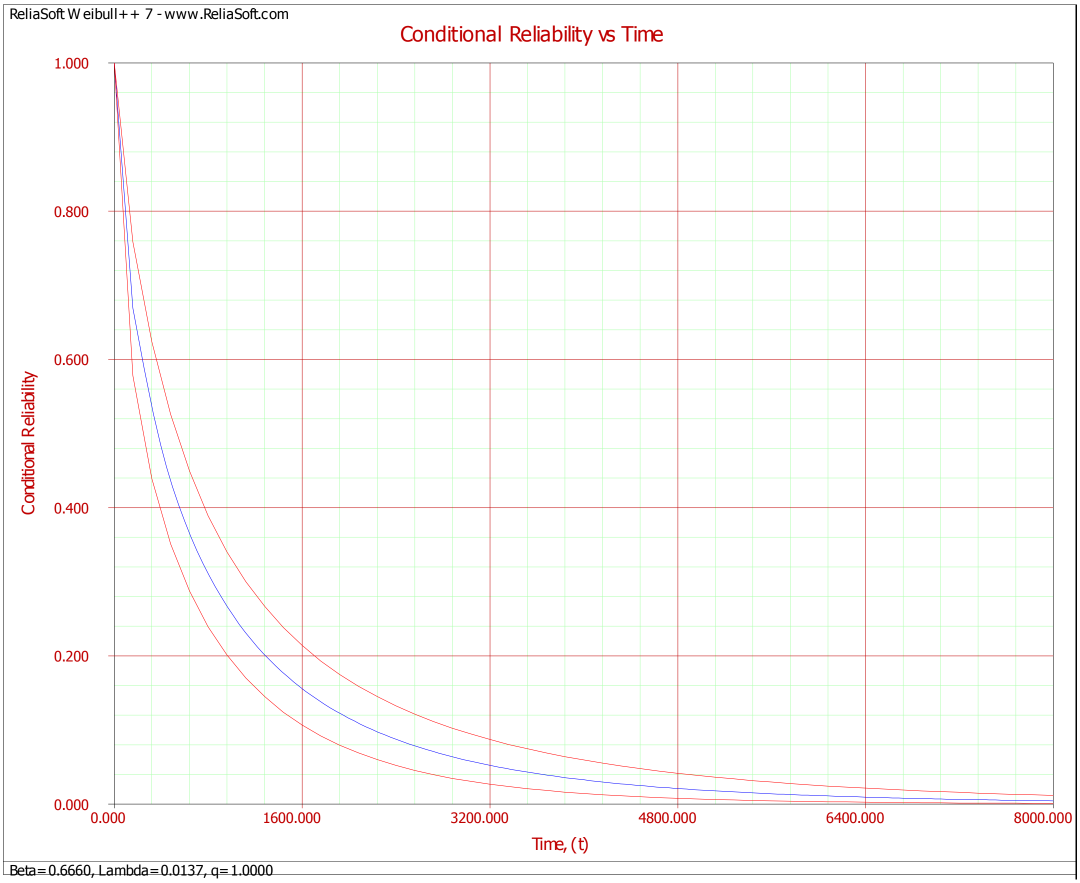


Figure 4.12: Conditional Reliability versus Time Graph for 1500 Operation Days

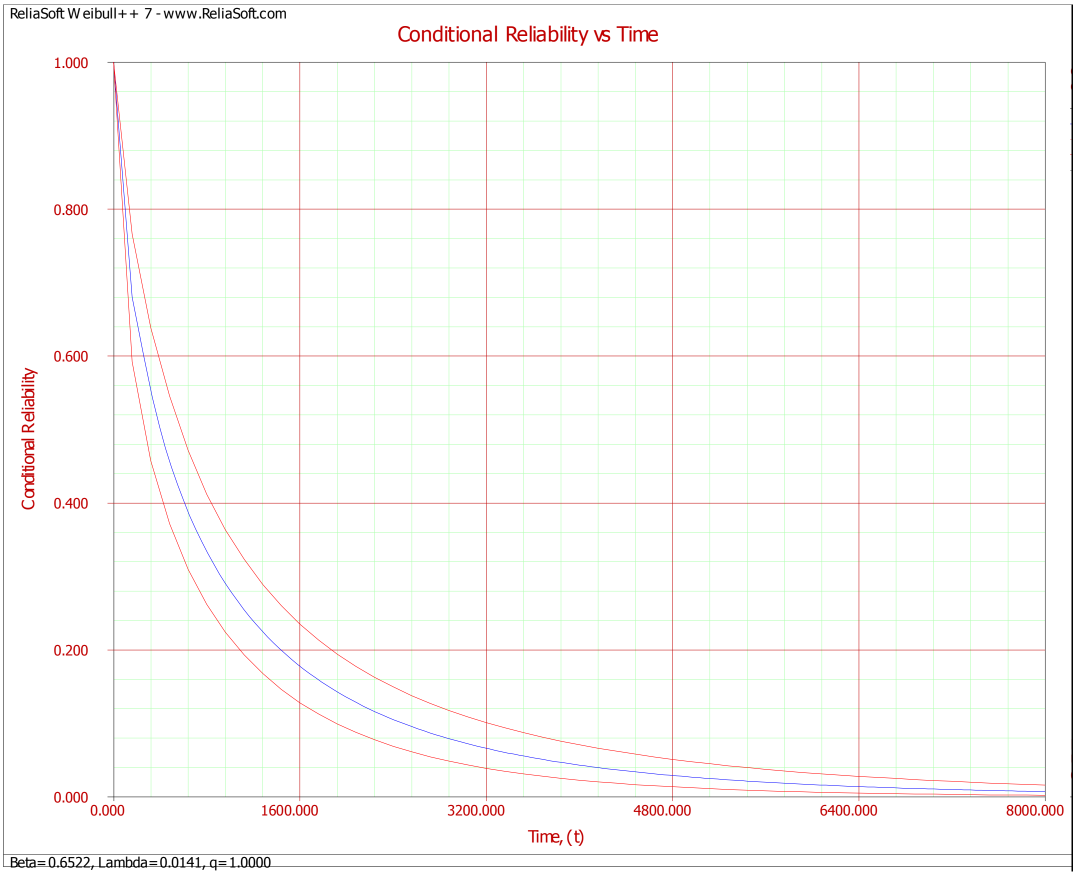


Figure 4.13: Conditional Reliability versus Time Graph for 2000 Operation Days

Figure 4.12 and Figure 4.13 displays the conditional reliability versus time graph for 1500 and 2000 operation days, respectively. As mentioned earlier, the reliability model is actually developed once the conditional reliability versus time graph is plotted. Both graphs displays similar plot with the reliability model developed earlier thus the early conclusion that can be made is the models are the same. Somehow, further analysis is conducted to verify the similarities between both conditions with the actual failure data.

Figure 4.14 shows the expected cumulative number of failures within 3000 operation days which have been determined by using the reliability model of 1500 and 2000 operation days.

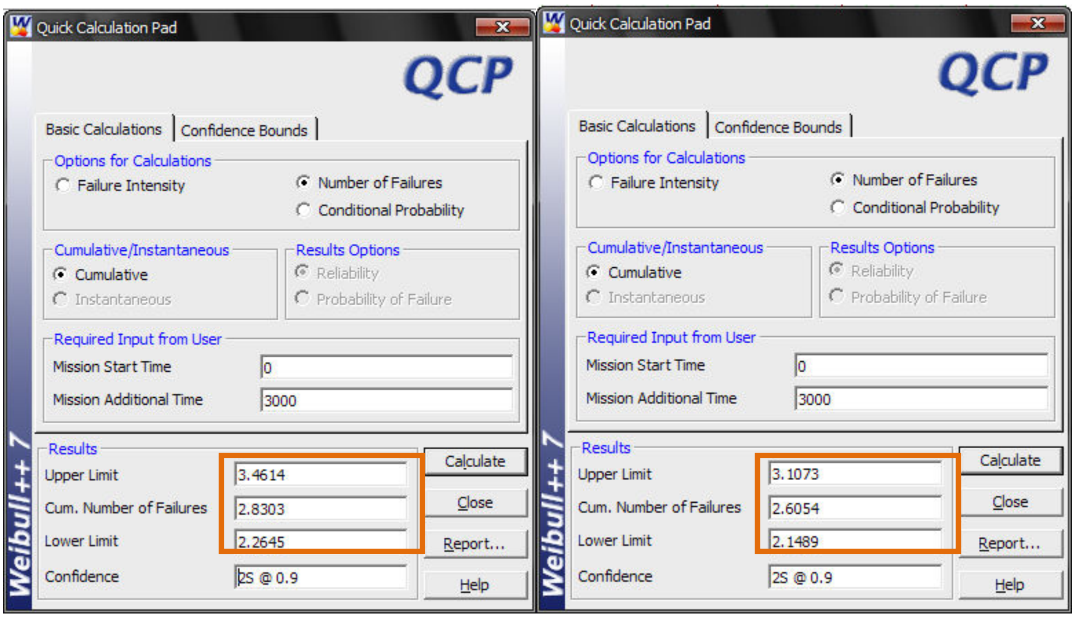


Figure 4.14: Expected Cumulative Number of Failures Within 3000 Operation Days Using 1500 Operation Days (left) and 2000 Operation Days (right)

For 1500 operation days, it is expected that approximately three (3) failures will likely to occur within 3000 operation days. This value is obtained by rounding off the value of 2.8303 calculated by the software. The upper and lower limits for this model are 3.4614 and 2.2645, respectively. By rounding off these values, the limits will become three (3) and two (2), respectively limit. Similarly, the expected number of failures for 2000 operation days is also three (3) after rounding off the value of 2.6054 computed by the software. The upper and lower limits are 3.1073 (rounded off to three (3)) and 2.1489 (rounded off to two (2)), respectively. These values are compared with the actual cumulated failure which calculated by the 3000 operation days shown in Figure 4.15 below.

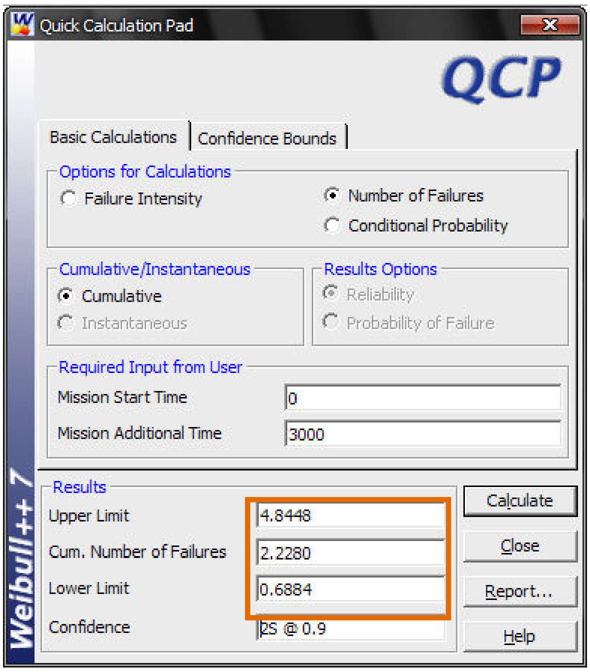


Figure 4.15: Actual Cumulative Number of Failures Within 3000 Operation Days

Based on Figure 4.15, the cumulative number of failure is two (2) with upper and lower limits four (4) and one (1), respectively. The summary of the comparison is summarized and tabulated in Table 4.2 below.

Table 4.2: Summary of Validation Comparison

Operation Days	Upper Limit	Cumulative Number of Failure	Lower Limit
1500	3.4614	2.8303	2.2645
2000	3.1073	2.6054	2.1489
3000 (actual)	4.8448	2.2280	0.6884

Table 4.2 shows the summary of the validation comparison. The cumulative number of failures for 1500 and 2000 operation days indicate three (3) failures which are slightly higher than the actual data. However, when the upper and lower limits are compared with the actual model, it can be concluded that the results produced are within the control limit. Thus, the results for 1500 and 2000 operation are considered acceptable and possess similarities with the actual data. This shows that all the three models produce the same value of cumulative number of failures. Since all the models produce the same results, it can be concluded that the reliability model developed earlier is validated and can be used to predict the next failure of the system.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this project, the historical maintenance data was collected and used to determine the failure distribution and the maintenance effectiveness of the pump. By using reliability software, Weibull ++7, the failure distribution was concluded as Weibull distribution with two parameters.

In the first phase, the maintenance action done on the system was explained with the probabilistic models based on the computed value of q. The data analysis showed that the maintenance actions for pumps in the plant were imperfect which characterized by Generalized Renewal Process (GRP) assumption. Since GRP assumptions possess two types of models, the reliability model was developed based on the conditional reliability versus time graph plotted during the data analysis for both Type I and Type II models. The likelihood value (LV) for both models were calculated and compared to determine the most suitable model which produces highest LV. Based on the comparison, GRP model Type I produced the highest LV which is -822.4856 hence it was selected. By using this model, numbers of expected cumulative failures within five and ten years were estimated.

Further evaluation of the model was continued in order to verify the most suitable model to best fit the data. The model was developed based on RP assumptions, NHPP assumption, and GRP models of Type I and Type II. Upon comparing the models, the GRP model Type I exhibited the best fit model with the highest value of likelihood value (LV) thus it had been concluded that this model was the most suitable to be used for reliability model.

The final phase was the validation model by using different value of operation days; namely 1500 and 2000 operation days. The reliability models were developed by using these two conditions and the expected cumulative numbers of failures within 3000 operation days were computed. The results were then compared with the actual cumulative number of failure based on the actual data which uses 3000 operation days. The expected cumulative numbers of failures computed in this stage indicated similarities with the actual cumulative number of failures. Based on the comparison, the reliability model was validated.

The results obtained from this project represent the potential of this reliability model to be executed with the failures data provided and then used to predict the future failure for a repairable system in petrochemical industry. Current industrial practices have been implementing the Preventive Maintenance (PM) approach hence the integration and application of this model can positively improve the efficiency of the activities. This will translates into much greater reduction of maintenance cost. As a conclusion, the objectives of this project had been accomplished and it is hoped that this project can be used as a reference for further research and study in the future.

5.2 Recommendation

This final year project had been completed within the stipulated time frame. However, there are several improvements can be made to produce a better reliability model. Firstly, the constraint of this model is the limited number of data. This affected the value predicted by the model. Therefore for future study, it is recommended that more data should be collected. This would help in obtaining more accurate reliability model. Secondly, it is recommended to use a more detailed failure data in developing the reliability model. In this project, several failure data were removed due to missing of various details such failure date, tag number and type of process fluid. Thus, by using more detailed data, the reliability model can be developed better. As a result, it would produce better accuracy in predicting the future failures.

REFERENCES

[1] Yañez, M., Joglar, F. and Modarres, M. 2002, "Generalized Renewal Process for Analysis of Repairable Systems with Limited Failure Experience", *Reliability Engineering and System Safety (77),* pp. 167-180

[2] Beebe, Ray S. 2004, "Predictive Maintenance of Pumps using Condition Monitoring", Elsevier Ltd., United Kingdom.

[3] Davidson, John. 1988, "The Reliability of Mechanical Systems", *IMechE Guides for the Process Industries*, Mechanical Engineering Publications, London.

[4] Shwu-Tzy Jiang, Thomas L. Landers, and Teri Reed Rhoads. 2006. "Assessment of Repairable-System Using Proportional Intensity Models: A Review," *IEEE Transactions on Reliability*, vol. 55, no. 2, 328 – 329.

[5] "Bathtub" Curve <viewed on March 14, 2009>
http://www.itl.nist.gov/div898/handbook/apr/section1/apr124.htm

[6] Krivtsov, V. 2000, "A Monte Carlo approach to modeling and estimation of the generalized renewal process in repairable system reliability analysis", University of Maryland.

[7] Exponential Distribution – Wikipedia <viewed on August 18, 2008>
http://en.wikipedia.org/wiki/Exponential_distribution

[8] Adamantios Mettas and Wenbiao Zhao, Ph.D. 2005, "Modeling and Analysis of Repairable Systems with General Repair", ReliaSoft Corporation.

[9] Rausand, M. and Høyland, A. 2004, "System Reliability Theory: Models, Statistical Methods, and Applications", Second Edition, John Wiley & Sons, Inc., New Jersey.

[10] Life Data Analysis Reference On-Line Help <viewed on August 30, 2008>
http://www.weibull.com/LifeDataWeb/lifedataweb.htm

[11] Life Data Analysis Basics <viewed on August 30, 2008>
http://www.weibull.com/basics/parameters.htm

[12] Bo HendryLindqvist. 1997, "Statistical Modeling and Analysis of Repairable System", Norwegian University of Science and Technology, Trondheim

[13] Repairable System Analysis Training. <viewed on September 9, 2008>
http://www.reliasoft.com/seminars/gencourses/rs540.htm

[14] I.J. Myung. 2002, "Tutorial on Maximum Likelihood Estimation", *Journal of Mathematical Psychology 47 (2003)* 90-100

[15] Maximum Likelihood Estimation <viewed on February 14, 2009> http://www.itl.nist.gov/div898/handbook/apr/section4/apr412.htm

[16] Maximum Likelihood Function <viewed on February 14, 2009> http://www.weibull.com/hotwire/issue33/relbasics33.htm

[17] Engineering Pump Handbook. 2002. *Pump Information*.

[18] Sahdev, Mukesh. 2008, "Centrifugal Pumps: Basic Concepts of Operation, Maintenance and Troubleshooting Part I", *The Chemical Engineer's Resource Page Presentation,www.cheresources.com*

[19] Izatul Husna Zakaria (2008), Industrial Internship Final Report in PETRONAS Penapisan Terengganu Sdn. Bhd., Universiti Teknologi Petronas, Bandar Seri Iskandar.

APPENDIX

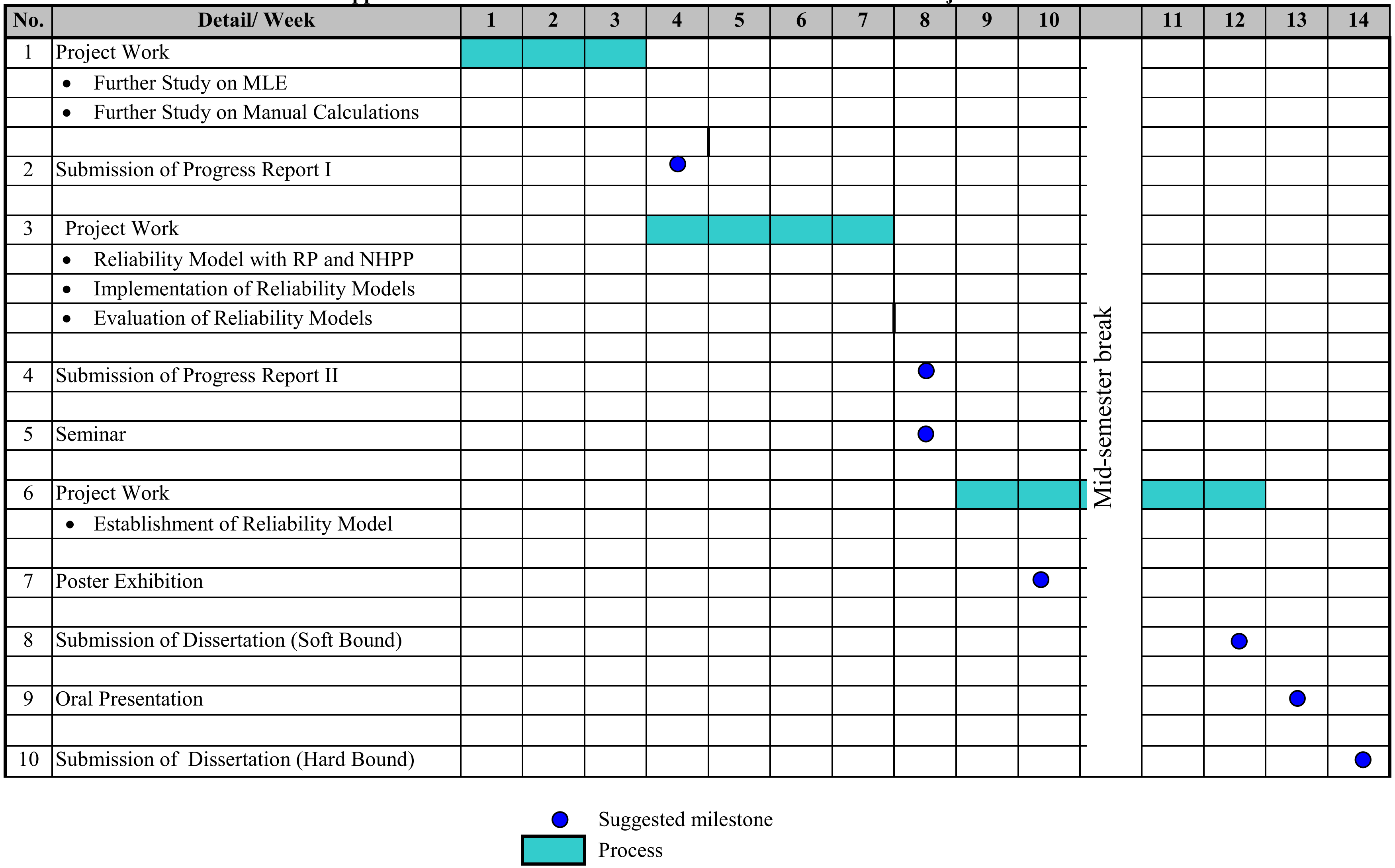
Appendix A1 : Gantt Chart for First Semester of Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10		11	12	13	14
1	Selection of Project Topic	■	■									Mid-semester break				
	• Confirmation of Topic Selection															
2	Preliminary Research Work		■	■	■											
	• Literature review on reliability system															
	• Tools and software required identified															
3	Submission of Preliminary Report				●											
4	Project Work					■	■	■	■							
	• Maintenance data collection					■	■									
	• Data Analysis							■	■							
5	Submission of Progress Report								●							
6	Seminar I								●							
	• Presentation															
7	Project work continues : Data Analysis								■	■	■		■	■	■	■
8	Submission of Interim Report Final Draft													●		
9	Oral Presentation														●	
10	Submission of Interim Report															●

● Suggested milestone

■ Process

Appendix A2 : Gantt Chart for Second Semester of Final Year Project



Appendix B : Historical Maintenance Data for Centrifugal Pumps

MACHINERY SUMMARY

Refinery : Plant : Type of Unit : Centrifugal Pumps

No	Equip. No	No and Categories of Repairs										
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
1	P 22101 A	25/04/01-3a,7f	13/10/02-2a									
2	P 22101 B	27/11/00-2a	18/04/01-2a									
3	P 22201 A	24/01/01-2a	**11/11/02-2b**									
4	P 22201 B	06/01/01-2a	17/04/01-2a									
5	P 22202 A	25/06/06-2a,b	16/03/08-2b,7c,3a									
6	P 22202 B	29/01/02-2b	14/12/03-3a7c	04/10/05-2a	09/10/06-2a,3a,3b,7a,11							
7	P 22204 A	10/06/01-3a	17/11/04-3a									
8	P 22204 B	26/11/07-2b,3a										
9	P 22302 A	22/09/05-2a										
10	P 22302 B	13/003/06-2a										
11	P 22303 A	20/11/00-2a	19/12/00-2a	23/12/00-2a	06/06/01-7f							
12	P 22303 B	01/02/01-2a	18/02/01-2a	23/06/08-2a								
13	P 22304 A	11/10/00-2a	05/09/03-2a	28/06/04-2a	20/12/05- Check	28/11/06-2a						
14	A22305P1A	27/10/00-2a	07/01/02-2a	07/01/02-2a								
15	A22305P1B	23/07/00-2a	31/07/00-2a	13/08/00-2a								

16	**A22305P2A**	20/08/00-2a										
17	**A22305P2B**	12/08/00-2a										
18	**A22305P3B**	18/02/08-2a										
19	**P 22352 A**	12/02/01-3b,7a	-5.994505495	22/12/02-7c	07/01/03-3c	04/06/03-7e, Modification	13/07/03-7h	07/08/03-3c	25/09/03-3c	07/10/03-3c,7c	25/03/04-3c,8	17/11/04-3c
20	**P 22352 B**	17/10/00-3b	20/10/00-3c	06/11/02-3b,7ac	12/03/04-3c,8	12/12/04-clean outer magnet	11/07/07-3b,7c	28/01/08-3b,7ac,12	04/09/08-3b,7b,7i			
21	**P 22401 A**	14/06/01-2a	19/06/06-2a	04/11/07-4,2a,3a								
22	**P 22502 A**	23/07/02-2a										
23	**P 22504 A**	02/07/02-2a										
24	**P 22505 B**	03/12/00-2a										
25	**P 22506 A**	28/08/06-3c										
26	**P 22507 A**	25/02/01-2a	14/06/01-2a	02/12/01-2a	19/06/02-2a							
27	**P 22507 B**	29/11/01-2a	11/06/02-2a	11/06/04-2a	04/03/05-2a							
28	**P 22509 A**	03/01/2008 - 7e,a,2a										
29	**P 22513 A**	11/05/06 - 2a,3a	04/07/06 -10	26/03/07 -10	27/09/07 -Internal coating							
30	**P 22513 B**	21/05/06 - 2a,3b,7b,7f	21/08/06 -10	30/05/07 - 10,2a,3b,7b,7f								
31	**P 22514 A**	15/01/03-3a,2b	23/03/03-2b	12/03/08-9								
32	**P 22514 B**	31/07/03-7h	27/04/06-3a,c									
33	**P 22515 B**	22/07/02-2b,3a										
34	**P 22518 A**	11/06/02-2a,3a										
35	**P 22518 B**	22/06/08-3a(IB)										

35	**P 22519 A**	07/01/01-2a	13/05/02-2a										
36	**P 22519 B**	16/10/01-2a	04/09/02-2a	**25/02/03-2a**	**02/12/07-2a**								
37	**P 22520 B**	30/07/01-2b,3a											
38	**P 22521 A**	07/04/03-2a	21/02/05-2c,7c	27/12/05-3a	10/12/06-12	02/12/08-12,7i,3a,b							
39	**P 22521 B**	22/02/05-2a,c	04/05/08-12,7i,3a										
40	**P 22522 A**	04/05/00-2a	**4/02/03-2b**	21/01/08-2a									
41	**P 22522 B**	24/12/01-2a											
42	**P 22523 A**	12/9/04-2a											
43	**P 22601 A**	10/06/01-2a	06/11/01-3a	24/11/01-2b,3a	05/12/07-2b,3a(OB)								
44	**P 22601 B**	05/10/00-2ab,3a											
45	**P 22602**	06/09/01-3a	06/10/05-3c	19/06/06-3b									
46	**P 22603 B**	18/06/01-2a	28/09/01-2a	26/01/06-2a	24/11/07-2a,3a(OB)								
47	**P 22603 C**	02/04/02-2a											
48	**P 22604 B**	04/01/02-2a											
49	**P 22605 B**	31/10/00-2a	30/04/07-2a										
50	**P 22606 A**	25/04/06-3a											
51	**P 22606 B**	10/09/01-3a	29/05/03-3a	18/01/05-3a									
52	**P 22701 A**	10/09/03-3a,b											
53	**P 22701 B**	27/03/03-2b	31/12/03-2b3c7i	10/02/04- 2b	19/09/05- 2b								
54	**P 22701 S**	03/12/00-3a	25/03/03-2b	02/07/08-3a									
55	**P 22702 A**	10/07/00-2a,7b	14/08/00-2a	13/11/07-2a,3a(IB)									
56	**P 22702 S**	01/10/01-2a,7e	12/12/07-2a,3a										
57	**P 22703 B**	07/05/02-2a											

58	**P 22706 A**	08/01/01-2a	01/07/01-2a	16/08/06-2a								
59	**P 22709 B**	05/02/02-3a	16/06/04-3a	06/05/08-3a								
60	**P 22710 A**	15/07/08-3a,2b										
60	**P 22715**	09/10/01-2a	02/09/02-2a									
61	**P 22802 A**	25/10/00-2a	18/12/00-2a									
62	**P 22802 B**	09/08/00-2a	07/03/01-2a	05/02/02-2a	23/09/02-2b	29/03/04-2b						
63	**P 22803 B**	07/04/02-3a										
64	**P 22804 A**	08/01/06-2a	27/06/07-2b,a,3a	12/07/07-2a,b								
65	**P 22804 B**	08/08/01-2a,3a	16/08/01-2a									
66	**P 22808 A**	16/09/01-2a	21/10/01-2a	23/12/02-2a	23/12/02-2a	12/09/04-2a	28/12/04-2a,7j					
67	**P 22808 B**	03/02/03-2a,7j	12/03/07-2a	21/06/07-2a	15/09/07-2a							
68	**P 22901 A**	10/03/02-2a	29/08/04-2a									
69	**P 22901 B**	08/05/00-2a	22/08/00-2a	29/11/00-2a,7f	18/09/01-2a	24/08/05-2a	14/12/05-2a					
70	**P 22902 B**	12/02/01-2a	28/08/06-2a,3a									
71	**P 28356**	08/10/03-2a	16/01/04-3c									