CHAPTER 1
INTRODUCTION

1.1 Background

All products produced by human are bound to failure after certain usage duration. These products can be divided into two groups, repairable and non-repairable system. For example, complicated machines like cars, airplanes are repairable systems, which can be repaired after failures occurred. For those simple components such as light bulb, tire and one time use camera, they are non-repairable systems. E.g., light bulb is non-repairable, when it burned; a new light bulb is required to replace the spoilt one.

With the advanced technology nowadays, lots of complicated machines and systems were invented for the sake of convenience for human being. These advanced machines may contain from few parts to millions of parts. The more complicated a machine is, the more parts it contains. With the greater amount of components in a system, the probability of the system to experience failure is greatly increasing as well. This project "Predicting the reliability of a repairable system with competing failure modes" is to predict the numbers of failures for non-identical failure modes after certain operating duration of the system. By predicting the reliability of a repairable system, a variation of preventive maintenance can be suggested and applied on repairable system to reduce the maintenance cost.

1.2 Problem Statement

Preventive maintenances (PM) are performed for the purpose of maintaining the facilities and equipments in desired operating conditions. At present, the common methods to determine when to perform PM are based on original equipment manufacturer (OEM) recommendations. These kinds of PM are usually known as time based PM. Start from the previous overhaul or replacement of a component, a time-based PM will be performed after a fixed period of time. Time based PM is rather simple, as it has just one parameter, which is the maintenance interval.

However, time based PM is not consistent due to different loads, conditions and usages. For example, the life span of car batteries depends on the types of vehicles, locations of the batteries and the driving styles of the drivers. Due to this, time based PM is not accurate as a system may break down prior to the fixed period for PM. On the other hand, an identical system may still perform at desired performance after the fixed period for PM.

For the samples in this research, the centrifugal pumps had experienced failures such as mechanical seal leaked, lubricant oil contaminated, abnormal sound and others failure which had caused halt to the production. Therefore, the author decided to study on the reliability prediction of centrifugal pumps.

1.3 Objectives

The objectives of this research are:

- To analyse the failure data of centrifugal pumps to determine the reliability of the components/parts.

- To develop a model for failure prediction of the centrifugal pumps.

1.4 Scope of Study

Repair data of centrifugal pumps were collected from a refinery. The raw data contained large amount of details such as pump types, processed fluid types, operation temperature, etc. Any operation conditions will have a certain degree of impact on the reliability. To narrow the scope for this project, centrifugal pumps listed in APPENDIX I was selected as the samples for this research. After segregation, the sample size for this research became 47 out of 250 from the original data.

In this research, the main focus falls on the prediction of the reliability/mean time between failures (MTBF) of centrifugal pumps. Reliability/MTBF of the pump components were also determined to provide a clearer perception in depth.

Probabilistic model, Generalized Renewal Process (GRP) was applied as the basis of this research due to its flexibility to be able to apply on any distributions. Compare to other researches with sample size of more than 2000, the sample size for this research is considered very small. Due to this, Weibull distribution was applied as it can provide fairly accurate failure analyses and failure forecasts with extremely small data samples.

For the reliability modelling, Reliability Block Diagram (RBD) was applied. The model was based on the Weibull parameters obtained from the Weibull distribution. The model was verified by comparing the actual failure rates and the predicted failure rates. Further benchmarking with other researches was also included in this project.

1.5 Significant of The Work

The outcome of this project is to provide estimation on the optimal part replacement time. High accuracy and precision in predicting and propose the optimal replacement time for the parts is very critical in ensuring a system do not break down during its operation, and fully utilized the life span of the parts. With these advantages, the maintenance cost of the system can be reduced and lost due to system failure can be minimized.

1.6 Feasibility

The historical maintenance data was obtained from a petrochemical plant and the software such as Weibull++7 and BlockSim 7 were provided by UTP. Hence, this project is feasible before it was started. Now, it was successfully done.

CHAPTER 2
LITERATURE REVIEW

A system can be defined as a device which is assembled by two or more components and which is able to perform one or more functions. Most of the systems will fail during operation and need to be repaired to continue perform their intended tasks. The failing time of these systems can be predicted by using statistical models and modalities can be set in place to repair the system at the minimum cost [1].

All system can be categorized into 2 groups, repairable and non-repairable. In this research, the repairable system will be focused. Repairable system is one which can be restored to get back to work fully by any action such as parts replacements or changes to adjustable settings other than replacement of the entire system [2].

In repairable system, a system that experienced failure can either be repaired or replace the components that cause the failure, in order to restore its function and continue performs its intended tasks. Due to the complexity of complex systems such as airplanes, the optimizations of the system repair/replacement strategies become more complex. The repair strategies not only involve deciding when to replace, but also when to repair, which in itself creates another issue to be addressed, that is, to what extent to repair the system [3].

The term failure rates or hazard rates are not suitable for a repairable system, and these terms normally only apply to the first failure times of a population of non repairable components. As in non-repairable system, the individual failed items are removed permanently from the system. While in a repairable system, the failed components can be replace to repair the system. Hence, the rate of the failures occur on a repairable system is more suitable to define as Rate of Occurrence of Failure (ROCOF) or “repair rate” [4].

In a complex system, there are many components within the system. Imagine a car as the whole system; the components will be the chassis, engine, timing belt, tires, etc. Any failure in the components may lead to malfunction of the system. The component’s renewal process is governed by distribution function. When the car fails due to the failure in any of its component, the component will be replaced. The component will work well as good as new.

Although the system had been repaired, but there are others components in the car still operating in different ages. Hence the performance of the car may not work as good as new although one of the components had been replaced by an identical part and it works as good as new. Due to this, the distribution theory cannot be applied to the failure of the whole system and it only can be associated with a single event, in this case, a single failure.

There are 3 types of preventive maintenance, namely imperfect preventive maintenance (IPM), perfect preventive maintenance (PPM) and failed preventive maintenance (FPM). Preventive maintenance (PM) is essential in complex systems because it reduces downtime and breakdown risk [5].

For the purposes of assessing parametric distributional assumptions, probability plots are the popular graphical tools. They are particularly well suited for location-scale families or those that can be transformed to such families. The underlying location and scale parameters can be estimated by fitting a line through the plot when it indicates an appropriate conformity to the assumed family. This method is useful with censored data and it is used as the default estimation method by some statistical software [6].

2.1 Types of Probabilistic Models

Probabilistic Models are important applications to reliability analysis. They are often used to project (extrapolate) failure rates. So it is very important to "test" whether the models chosen fit with the given data. Different failures have different kinds of distribution which can be illustrated by different kinds of reliability models. As shown at figure 2.1 below, these 3 major models are used on different levels of reparability.

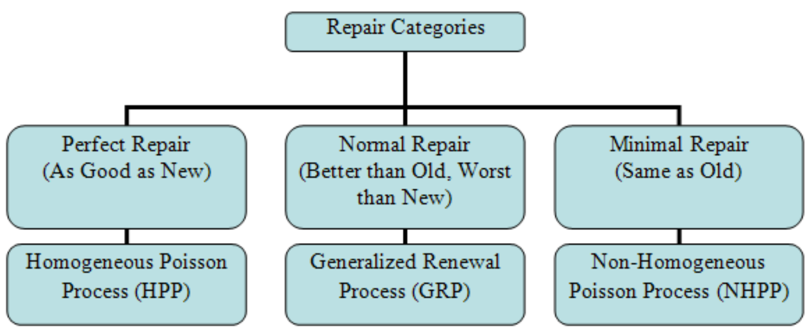
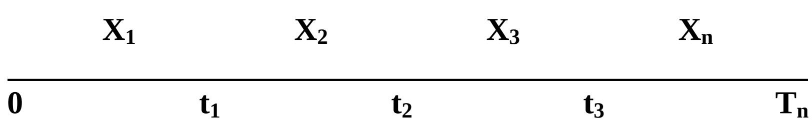


Figure 2.1: Categories of Repair [7]

2.1.1 Homogeneous Poisson Process (HPP)

Known as Ordinary Renewal Process (ORP), a Homogeneous Poisson Process model is widely used on repairable systems in the industry due to its simplicity. Most systems usually exhibit a failure rate that initially decreases to become constant for a while, and then finally increase. This decreasing-constant-increasing form of failure rate is known as the bathtub failure-rate curve. HPP is able to apply to the portion of the curve and it becomes the most used probabilistic model for the reliability estimation and planning. HPP is characterized by a rate parameter λ [4].

Assuming a component A is installed in the subsystem at time = 0. When component A is experienced failure, another identical component is instantly replaced it. Every time a new component is replaced, the performance of the subsystem will restored back to “As good as new” condition. Time to failure of a component is determined by the distribution and each distribution is always related to only 1 kind of failure. The sequence of failures for the component forms a random process which is called a renewal process. Below shows the component life $\mathbf{X_j}$ and time to failure $\mathbf{t_j}$**.** Every component life $\mathbf{X_j}$ is governed by same distribution, which is F(x).



A single lifetime is governed by a distribution, for example, a Weibull distribution and it is always associated only by one event. Distribution F(x) is the probability of a component will experience failure within time x. When component A fails, a similar component, B is replaced. The probability of the component B life will fail within time x by follow the same distribution function, F(x).

Cumulative distribution function (CDF) can be represented by:

$$F(x) = 1 - e^{-\lambda x^{\beta}} \qquad \text{(Eq. 1)}$$

Density function of a distribution is:

$$f(x) = \frac{d}{dx} F(x) \qquad \text{(Eq. 2)}$$

Hence, the density function for Weibull distribution is:

$$f(x) = \lambda \beta x^{\beta-1} \bullet e^{-\lambda \beta x} \quad \text{(Eq. 3)}$$

Failure rate can be represented by:

$$h(x) = \frac{f(x)}{1 - F(x)} \quad \text{(Eq. 4)}$$

Hence, the failure rate for a Weibull distribution can be represented by:

$$h(x) = \lambda \beta x^{\beta-1} \quad \text{(Eq. 5)}$$

From Equation 5, it can be concluded that the failure rate is increasing for $\beta > 1$, decreasing for $\beta < 1$ and constant for $\beta = 1$ [7].

2.1.2 Non-Homogeneous Poisson Process (NHPP)

One of the key assumptions of a NHPP model is that upon a failure, the system is restored to the condition right before the failure, which is known as Same-As-Old repair assumption. The Same-As-Old repair assumption is appropriate for a repairable system such as an automobile, since only a component of the automobile is being replaced at a time; the automobile will be restored back to the condition right before the failure [3].

In reality, repair on most of the systems are only enough to get the system operational again. For example, if the timing belt breaks, a new timing belt will be replaced. When the battery failed to works, a new battery will be replaced with no further maintenance. This will be the concept for minimal repair. For a complex system, many potential failures may occur. Hence, a single repair on the failure will not improve the reliability significantly.

As a conclusion, when only minimal repair is done on a complex system without further maintenance, the reliability of the system will be same as just before the failure occurred. The reliability for minimal repair can be predicted by using NHPP model. Below is the mathematical definition of NHPP.

1) $N(0) = 0$
2) Non-overlapping increments are independent
3) $P(N(t + h) – N(t) = 1) = \lambda(t)h + o(h)$
4) $P(N(t + h) – N(t) > 1) = o(h)$

For all t and where $\frac{o(h)}{h} = 0$ as $h \to 0$

Where,

N (t) is the number of failures during time t
λ (t) is the intensity function.

2.1.3 Generalized Renewal Process (GRP)

Perfect Repair assumes that after a repair, the system will returns to the as-good-as new condition, while NHPP assumes that the system will returns to Same-as-old condition. Due to the imperfection and flaws in traditional probabilistic models such as HPP and NHPP, a more accurate analysis and prediction is needed. Kijima and Sumita had proposed a new probabilistic model to address all after-repair states called ‘generalized renewal process’ (GRP). [8] From the analytical results, it shown that GRP have significantly lower error in statistical warranty forecasting compared to HPP and NHPP.

GRP is able to perform the estimation of repair effectiveness in certain conditions, which is impossible for HPP and NHPP. GRP are able to apply on almost all kinds of distributions, including the ability to perform what HPP and NHPP capable of [9].

2.2 Weibull Distribution

There are many variations of Weibull models, such as 1 parameter, 2 parameters, 3 parameters and mixed Weibull models. The most general Weibull PDF is given by the 3 parameters Weibull distribution expression and shown at Equation 6.

$$f(T)=\frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-(\frac{T-\gamma}{\eta})\beta} \text{ [10]} \qquad \text{(Eq. 6)}$$

The 3 parameters are,

1. β , a shape parameter to the distribution
2. η , a scale parameter to the distribution
3. γ , a location parameter to the distribution

Where

$f(T) \geq 0$,

$T \geq 0$ or γ

$\beta > 0$,

$\eta \geq 0$

$-\infty < \gamma < \infty$

Weibull distribution is widely used in reliability and life data analysis due to its versatility. Weibull distribution can be used to model a variety of life behaviours depending on the values of the parameters. The distribution characteristics of the PDF curve, the reliability and the failure rate are governed by all the 3 parameters. The effect of each parameter to the distribution will be shown in Figure 2.2, 2.3 and 2.4.

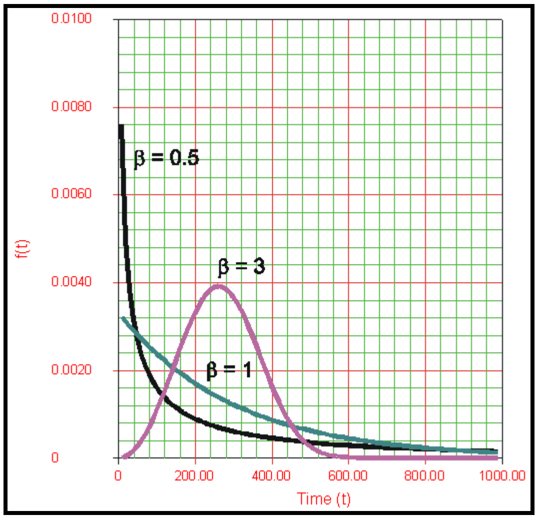


Figure 2.2: Effect of β to Weibull PDF

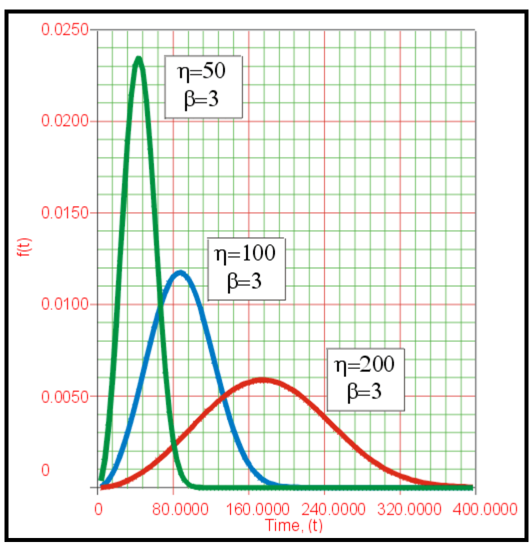


Figure 2.3: Effect of η to Weibull PDF

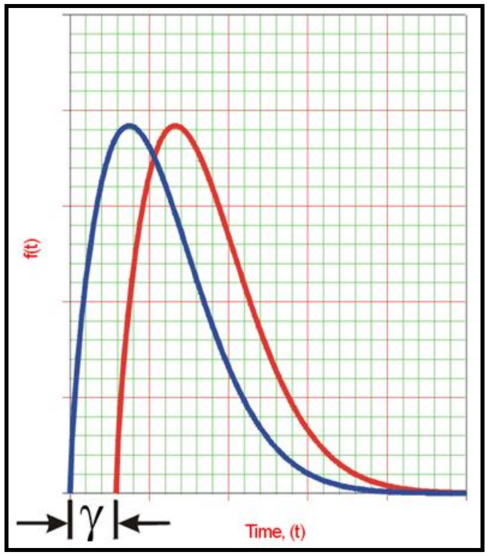


Figure 2.4: Effect of γ to Weibull PDF

The Weibull reliability function can be express as:

$$R(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \quad [10] \qquad \text{(Eq. 7)}$$

The Weibull conditional reliability function can be express as:

$$R(t \mid T) = \frac{R(T+t)}{R(T)}$$

$$= \frac{e^{-\left(\frac{T+t-\gamma}{\eta}\right)^{\beta}}}{e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}}$$

$$R(t \mid T) = e^{-\left[\left(\frac{T+t-\gamma}{\eta}\right)^{\beta} - \left(\frac{T-\gamma}{\eta}\right)^{\beta}\right]} [10] \qquad \text{(Eq. 8)}$$

The MTBF of Weibull distribution can be express as:

$$\overline{\mathrm{T}} = \gamma + \eta \bullet \Gamma\left(\frac{1}{\beta} + 1\right) \text{ [10]} \qquad \text{(Eq. 9)}$$

Where $\Gamma\left(\frac{1}{\beta} + 1\right)$ is the gamma function evaluated at the value of $\left(\frac{1}{\beta} + 1\right)$. This function is provided within Weibull++ for calculating the values of $\Gamma(n)$ at any value of *n*. In Weibull++, this function can be calculated by using the Quick Statistical Reference. The gamma function is defined as:

$$\Gamma(n) = \int_0^\infty e^{-x} x^{n-1} dx \qquad \text{(Eq. 10)}$$

For the 2 parameters Weibull distribution which only consists of parameters β and η, the MTBF are reduced to:

$$\overline{\mathrm{T}} = \eta \bullet \Gamma\left(\frac{1}{\beta} + 1\right) \qquad \text{(Eq. 11)}$$

In this research, Generalized Renewal Process (GRP) was chosen as the intent of study due to its versatility and applicability to various failure processes while Weibull distribution is applied to perform analysis.

2.2.1 Parameter Estimation

Weibull parameters are critical components in modelling the characteristic of the Weibull distribution, so it is crucial in the parameter estimation procedure. Parameter estimation is a method to evaluate how well a model fits with the data of the samples. There are 2 basic methods of parameter estimation; they are least-squares estimation (LSE) and maximum likelihood estimation (MLE). MLE is a popular statistical method used for fitting a statistical model to data and used for estimating the model's parameters. In the point of view of most statisticians, LSE is merely an approach that is primarily used with linear regression models. This is due to the optimal properties in estimation such as efficiency, sufficiency, consistency and parameterization invariance which can only be obtained from MLE and not from LSE.

Many models in statistics are developed based on MLE such as, chi-square test, the G-square test, Bayesian methods, inference with missing data, modelling of random effects, etc. Maximum likelihood estimation is applied to pick the values of the model's parameters that would make the data "more likely" than any other values of the parameters.

According to In Jae Myung, he had provided an example of MLE for the two functions, power and exponential. In his research, he found that the exponential model fit better than the power model. Equations 12 and 13 below show the exponential model in applied by him in MLE [11].

$$p(w,t) = w_1 \exp(-w_2 t) \qquad (w_1, w_2 > 0) \ [11] \qquad \text{(Eq. 12)}$$

Where,

$p(w,t)$	The model's prediction of the probability of correct recall at time t
$w = (w_1,...,w_k)$	A vector defined on a multi-dimensional parameter space

The PDF of the binomial distribution for arbitrary values of w and n can be expressed as:

$$f(y \mid n, w) = \frac{n!}{y!(n-y)!} w^{y} (1-w)^{n-y} \text{ [11]} \qquad \text{(Eq. 13)}$$

Each observed proportion y_i is obtained by dividing the number of correct responses (x_i) by the total number of independent trials (n), $y_i = \frac{x_i}{n}$ $(0 \le y_i \le 1)$. Noted that each x_i is binomially distributed with probability $p(w,t)$ so that the PDF for the exponential model are obtained as Equation 14:

$$f(x_i \mid n, w) = (1 - w_1 \exp(-w_2 t_i))^{n-x_i} \text{ [11]} \qquad \text{(Eq. 14)}$$

Where,

$x_i = 0,1,\ldots,n$

$i = 1,2,\ldots,m$

2.3 Reliability Block Diagram (RBD)

Reliability Block Diagram, known as RBD is used to model the system reliability on the complicated and large system. RBD approach using block diagrams to shows the reliability relations of each components in the system that contribute to the total reliability of the system. Each component of the system will be represented by a block and will be interlink with other blocks. The simplest RBD system can be configured in either series or parallel configuration. Some of the more complex systems will have the combination of both configurations. All RBD should have one input node and one output node.

2.3.1 Series Configuration

In the basic series configuration, all of the components in the system must be able to work in order to keep the system performing. If any one of the component experienced failure to perform, the entire system will experienced failure or forced to shut down. In short, all N units of the system must succeed for the system to succeed and the reliability of this system can be represented by Equation 15:

$$R_{system} = R_A \bullet R_B \bullet R_C \bullet \ldots \bullet R_N \qquad \text{(Eq. 15)}$$

Where R_i = The reliability of unit i

From the formula, it can conclude that the reliability of a series system will not exceed the reliability of its weakest components. And the reliability of the system will diminished with the additional numbers of components in the system. Figure 2.5 below shows an example of RBD in basic series configuration

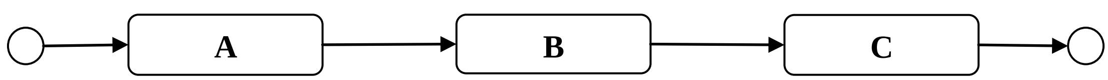


Figure 2.5: RBD in basic series configuration

Figure 2.6 below is an example of the system that can be configured in series is the computer system, which consists of Monitor, CPU, and Keyboard

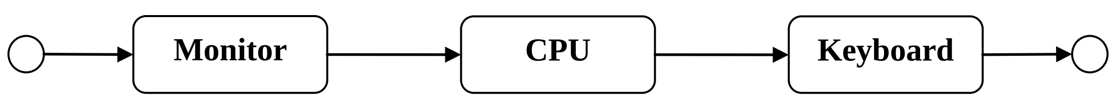


Figure 2.6: RBD of a computer system in series configuration [10]

2.3.2 Parallel Configuration

In basic parallel configuration, the system will continue to perform although some of the components in parallel experienced failure. Units in parallel are also known as redundant units which will help in increasing the system reliability. In short, at least one of the units must succeed for the system to succeed. The reliability of a system in parallel configuration can be represented by Equation 16:

$$R_{system} = 1 - [(1- R_A) \bullet (1- R_B) \bullet (1-R_C) \bullet \ldots \bullet (1-R_N)] \qquad \text{(Eq. 16)}$$

Where R_i = The reliability of unit i

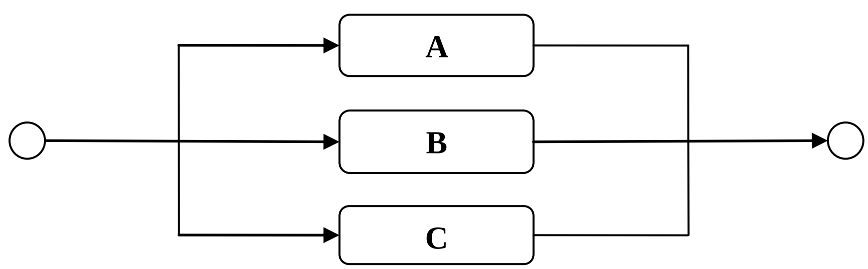


Figure 2.7: RBD in basic parallel configuration

Figure 2.7 at above shows an example of RBD in basic parallel configuration. While in the figure 2.8 shows an example of the system that can be configured in parallel is the RAID computer hard drive systems, where several hard disks were being used in a server to store the important data for the company.

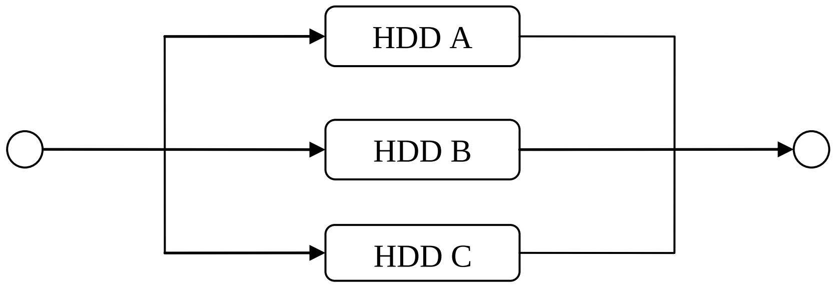


Figure 2.8: RBD of a RAID system in basic parallel configuration [10]

Parallel system is more reliable than the series system, and this can be proven by the following example with 3 identical elements arranged in series and parallel configurations.

Assume,

$R_A = R_B = R_C = 0.95$

- Series configuration

  $R_{system} = R_A \cdot R_B \cdot R_C$

  $= 0.95 \cdot 0.95 \cdot 0.95$

  $= 0.857375$

- Parallel configuration

  $R_{system} = 1 - [(1- R_A) \cdot (1- R_B) \cdot (1-R_C)]$

  $= 1- [(1-0.95) \cdot (1- 0.95) \cdot (1-0.95)]$

  $= 0.999875$

Hence, with additional numbers of components in the parallel configuration systems, the reliability will be increased as well. Due to characteristic of the parallel system, adding redundancy in parallel becomes one of several methods to improve the reliability of a system, especially in aerospace industry and others industry where reliability is one of the most critical element [10].

2.3.3 Combination of Series and Parallel

In larger system, a basic series or a basic parallel configuration may not appropriate represent the system but the combination of both will perform the tasks well. In this case, the overall system reliability can be obtained by calculating the reliabilities of the individual series and parallel parts and combining them. Figure 2.9 at below is an example of the combination of series and parallel system [10].

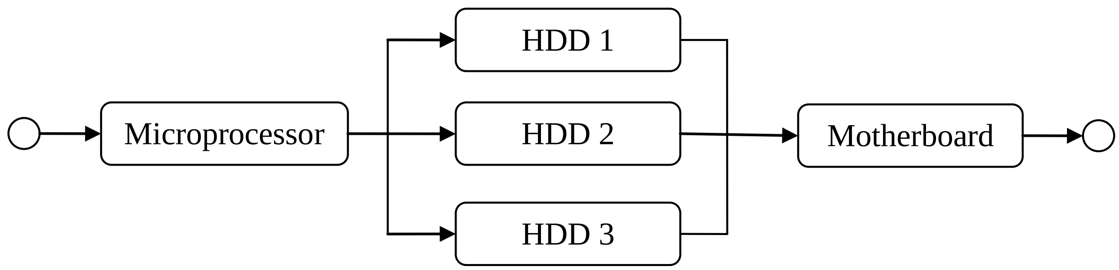


Figure 2.9: RBD of a CPU system in combination configuration

Assuming

$R_{Microprocessor} = 0.8$

$R_{HDD\,1} = R_{HDD\,2} = R_{HDD\,3} = 0.95$

$R_{Motherboard} = 0.7$

Firstly, the reliability of the RAID hard disk system is calculated. (Parallel Configuration)

$$\begin{aligned} R_{HDD} &= 1 - [(1- R_{HDD\,1}) \bullet (1- R_{HDD\,2}) \bullet (1-R_{HDD\,3})] \\ &= 1- [(1-0.95) \bullet (1- 0.95) \bullet (1-0.95)] \\ &= 0.999875 \end{aligned}$$

Then, the overall system reliability is calculated. (Series Configuration)

$$R_{system} = R_{Microprocessor} \cdot R_{HDD} \cdot R_{Motherboard}$$
$$= 0.8 \cdot 0.999875 \cdot 0.7$$
$$= 0.55993$$

2.3.4 Complex Configurations

A complex system looks similar to combination system, but the components in complex system cannot be clearly categorized into series or parallel configuration. Figure 2.10 below shows an example of complex system.

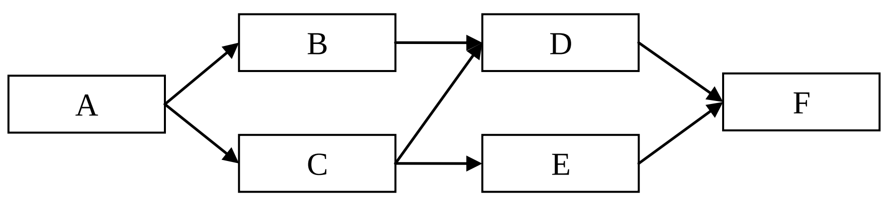


Figure 2.10: RBD of a complex system

Due to the complexity, the reliability of a complex system cannot be calculated using the method shown in the previous systems. Hence, several different approaches will be applied to obtain the reliability of the complex systems. These approaches are decomposition, event space and path-tracing. Due to the complicated and tedious process in these 3 methods, further explanations on these methods will not be included in this report [10].

2.3.5 K-Out-Of-N Parallel Configuration

Same like parallel configuration, K-out-of-N configuration is also in parallel form with redundancy units. What differ K-out-of-N from the basic parallel configuration is K-out-of-N requires K units out of N components in parallel to be succeeded for the system to succeed. For example, a 4 engines aeroplane that needs at least 2 engines to function to continue its flight has a 2-out-of-4 configuration.

If the components in the system are identical and independent in terms of failure distribution, the reliability of the system can be calculated by using Equation 17. The more components that are required to be succeeded for the system to succeed, the lower the reliability of the system will become.

$$R_S(k, n, R) = \sum_{r=k}^{n} \binom{n}{r} R^r (1 - R)^{n-r} \quad \text{(Eq. 17)}$$

Where:

- n = Total number of units in parallel.
- k = Minimum number of units required for system success.
- R = Reliability of each unit.

In the case where the components are non-identical and the reliability of the components is affected by the others in the system, the reliability of the system had to be calculated by another method. This method is called event space method and it is one of the methods used in solving the reliability of complex configuration [10].

2.3.6 Load Sharing Container

In the previous cases, most of the components in the system are independent from others, which indicated that the reliability of the components is not affected by each others. However, in some cases where the components are sharing the same load, the reliability of the components will be affected by each others. A 6-wheels bus has 2 tyres at the front, while 4 tyres at the rear side. If one of the tyre at rear side burst while the bus are travelling, the tyre next to the burst tyre will need to bear the extra load from the burst tyre, which in turn will double the burden from the original condition. In such case, the remaining tyres will bear extra load, thus its reliability will be reduced. Figure 2.11 at below shows an example of RBD of load sharing container.

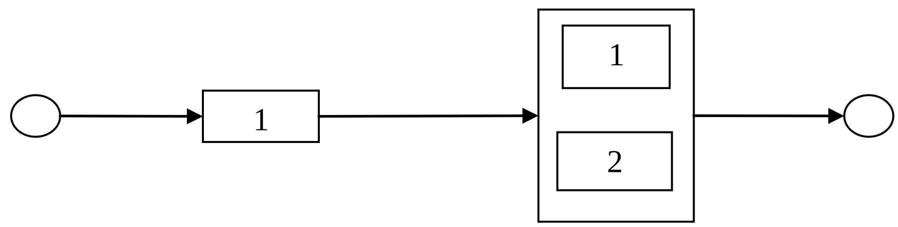


Figure 2.11: RBD of Load Sharing Container

In the figure 2.11, the system will have a reliability of $R_{System} = +R_{LS} \bullet R_1$, with

$$R_{LS} = R_1(t,S_1) \bullet R_2(t,S_2) + \int_0^t f_1(x,S_1) \bullet R_2(x,S_2) \bullet \left(\frac{R_2(t_{1e} + (t-x), S)}{R_2(t_{1e}, S)} \right) dx$$
$$+ \int_0^t f_2(x,S_2) \bullet R_1(x,S_1) \bullet \left(\frac{R_1(t_{2e} + (t-x), S)}{R_1(t_{2e}, S)} \right) dx \qquad [10] \qquad \text{(Eq. 18)}$$

Where

$S_1 = P_1 S$

$S_2 = P_2 S$

And

- S is the total load
- P_1 and P_2 are the portion of the total load that each unit supports
- S_1 and S_2 are the portions of the load that unit 1 and unit 2 must support when both units are operational.
- t_1 is the equivalent operating time for unit 1 if it had been operating at S instead of S_1 [10].

2.3.7 Standby Container

In Standby configuration, some blocks are in idle mode until they are needed for the task. The idle standby unit will be activated and switched to perform the task when there is a unit in parallel with the standby unit failed. Similar to the parallel configuration, the standby container is also in parallel configuration, except the standby unit will be under a light load or no load condition while not needed. An example of standby unit is the spare tyre of the car. When one of the tyres was punctured, the spare tyre will be switched for temporary usage, while the punctured tyre will be fixed or a new pairs of tyres will be replaced during the temporary period.

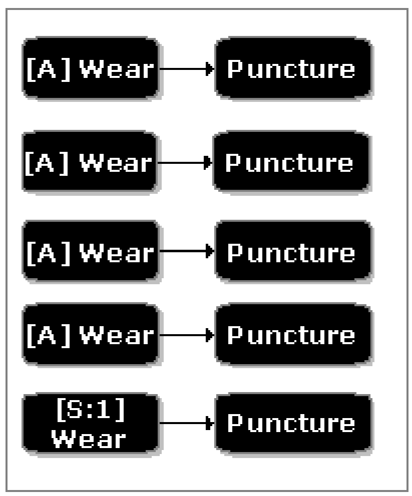


Figure 2.12: RBD of standby container of tyre [10]

Figure 2.12 at above is an example of RBD with standby container of tyre with 4-out-of-5 configuration. There are 5 tyres, with 4 active tyres and 1 standby tyre. The reliability of a simple standby container with one active component and one standby component can be calculated by using Equation 19:

$$R(t) = R_1(t) + \int_0^t f_1(x) \bullet R_{2;SB}(x) \bullet \frac{R_{2;A}(t_e + t - x)}{R_{2;A}(t_e)} dx \ [10] \qquad \text{(Eq. 19)}$$

Where:

- R_1 = Reliability of active component
- f_1 = PDF of the active component
- $R_{2;SB}$ = Reliability of the standby component when in idle/standby mode
- $R_{2;A}$ = Reliability of the standby component when in active mode
- t_e = The equivalent operating time for the standby unit if it had been operating at an active mode, such that

$$R_{2;SB}(x) = R_{2;A}(t_e)$$

2.4 Centrifugal Pump

2.4.1 What is Centrifugal Pump?

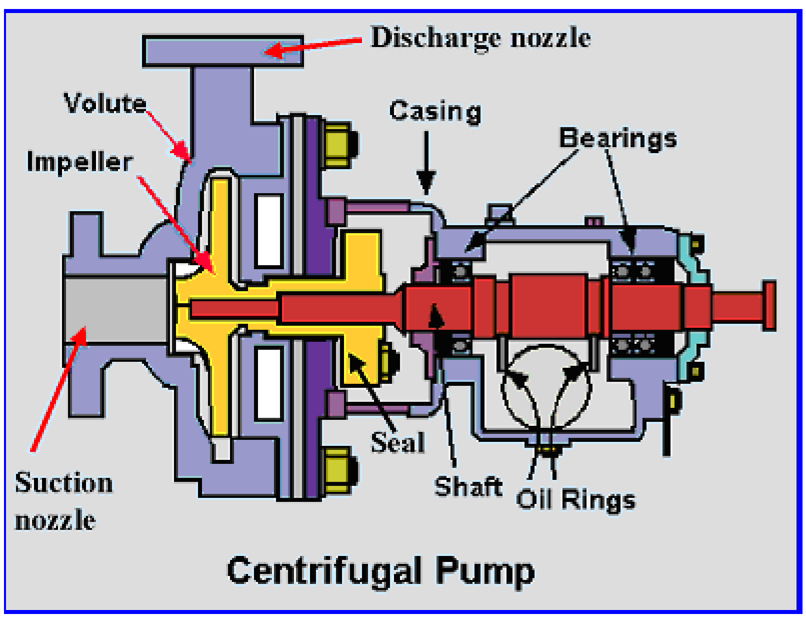


Figure 2.13: Centrifugal Pump [12]

Centrifugal pump, also known as C pump, being one of the simplest equipment in the process plant, is commonly used in the handling and mixing of oilfield fluids. C pump convert energy from a driving input (an electric motor or a turbine) into kinetic energy and then into pressure energy of the fluid that is being pumped. An impeller is used to convert the driver energy into the kinetic energy, while the diffuser or volute is used to convert the kinetic energy into the pressure energy of the fluid. Figure 2.13 at above shows an overview of centrifugal pump.

Centrifugal force will be produced by the rotary motion of the impeller together with a shaped housing or volute of the pump. The centrifugal force generated will discharge fluids from the pump. Generally, centrifugal pumps are used to perform in high volume, low-output- pressure conditions. Compared to positive displacement pumps, the centrifugal pumps can be used to control the flow easier, completely closed off the flow by using valves on the pump discharge manifold while the pump is still operating.

As shown on Figure 2.13, a centrifugal pump has two main components, which are stationary component and rotating component. The stationary components consist of a casing, casing cover, and bearings, while the rotating components consist of an impeller and a shaft. The rotating components are the main components in developing pressure, while stationary components served as the frame and the supporting structures of the centrifugal pump.

The pressure developed at the discharge nozzle is almost equal to the velocity energy converted at the impeller. There are 2 equations which can be used to calculate the pressure developed and the velocity converted.

$$H = \frac{v^2}{2g} \quad \text{(Eq. 20)}$$

Where,

- H = Pressure developed at discharge nozzle (In terms of height of liquid in ft.)
- v = Velocity at the impeller (ft/sec)
- g = Gravitational acceleration (32.2 ft/sec^2)

$$v = \frac{NxD}{229} \quad \text{(Eq. 21)}$$

Where,

- N = RPM of the Impeller (rev/min)
- D = Diameter of the Impeller (inches)

From Equations 20 and 21, it clearly shows that the pressure developed at the discharge nozzle is dependant to 2 parameters; they are the sizes and the rotational speeds of the impeller [12, 13].

2.4.2 Pump as a Repairable System

Pump is a repairable system, and certain failures can be happened to the pump during its operation life. Due to this, it is important for the pump users to examine pump repair records and MTBF (mean time between failures) for any further improvement on the pump technology. For the sake of convenience, pumps failure statistics are often translated into MTBF (installed life before failure). In October 2008, an article on pump statistics is posted on the website of Maintenance Technology, *www.mt-online.com*. The author had summarized the articles and the details are discussed in the paragraphs below.

During the early 2000s, many best-practices firms divided that number of the pumps installed at their plants by the number of repair incidents per year. In a reliability-focused U.S. refinery with 1200 installed pumps and 156 repair incidents in one year, the MTBF is (1200/156) =7.7 years. The refinery would count a repair incident as the replacement of any parts, regardless of its cost. The replacement of lube oil was not counted as a repair in their statistical analysis.

By using the same measurement strategy, and from published data and observations made in the course of performing maintenance effectiveness studies and reliability audits in the late 1990s and early 2000s—the MTBF Table have been estimated. The data used to generate the Table 2.1 is from a plant with more than 2000 installed pumps, with an average sizes around 30 hp.

Table 2.1: Pumps MTBFs [14]

ANSI pumps, average, USA:	2.5 years
ANSI/ISO pumps average, Scandinavian P&P plants:	3.5 years
API pumps, average, USA:	5.5 years
API pumps, average, Western Europe:	6.1 years
API pumps, repair-focused refinery, developing country:	1.6 years
API pumps, Caribbean region:	3.9 years
API pumps, best-of-class, U.S. Refinery, California:	9.2 years
All pumps, best-of-class petrochemical plant, USA (Texas):	10.1 years
All pumps, major petrochemical company, USA (Texas):	7.5 years

Based on the lifetime of the pump components being achieved in practice in 2000, combined with the known "best practice" as stated in the available reference texts, the target pump component lives are recommended and shown in Table 2.3. Pump seal was always hot issues in the past due to its short life span; hence, a lot of efforts had been put on by manufacturer to increase the quality and MTBF of seal. The average MTBF of seal had been increased from 6 months to 70 months recent. According to Gordon Buck, John Crane's chief engineer for Field Operations in Baton Rouge, LA had concluded the suggested the seal target MTBF and it is shown in Table 2.2.

Table 2.2: Suggested Seal Target MTBF by Gordon Buck [14]

Target for seal MTBF in oil refineries	
Excellent	>90 months
Very good	70/90 months
Average	70 months
Fair	62/70 months
Poor	<62 months

Table 2.3: Realistic Target Pump and Components Lives [14]

		Refineries	Chemical and other plants
SEALS	Excellent	90 months	55 months
	Average	70 months	45 months
COUPLINGS	All plants	Membrane type	120 months
		Gear type	> 60 months
BEARINGS	All plants	Continuous operation:	60 months
		spared operation	120 months
PUMPS	Based on series system calculation		48 months

In the article, it emphasized that many plants are achieving these levels of installed lives. In fact, if ones wish to reach these pump lives, the pump components must be operating at the highest levels. An unsuitable seal with extremely low or high lives have great affection on the MTBF of the pump system, so the same with an under-performing coupling or bearing [14].

The article is intending to provide pump failure statistics on relatively inexpensive ANSI and ISO pumps, as well as API-compliant refinery centrifugal pumps. There was other articles/analysis which provided with different results as the one shown previously. This may due to different conditions, brands, technologies, etc. However, the author chose to use the results shown previously as the benchmark because these results are based on samples with more than 2000 pumps operated in the late 1990s to the early 2000s.

With the available data by others researchers, the author is interested in using centrifugal pump as the sample of research. While the available results from the article can be used to benchmarking with the samples used.

2.5 Oil Refinery

Oil refineries core business is to refine indigenous crude oil from off shore into high-value petroleum products for domestic and exports markets. The raw data samples are obtained from a oil refinery which consist of a Crude Distillation Unit (CDU) that is capable of processing 40,000 BPSD of Crude Oil, a Naphtha Hydrotreating Unit (NHTU) and a Catalytic Reforming Unit (CRU).

Besides this, the refinery also consists of a Condensate Fractionation Unit (CFU) that is capable of processing 63,500 BPSD of condensate. Some locations in the refinery were being used to produce Heavy Naphtha, Light Naphtha, Mixed LPG, Kerosene and Diesel. The rests of the places were being used to produce Paraxylene, Benzene, Heavy Aromatic and Raffinate [15].

In this research, the author had obtained the failure data of centrifugal pumps that were being used in the selected refinery which had started to operate since 1st Jan 2000 as the samples for this research.

CHAPTER 3
METHODOLOGY

The objective of this research is to analyze the failure data provided and predict the reliability of the system with competing failure modes. As for the Gantt Charts for this project, please refer to APPENTIX II and APPENTIX III.

3.1 Analysis Technique

In the research, the graphical analysis method is used. Graphs were draw to build models. There are 2 reliability software that were used in this research, they were Weibull++7 and BlockSim 7.

- Weibull++ 7
  Weibull++ 7 was used to determine the failure distribution of the pump components and perform parameter estimation to obtain the best parameters.

- BlockSim 7
  BlockSim 7 was used as a tool to perform reliability block diagram (RBD) approach to obtain the reliability of the pump system based on the components parameters from Weibull++ 7.

Microsoft Excel was used as the tool to segregate and sort the raw maintenance data before transferring the data to Weibull++ 7 and BlockSim 7.

3.2 Flow Chart of Project Execution

The planned work flow for the project is shown in Figure 3.1 at below.

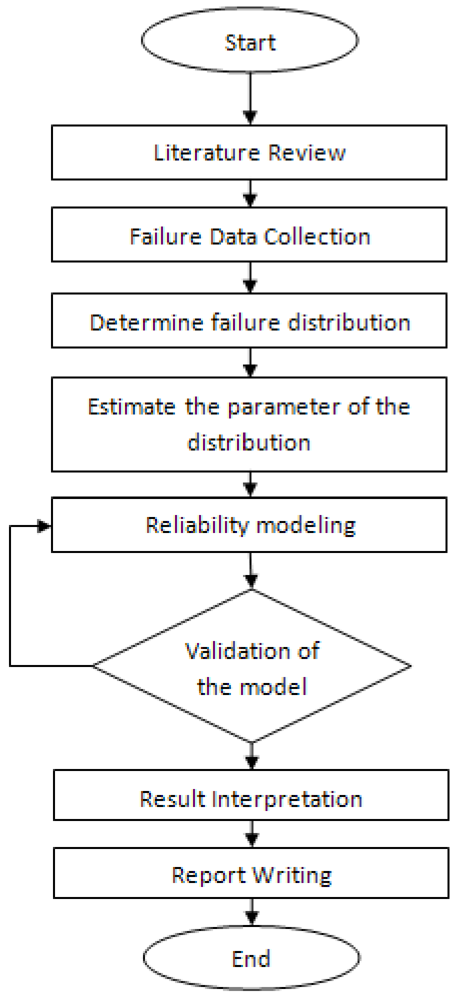


Figure 3.1: Flow chart of reliability modelling

I. Segregation of failure data

After collected the historical maintenance data and pump's specifications from PPTSB, segregation of data had been done by the author. The maintenance data collected contains the maintenance history from the selected refinery. The author had segregated out the failure data of certain pumps to narrow the scope of study. Informations included in the pump's specifications database are details such as the process fluid, operating temperature, RPM, etc. With the available data on hand, the author had calculated the time to failure and time to event based on the conditions below:

1. All of the pumps were started to operate on 1st Jan 2000.
2. The collection of maintenance data stopped at 1st February 2009.

II. Identify the distribution

The failure distribution for each component of the pump was determined after the segregation of data. The failure distribution can be in the form of Exponential, Extreme Value, Lognormal, Weibull, etc. By using Weibull analysis tool, the failure distribution was determined.

III. Estimation of the parameter

Parameters are important in building the reliability model. Hence, the estimation of the parameters for the failure distribution was carrying out. Weibull++7 was used to analyze the likelihood value for different assumptions. Based on maximum likelihood estimation MLE, the assumptions with greatest likelihood value were accepted and applied to the model.

IV. Modelling and validation

The reliability of each component was obtained by using Weibull analysis tool. After that, BlockSim was used as a tool to draw the reliability block diagram RBD. The purpose of RBD is to calculate and to obtain the overall pump's reliability. By using RBD, a reliability model was built; justifications were done to choose the most appropriate model. Validations of the models were done by comparing the models' projection with the actual failures.

V. Result Interpretation

After the models were "tested" to get the model that is best fitted to the actual failure data, the reliability of the pump components and pump samples were predicted. Benchmarking with the results obtained by other researches was also carried out to do comparisons.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Segregation of Repair Data

In this research, the historical repair data of the pump samples were collected from a selected oil refinery. Besides of the historical repair data, the author also obtained the details and specification of the pumps, such as the process fluid, operating temperature, RPM, etc. From the raw repair data and pump specifications, the author had compiled all the data into a single sheet of Microsoft Excel file.

By using the compiled sheet of Microsoft Excel file, the author able to segregate the pumps by choosing the criterions such as the process fluid of the pumps and put them into different group by using the function and formulae built in. As shown in Table 4.1, all the criterions were included in the raw data.

Table 4.1: Example of Raw Datasheet

Equip No.	Date	Repair Code	Time To Failure (days)	Description	Pump Type	Model No.
P-24701A	20/01/2004	3b	1480.00	CAUSTIC TRANSFER PUMP	Cent. 1St.	GSA 1.5X1X6 DA4
P-24701B	07/01/2004	3b	1467.00	CAUSTIC TRANSFER PUMP	Cent. 1St.	GSA 1.5X1X6 DA4
P 22204 A	10/06/2001	3a	526.00	STRIPPER REFLUX	Cent. 1St.	GSP 3 x 1.5 x1.3 EA-40
P 22204 A	17/11/2004	3a	1782.00	STRIPPER REFLUX	Cent. 1St.	GSP 3 x 1.5 x1.3 EA-40
P 22204 B	26/11/2007	2b	2886.00	STRIPPER REFLUX	Cent. 1St.	GSP 3 x 1.5 x1.3 EA-40
P 22204 B	26/11/2007	3a	2886.00	STRIPPER REFLUX	Cent. 1St.	GSP 3 x 1.5 x1.3 EA-40
P 22302 A	22/09/2005	2a	2091.00	DEBUTANIZER REBOILER	Cent. 1St.	250 x 150 UCWM 577
P 22302 B	13/03/2006	2a	2263.00	DEBUTANIZER REBOILER	Cent. 1St.	250 x 150 UCWM 577
P 22303 A	20/11/2000	2a	324.00	DEBUTANIZER OVERHEAD	Cent. 1St.	150 x 80 UCWM 405
P 22303 A	19/12/2000	2a	353.00	DEBUTANIZER OVERHEAD	Cent. 1St.	150 x 80 UCWM 405
P 22303 A	23/12/2000	2a	357.00	DEBUTANIZER OVERHEAD	Cent. 1St.	150 x 80 UCWM 405
P 22303 A	06/06/2001	7f	522.00	DEBUTANIZER OVERHEAD	Cent. 1St.	150 x 80 UCWM 405
P 22303 B	01/02/2001	2a	397.00	DEBUTANIZER OVERHEAD	Cent. 1St.	150 x 80 UCWM 405
P 22303 B	18/02/2001	2a	414.00	DEBUTANIZER OVERHEAD	Cent. 1St.	150 x 80 UCWM 405
P 22303 B	23/06/2008	2a	3096.00	DEBUTANIZER OVERHEAD	Cent. 1St.	150 x 80 UCWM 405
P 22304 A	11/10/2000	2a	284.00	CIRCULATING WATER	Cent. 1St.	200 x 150 UCWT, M 50T
P 22304 A	05/09/2003	2a	1343.00	CIRCULATING WATER	Cent. 1St.	200 x 150 UCWT, M 50T
P 22304 A	28/06/2004	2a	1640.00	CIRCULATING WATER	Cent. 1St.	200 x 150 UCWT, M 50T
P 22304 A	28/11/2006	2a	2523.00	CIRCULATING WATER	Cent. 1St.	200 x 150 UCWT, M 50T

Due to different time zero of the pumps from different locations, the author decided to use the pump data from certain locations which had started to operate since 1st Jan 2000. Thus, pump data from the other locations were excluded from this project.

The author had sorted the failure data according to the types of failure, types of pumps and the process fluid. The time to failure of each failure is calculated using the formulae function from Microsoft Excel. As mention earlier, the starting date for the selected pumps to operate was started on 1st Jan 2000. As shown in Table 4.2 is the example of repair code and the number of occurrence for all the refineries.

Table 4.2: Repair codes and the number of occurrence

Repair Code Category for Pump			# of occurrence
Packing	1	Packing	9
Seal	2a	Mechanical Seal	329
	2a(OB)	Mechanical Seal (OB)	5
	2a(IB)	Mechanical Seal (IB)	1
	2b	Lubrication	43
Bearing	3a	Antifriction	187
	3a(OB)	Antifriction (OB)	3
	3a(IB)	Antifriction (IB)	7
	3b	Plain	76
	3c	Carbon	24
Vibration	4	Vibration	26
Coupling	5	Coupling	22
Misalignment	6	Misalignment	6
Mechanical	7a	Impeller	27
	7b	Wear ring	29
	7c	Shaft	43
	7d	Gear	3
	7e	Casing	20
	7f	Oiler ring	6
	7g	Lube oil pump	0
	7h	Head gasket	7
	7i	Magnet ring/stator	22
	7j	Shaft sleeve	9
	7k	Bearing Housing	2
	7l	Throat bush	5
	8	Modification	3
	9	Dirty	6
	10	Total overhaul (open all part)	9
	11	Diffuser (Sundyne only)	1
	12	Shroud leak	4

The Figure 4.1 below shows the numbers and percentages of failures that occurred in each location. From 1st Jan 2000 to 1st February 2009, there were 935 failures occurred at whole refinery. From the pie chart, it shows that there were 276 failures occurred at location A, which were 29.5% from the total. For location B, there were 106 failures occurred and there were 247 failures occurred in location C, which were 11.34% and 26.42% respectively. While location D had 116 of failures occurred and location E had 190 of failures occurred, which were 12.41% and 20.32% respectively.

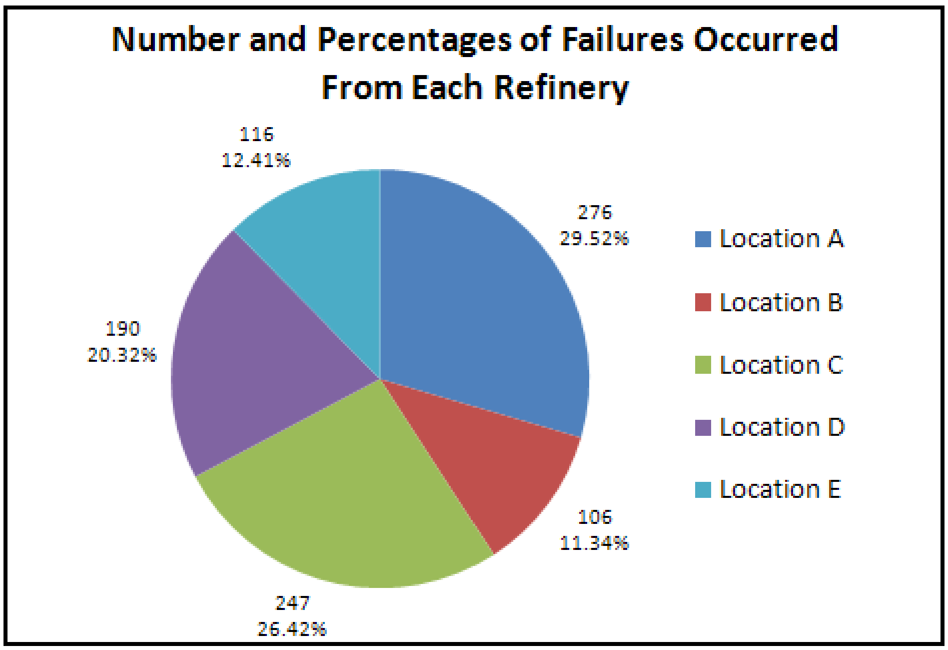


Figure 4.1: Number and percentages of failures occurred at each location from 1st Jan 2000 to 1st Feb 2009

As mentioned earlier, pumps which were started to operate since 1st January 2000 were selected as they had the same time zero. All the pumps from location B and C were selected as the samples because they were the mentioned pumps. Hence, the samples in this research had occupied 37.8% of the failures from the entire populations.

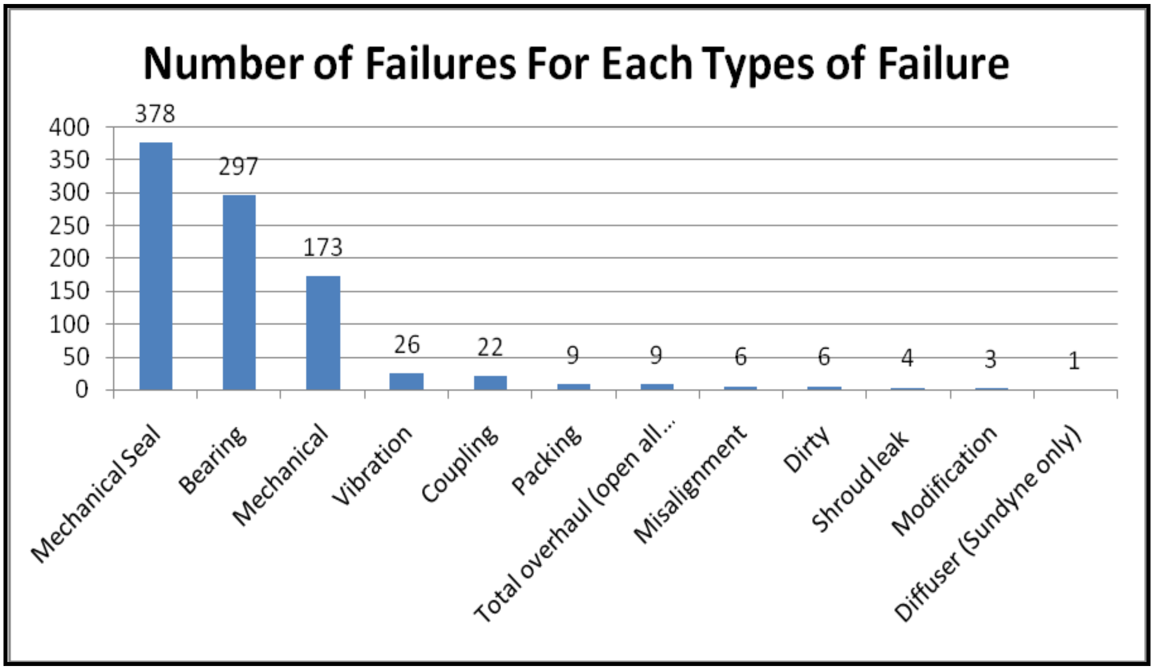


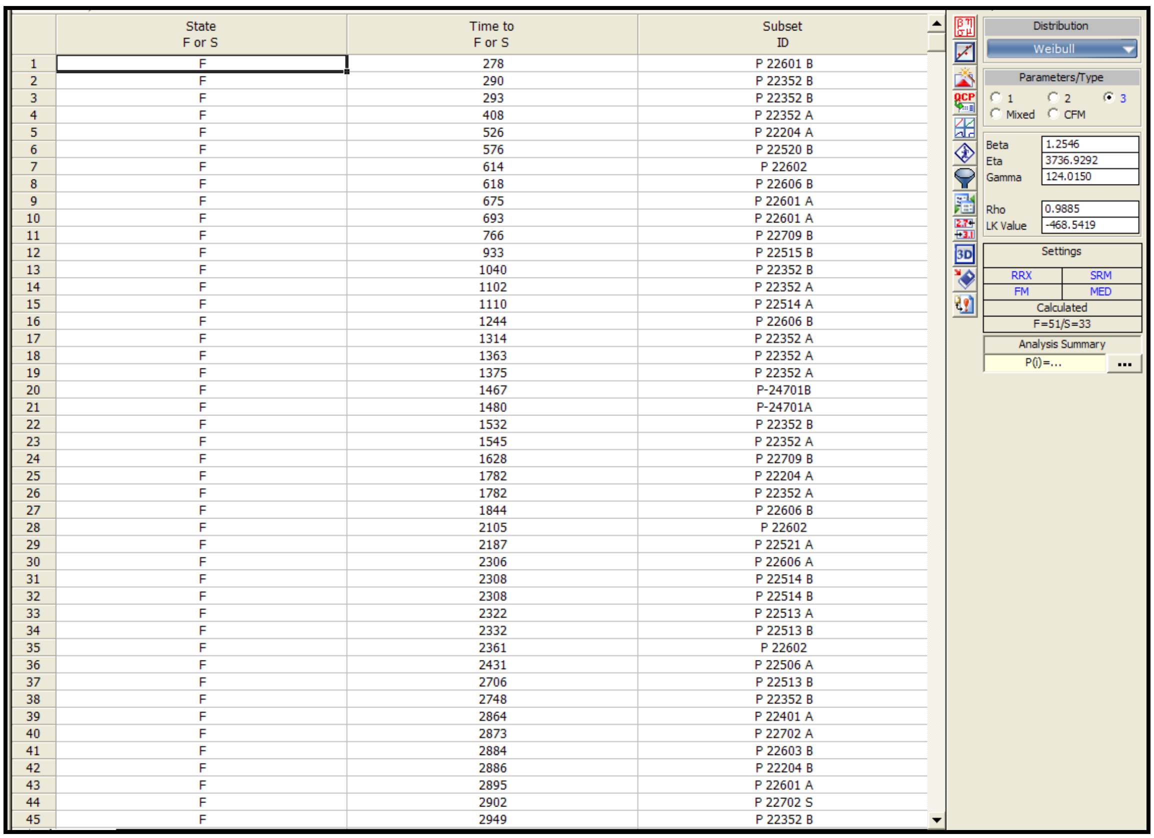
Figure 4.2: Number of Failures For Each Types of Failure

From Figure 4.2, there are 935 failures; it can be categorized into 12 types of failure, which are shown at figure 4.2. There are three major failures that were experienced by all the pumps in all refinery. Among all the failures, failure on the mechanical seals happened the most, which were 378 failures or 40.43% of all the pump failure. The second highest failure were the failure of the bearing, which were 297 failures, and it contributes 31.76% to the total failures. On the other hand, there were 173 failures happened on the mechanical components of the pumps, which contributes 18.50% to the total numbers of failure.

For the other failures, they were not significant as comparing to the three major failures. There were only 86 failures and only contributes 9.31% of total failures. The least failure that happened was the Diffuser failure, which only experienced once since 1st Jan 2000.

4.2 Building of the Reliability Model

Weibull++ 7, a reliability analysis tool is used to find out the failure distribution of the pump. For the very first step in using Weibull, the data filtered by Microsoft Excel must be transferred to Weibull. Similar to others reliability analysis software, Weibull had the interface which looks similar to Microsoft Excel. Figure 4.3 below shows the interface of the Weibull software.



	State F or S	Time to F or S	Subset ID
1	F	278	P 22601 B
2	F	290	P 22352 B
3	F	293	P 22352 B
4	F	408	P 22352 A
5	F	526	P 22204 A
6	F	576	P 22520 B
7	F	614	P 22602
8	F	618	P 22606 B
9	F	675	P 22601 A
10	F	693	P 22601 A
11	F	766	P 22709 B
12	F	933	P 22515 B
13	F	1040	P 22352 B
14	F	1102	P 22352 A
15	F	1110	P 22514 A
16	F	1244	P 22606 B
17	F	1314	P 22352 A
18	F	1363	P 22352 A
19	F	1375	P 22352 A
20	F	1467	P-24701B
21	F	1480	P-24701A
22	F	1532	P 22352 B
23	F	1545	P 22352 A
24	F	1628	P 22709 B
25	F	1782	P 22204 A
26	F	1782	P 22352 A
27	F	1844	P 22606 B
28	F	2105	P 22602
29	F	2187	P 22521 A
30	F	2306	P 22606 A
31	F	2308	P 22514 B
32	F	2308	P 22514 B
33	F	2322	P 22513 A
34	F	2332	P 22513 B
35	F	2361	P 22602
36	F	2431	P 22506 A
37	F	2706	P 22513 B
38	F	2748	P 22352 B
39	F	2864	P 22401 A
40	F	2873	P 22702 A
41	F	2884	P 22603 B
42	F	2886	P 22204 B
43	F	2895	P 22601 A
44	F	2902	P 22702 S
45	F	2949	P 22352 B

Figure 4.3: Interface of Weibull++ 7

After the time to failure and the pumps' tag name are transferred to Weibull, the failure distributions of the pumps are obtained. Pumps were grouped according to the types of the pump. By using the same setting, all graphs will be calculated and draw by

Weibull. In order to compare the failure distribution of each component, all the settings are same for each component.

- General Renewal Process

  GRP model was applied in this study, due to its advantages over HPP and NHPP. The details of GRP were discussed earlier in the literature review section.

- 2 parameters Weibull distribution

  All the pumps in this research started to operate since 1st Jan 2000, hence shift parameter, γ is not needed. Due to this, the author decided to apply 2 parameters Weibull distribution in this study. The parameters were chosen based on MLE, which means that the parameters with greater likelihood value will be chosen and apply on the model. The details of Weibull distribution and parameter estimation were discussed earlier in the literature review.

- Confidence level = 0.9

  The confidence level tells you how sure you can be. Confidence level of 95% means one can be 95% certain. 95% confidence level is most used by most of the researchers. The higher the confidence level, the wider the confidence interval are; vice versa. [16]

4.2.1 Seal Failure

By using the Weibull++ 7, the author had obtained some results for all the failure modes. The results such as cumulative number of failures, conditional reliability and MTBF/lives are shown in the figures below:

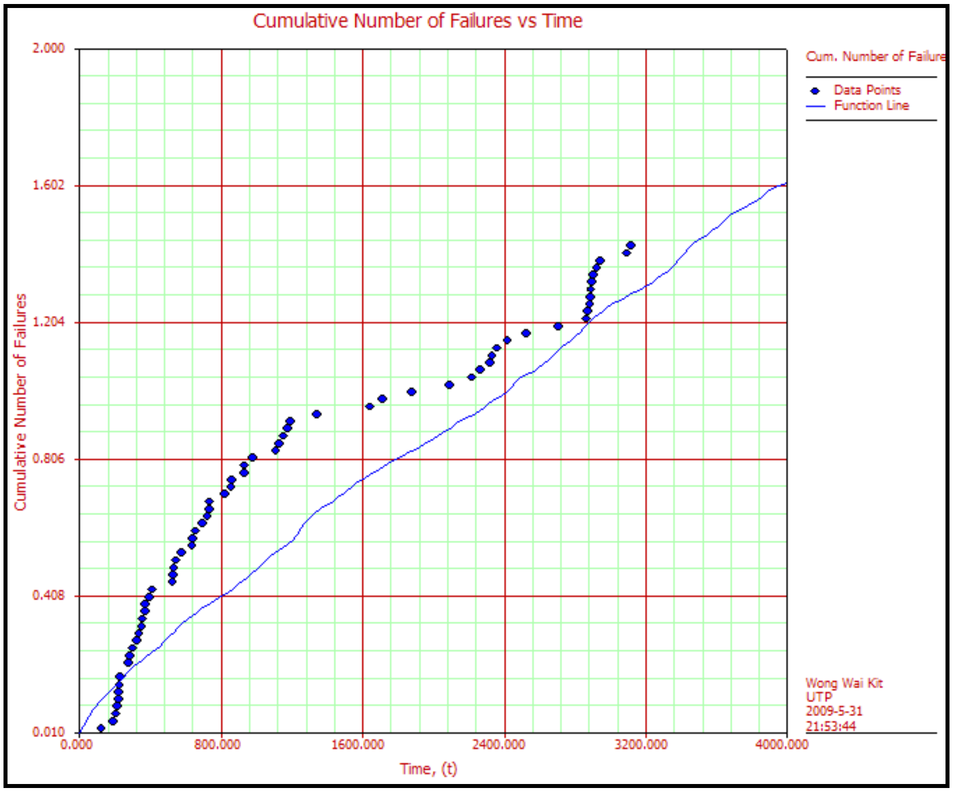


Figure 4.4: Cumulative number of failures vs. time of seal

From figure 4.4 above, the seal predicted to have an average of 1.5080 failures in 10 years period. On the other hand, figure 4.5 shows the conditional reliability plot vs. time for seal failure.

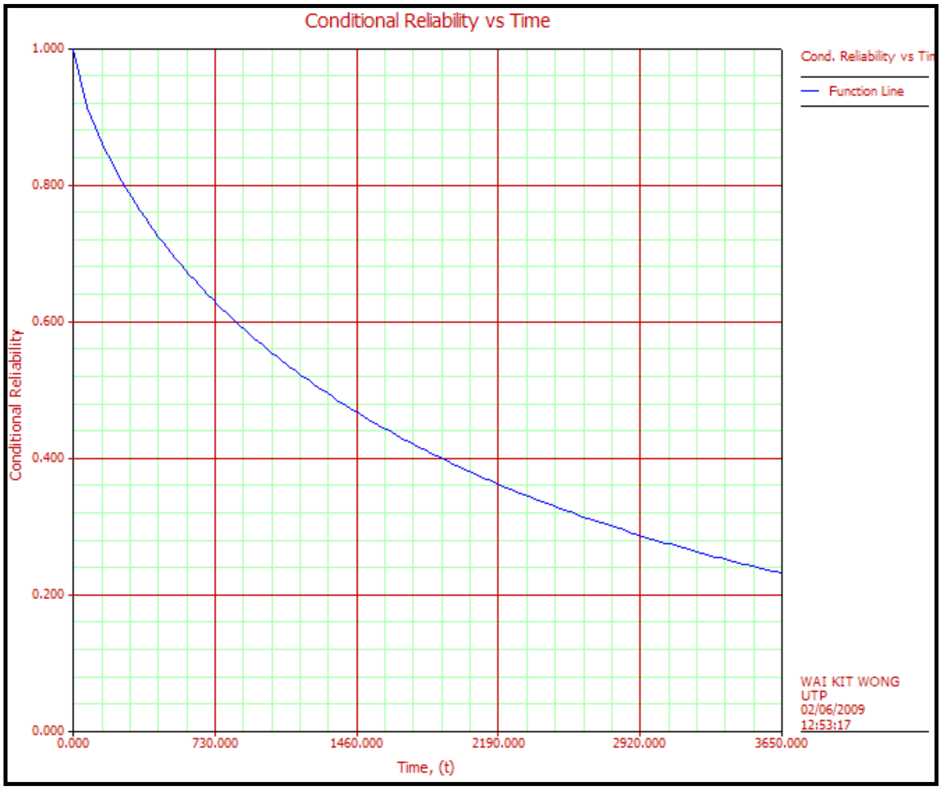


Figure 4.5: Conditional reliability vs. time of seal

By using Weibull++, 2 Weibull parameters were calculated, they are:

- $\beta = 0.714$
- η = 2140.0608

By using $\overline{\mathrm{T}} = \eta \bullet \Gamma\left(\frac{1}{\beta} + 1\right)$:

MTBF of Seal = 2659.29 days = 88.64 months = 7.29 years

Refering to Table 2.2, the seal in this research falled into “Very Good” catogery with MTBF from 70 to 90 months. Compare with seal MTBF of 12 months in the past, the results obtained shows that the effort put in by the seal manufacturer to increase the seal life had beared its fruit.

4.2.2 Bearing Failure

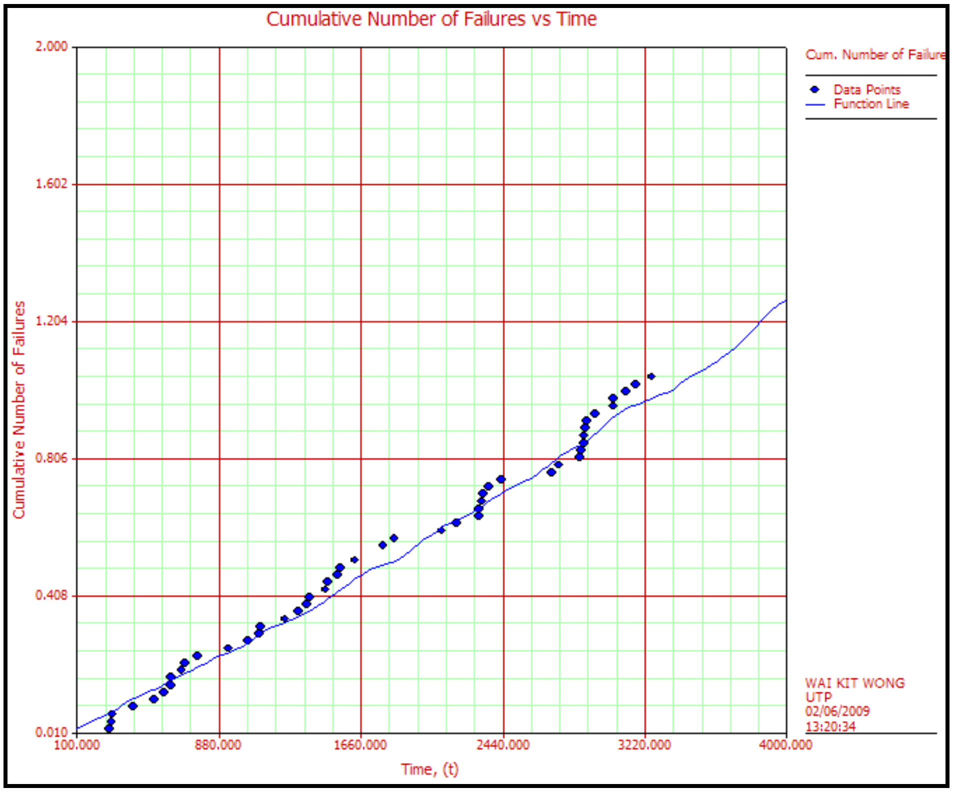


Figure 4.6: Cumulative number of failures vs. time of bearing

From figure 4.6 above, the bearing predicted to have an average of 1.1040 failures in 10 years period. On the other hand, figure 4.7 shows the conditional reliability plot vs. time for bearing failure.

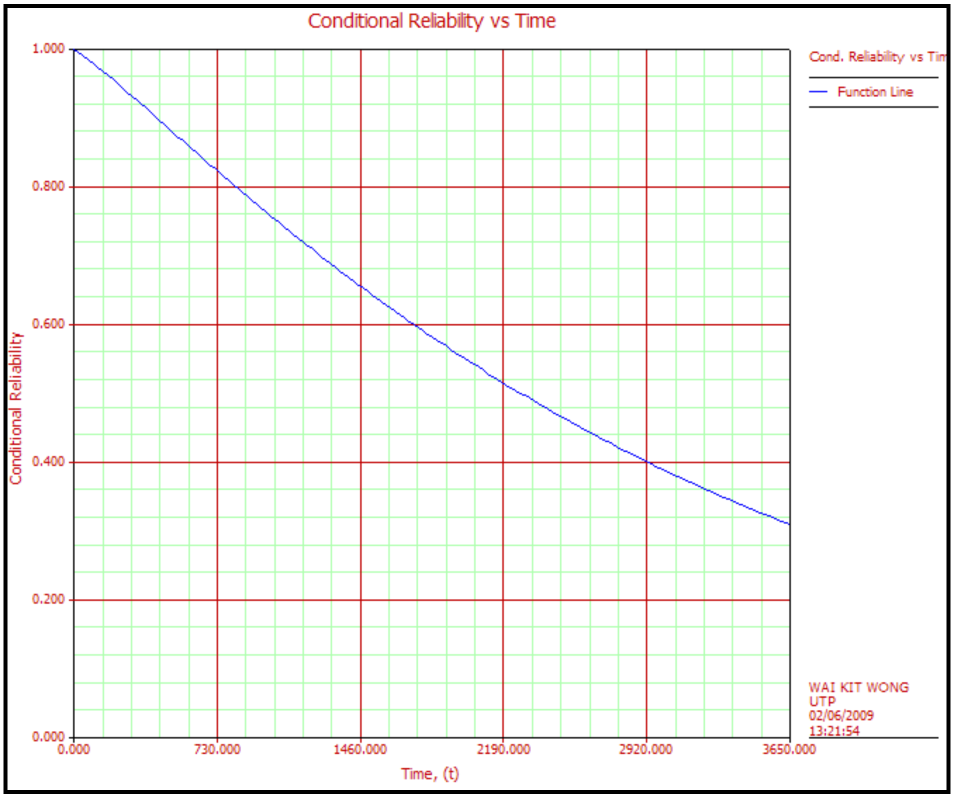


Figure 4.7: Conditional reliability vs. time of bearing

By using Weibull++, 2 Weibull parameters were calculated, they are:

- $\beta = 1.1147$
- $\eta = 3159.7744$

By using $\overline{T} = \eta \bullet \Gamma\left(\frac{1}{\beta}+1\right)$:

MTBF of Bearing = 3035.83 days = 101.19 months = 8.317 years

The target lives of continuous pump are 60 months and spared operation pump are 120 months. The MTBF of the sample is able to achieve 101.19 months. The result indicates that the pumps are operating in between continuous and spared operation condition.

4.2.3 Mechanical Failure

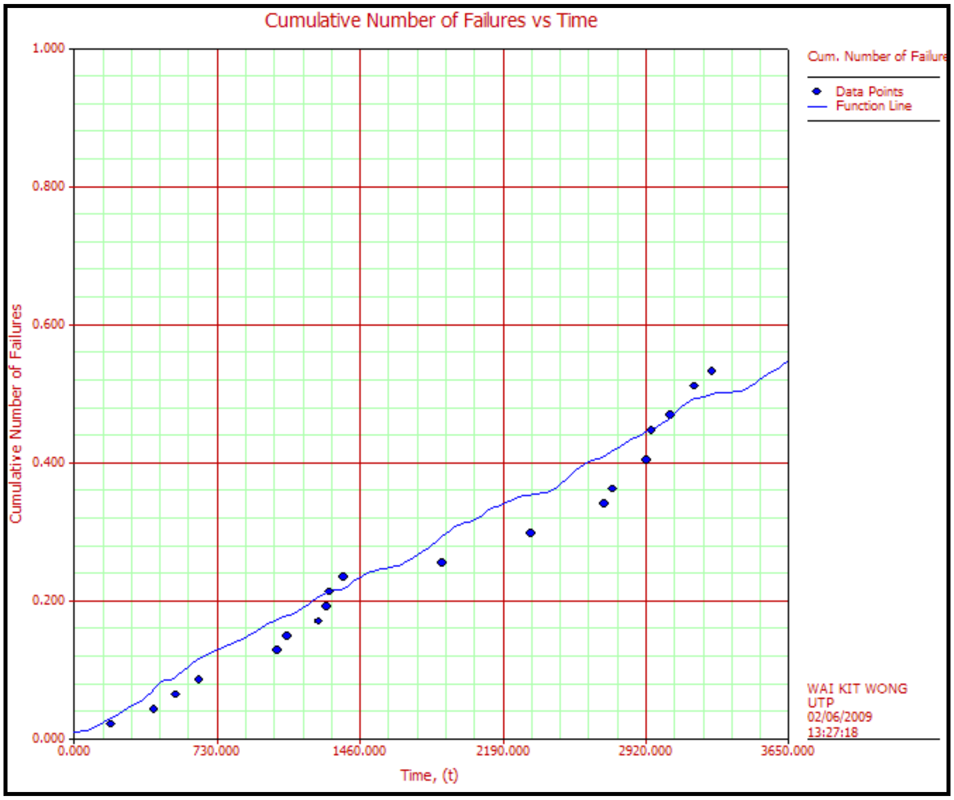


Figure 4.8: Cumulative number of failures vs. time of mechanical

From Figure 4.8 above, the mechanical predicted to have an average of 0.5480 failures in 10 years period. On the other hand, Figure 4.9 shows the conditional reliability plot vs. time for bearing failure.

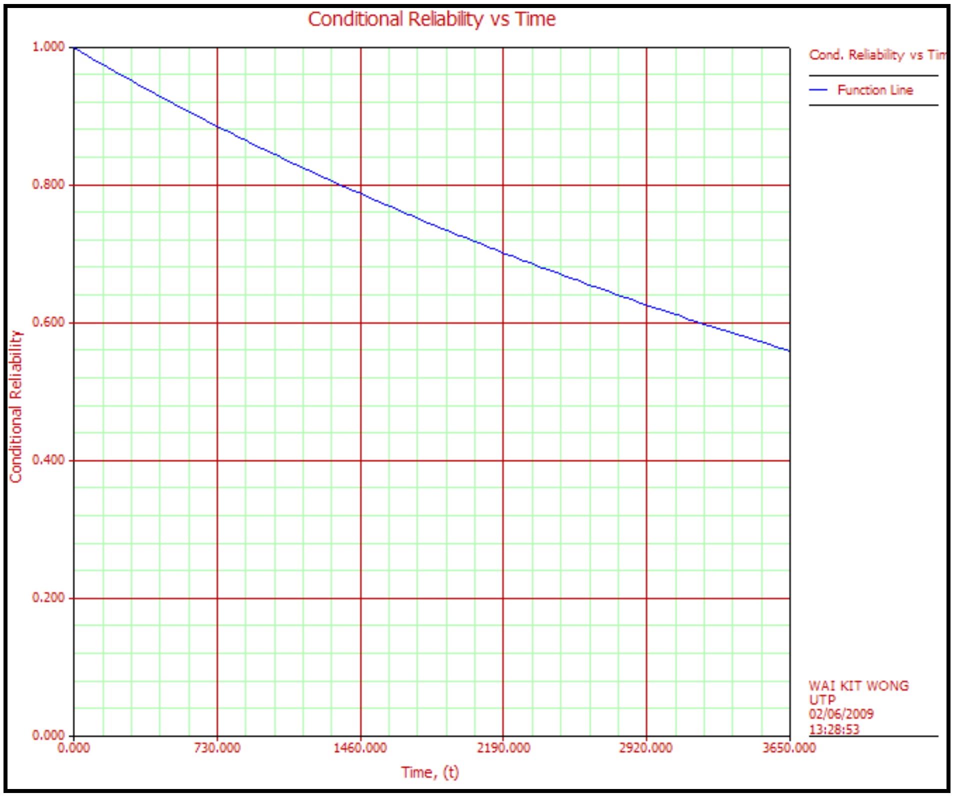


Figure 4.9: Conditional reliability vs. time of mechanical

By using Weibull++, 2 Weibull parameters were calculated, they are:

- $\beta = 0.9683$
- $\eta = 6377.9354$

By using $\overline{T} = \eta \bullet \Gamma\left(\frac{1}{\beta}+1\right)$:

MTBF of Mechanical = 6468.966 days = 17.72 years

There was no target lives for mechanical failure because it consists of various minor failures such as impeller, wear ring, shaft, etc. Hence there is no benchmark to compare the MTBF of mechanical components. From some researches, the MTBF of shaft could reach 15 years. This had provided supports that the MTBF of mechanical with 17.72 years is possible to a degree. However, further investigation needs to be done to explain the long MTBF of mechanical components.

4.3 Model Verification

In this project, the author had run several simulations by using data with different operating durations. There were two data sets with different operating durations used by author to verify the model. Both sets of data had same time zero, which was started from 01/01/2000. These two sets of data had time to event at 01/01/2006 (set A) and 01/02/2009 (set B) respectively.

The verification method done in this research is by comparing the projection of data set A with the actual failure in data set B. The author had used Weibull++ 7 to predict the cumulative number of failures for each failure modes. By comparing with the actual cumulative number of failure from the samples, the validity of the model can be proved. Figures 4.10, 4.11 and 4.12 below show the predicted and actual cumulative number of failures for each failure from the time zero to 3319 days.

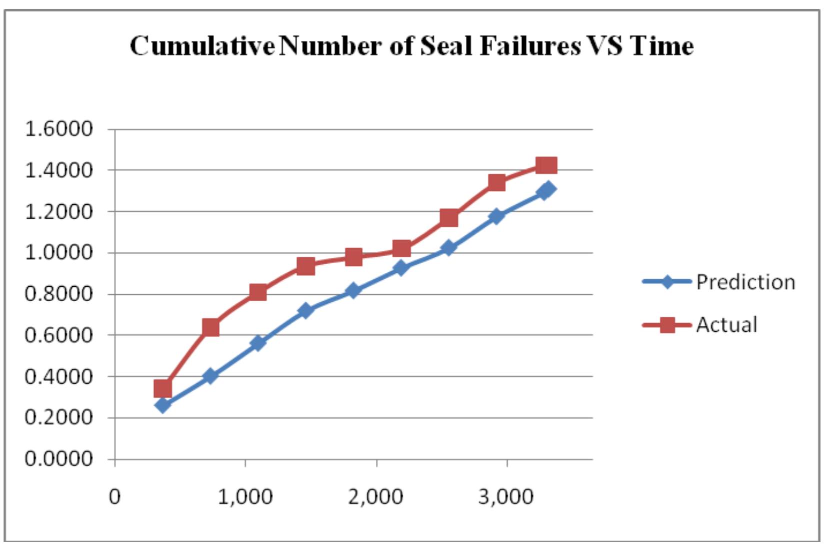


Figure 4.10: Prediction and actual cumulative number of failures for Seal

The model has an average difference of 0.1583 failures between the projection and the actual cumulative number of seal failures.

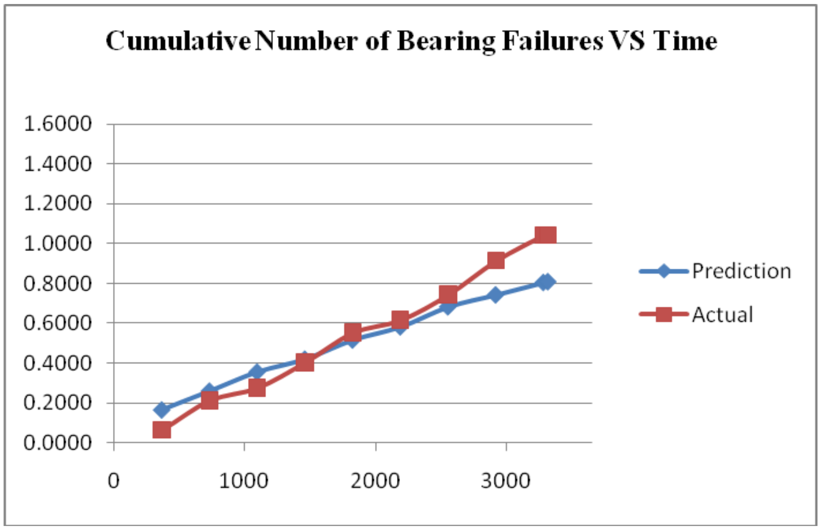


Figure 4.11: Prediction and actual cumulative number of failures for Bearing

The model has an average difference of 0.1026 failures between the projection and the actual cumulative number of bearing failures.

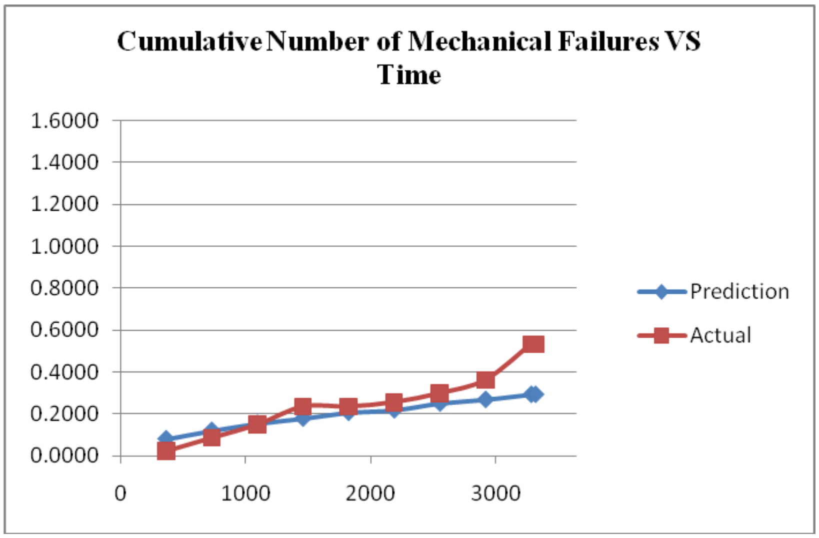


Figure 4.12: Prediction and actual cumulative number of failures for Mechanical

The model has an average difference of 0.0841 failures between the projection and the actual cumulative number of mechanical failures.

Take note that the actual cumulative number of failures is always higher than the prediction and the differences is increasing with time for bearing and mechanical failures. These phenomena were caused by the deteriorated pump components' reliability over time. With longer duration of operation, the pump's conditions will gradually deteriorate and thus deviated from the projection.

From the figures shown, it can be seen that the difference between the forecast and the actual results will tend to distance greater with the increasing in time. In short, long term forecasting has higher error compared to short range forecasting. Hence, the models need to be updated frequently and more suitable to apply in short term forecasting rather than long term forecasting.

Figure 4.12 shows that the actual cumulative number of failure is deviated from the prediction in year 9 with exponential trend. This may explain why the MTBF of mechanical components seems abnormally long. Assuming that the mechanical components had an average MTBF of 15 years, the data from the sample may not reflect the truth as it only contains 9 year and 1 month of failure data. Hence, further investigation and further updating on the model needs to be done to verify this problem.

From the figures above, it showed that the prediction and the actual cumulative number of failures seem closed to each other in the early stage. Hence the model was verified for the time being. However, the model will be changed with further updating in the future.

4.4 Reliability Block Diagram (RBD)

After the author obtained and verified the reliability results for each failure modes from Weibull++ 7, BlockSim 7 was used to calculate the overall reliability, expected number of failure, etc of the pump in KR2. Since the pump will stop to operate if either one of the failure occurred, the configuration of the RBD for the pump had to be arranged in series configuration. Figure 4.13 at below shows the RBD from BlockSim 7:

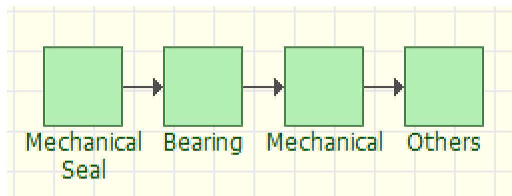


Figure 4.13: RBD of the pump system in KR2

After RBD was draw, the Weibull parameters for each failure modes were inserted in the corresponding block's properties. In BlockSim 7, the parameters of the failure distribution for each failure modes were entered to build the reliability model. Since the sample size of failures such as shroud leak, diffuser, modification, etc are too few to obtain the reliability plot, the author assumed the reliability of the other components as 1, which is virtually no failures.

By using analytical method, the reliability of the pump system in basic series configuration will be calculated by BlockSim 7 using the following equation. The reliability plot vs. time of the system was also obtained and shown in Figure 4.14.

$$R_{Pump} = (R_{Mechanical\ Seal} \bullet R_{Bearing} \bullet R_{Mechanical} \bullet R_{Others}) \qquad \text{(Eq. 22)}$$

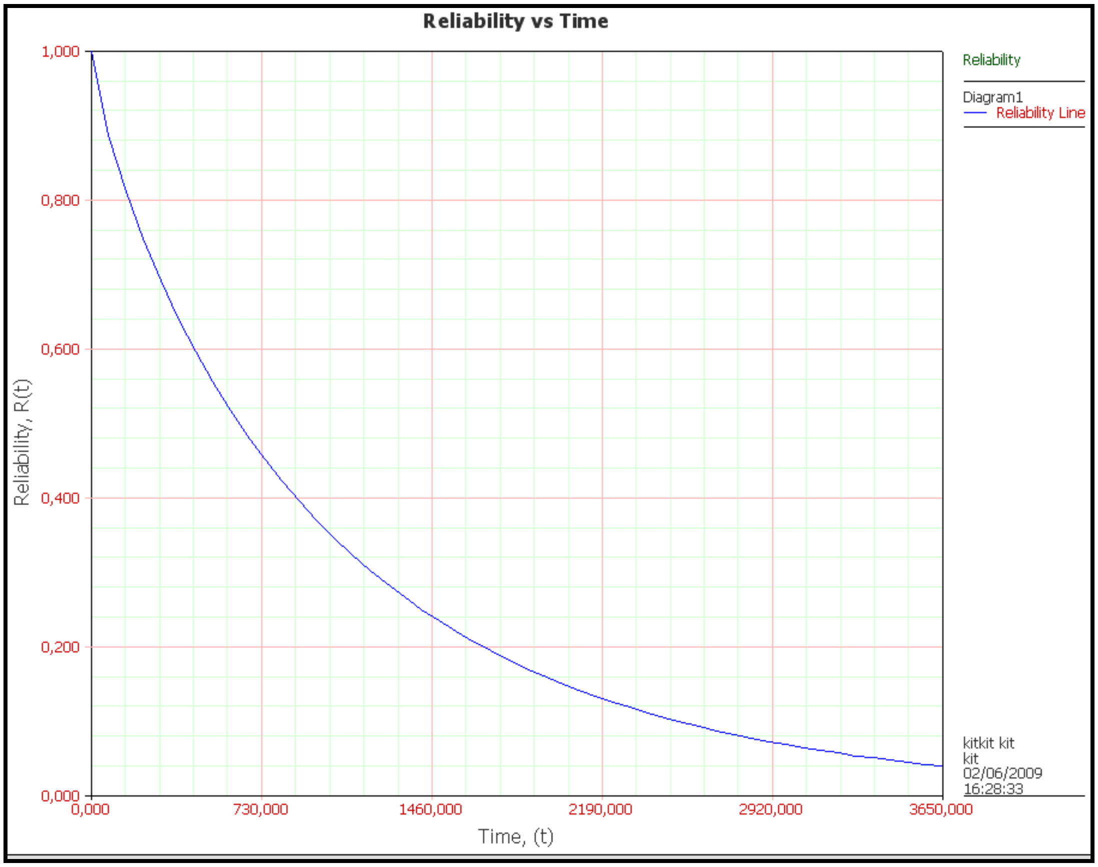


Figure 4.14: Reliability vs. time of pump system

4.5 Benchmarking

By using quick calculation pad from BlockSim 7, the mean time/MTBF of the pump system is calculated and shown in Figure 4.15. The result shows that the MTBF of the pump system is 1026.5670 days, which are 2.81 years. When comparing the results with Table 2.1, the result is far better than the category of API pumps, repair-focused refinery, developing country, which has a MTBF of 1.6 years. The MTBF of the samples are 75.63% greater than the MTBF of the mentioned category.

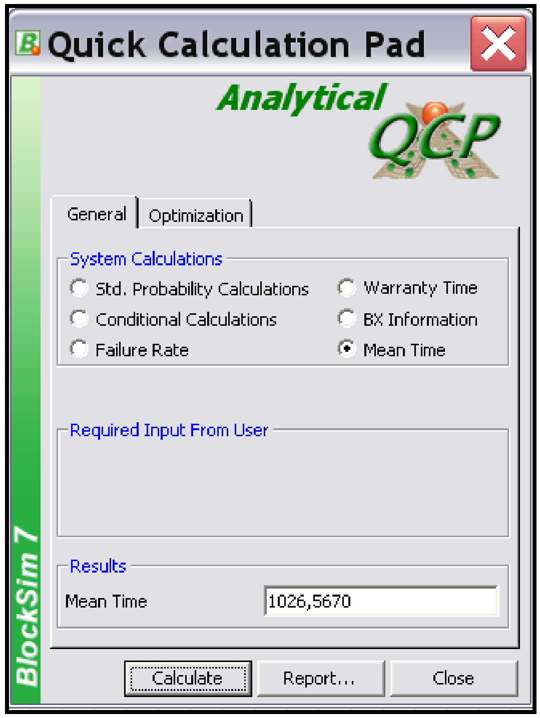


Figure 4.15: Mean time/MTBF of the pump samples

The author chose to benchmark the results with the mentioned category because Malaysia is still a developing country and all the samples are API pumps. Although the results obtained are better than the benchmark, but to achieve the target pump lives of 48 month, more efforts need to be done by the firm. If the firm aims to achieve the best-of-class result, which is 10.1 years, there is still a long way to go. If one looks at Table 2.1, one will realize that the MTBF of different kinds of pumps can be varied from 1.6 years to 10.1 years. This shows that the MTBF of pumps can be affected significantly when operating in different conditions with different sets of the pumps.

Table 4.3 at below shows the summary of the MTBF/lives of the components and pumps. Take note that there was no benchmark for mechanical failures as the author lump all failures, from bearing housing to throat bush into one group. This is caused by insufficient data to be divided into individual failure modes.

Table 4.3: Results and Target lives

Pump and components	MTBF/Lives (Years)	
	Results	Benchmark
Seal	7.29	7.5
Bearing	8.317	10
Mechanical	17.72	N/A
Pumps	2.81	4

As a conclusion, the Table 4.3 above shows that all the results obtained are either close or fall within the range of the benchmark in Table 2.1 and 2.3. Hence, the author concluded that the model applied in this research by using GRP model, Weibull distribution and RBD are able to obtain results which are comparable to the results obtained by others researches.

CHAPTER 5
CONCLUSION

The purpose of this research is to study on the reliability of centrifugal pumps and pump components and to develop a model for centrifugal pumps failure prediction. Findings indicate that GRP is better than HPP and NHPP in terms of flexibility and accuracy. Due to this, GRP was selected as the basis for this research. In this research, centrifugal pumps from a selected oil refinery were selected as the intent of study. To narrow the scope of study, segregation was done to filter and leave only the pumps that were started to operate since 1^{st} Jan 2009 as the samples. The sample size used in this research was made up of 47 pumps. Modelling of the pump components reliability was done by using Weibull++ 7 to determine the failure distribution and the estimation of Weibull parameters. Then, BlockSim 7 was used to determine the reliability of the pump system based on the Weibull parameters obtained from Weibull++ 7. The models used in this research were verified by comparing the projection of data set A with the actual failure in data set B. The reliability of seals, bearings and mechanical components were predicted to have MTBF of 7.29 years, 8.317 years and 17.72 years with benchmark of 7.5 years, 10 years and N/A respectively. For the centrifugal pump system, it was predicted to have an average MTBF of 2.81 years with benchmark of 4 years. Benchmarking shows that the results obtained in this research is comparable with the other researches. Although the results seem good, but there is still a need to improve the reliability and quality of the pump components to achieve best-of-class standard.

RECOMMENDATIONS

In order to increase the accuracy of the model, the data collection plays an important role. An effective reliability program requires accurate records. Other than that, a complete database that contains information, such as the pump type, operating conditions, operating temperature, process liquid type, etc are critical as well. By collecting failure data properly, more precise reliability plots can be obtained. Hence, a more accurate model can be obtained.

At the same time, the data used in building the model need to be updated frequently to obtain a more accurate reliability projection. Since the reliability of the components is not constant over time, there is a need to make adjustment on the model to get a more appropriate model which could reflect the latest pump conditions. After certain operating duration, all the failure data obtained since the last record till the latest record must be included in the existed model to provide a more accurate solution.

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APPENDIX I

REPAIR RECORD OF KR2

Equip No.	Date	Repair Code	Time To Failure	Pump Type
21104A	06/08/2003	2a	1678	
21106A	07/11/2005	2a(OB)	2502	
21106A	26/04/2006	2a	2672	
21106A	26/04/2006	3a(OB)	2672	
21106A	21/02/2007	2a	2973	
21106A	21/02/2007	3a(OB)	2973	
21106A	13/03/2007	2a	2993	
21106A	01/10/2007	2a	3195	
21106A	29/10/2007	3a	3223	
21106A	29/10/2007	7a	3223	
21106A	29/10/2007	7l	3223	
21106A	29/10/2007	7j	3223	
21106A	30/12/2007	2a	3285	
21106B	14/08/2005	2a	2417	
21106B	14/08/2005	3a(IB)	2417	
21106B	04/12/2005	7b	2529	
21106B	09/01/2007	2a	2930	
21106B	09/01/2007	3a(OB)	2930	
21106B	08/03/2007	2a	2988	
21106B	08/03/2007	3a(OB)	2988	
21106B	22/03/2007	2a	3002	
21106B	22/03/2007	3a	3002	
21106B	22/03/2007	7j	3002	
21106B	22/03/2007	7l	3002	
21106B	24/01/2008	3a	3310	
21106B	24/01/2008	7a	3310	
21106B	24/01/2008	7l	3310	
21106B	24/01/2008	7j	3310	
21107A	18/12/2002	2a	1447	
21107A	03/01/2002	7a	1098	
21107A	03/01/2002	7b	1098	
21107A	02/06/2004	2a	1979	

21107B	30/01/2002	2a	1125	
21107B	13/03/2006	2a	2628	
21109B	26/09/2007	2a	3190	
21109B	26/06/2008	2a	3464	
21113A	06/06/2006	2b	2713	
21113A	06/06/2006	3a	2713	
21113A	06/06/2006	9	2713	
21113A	22/11/2007	3a	3247	
21113B	12/01/2004	3a	1837	
21113B	08/11/2006	3a	2868	
21113B	08/11/2006	3b	2868	
21113B	29/04/2008	8	3406	
21113B	06/08/2008	3b	3505	
21113C	30/05/2006	9	2706	
21114A	22/01/2003	2a	1482	
21114A	24/07/2003	2b	1665	
21114A	08/09/2003	2a	1711	
21114A	08/09/2003	2b	1711	
21114A	14/06/2006	2a	2721	
21114A	14/06/2006	2b	2721	
21114A	13/11/2006	2a	2873	
21114B	15/07/2001	2a	926	
21114B	18/09/2007	7d	3182	
21114C	11/06/2006	2a	2718	
21114C	09/11/2006	2a	2869	
21115A	23/03/2003	2b	1542	
21115A	25/08/2003	3a	1697	
21115B	04/06/2003	4	1615	
21116A	02/02/2001	2a	763	
21116A	06/02/2002	2a	1132	
21116A	10/06/2003	2a	1621	
21116A	10/04/2005	4	2291	
21116A	10/04/2005	7a	2291	
21116A	02/06/2005	2a	2344	
21116A	21/11/2005	2a	2516	
21116A	19/06/2006	2a	2726	
21116A	31/01/2007	2a	2952	
21116A	31/01/2007	7b	2952	

21116A	17/05/2007	2a	3058	
21116A	10/12/2007	2a	3265	
21116A	06/07/2008	2a	3474	
21116A	06/07/2008	3a	3474	
21116A	06/07/2008	7a	3474	
21116A	06/07/2008	7b	3474	
21116A	14/07/2008	2a	3482	
21116A	13/01/2009	2a	3665	
21116B	25/10/2001	2a	1028	
21116B	17/06/2002	2a	1263	
21116B	25/09/2002	2a	1363	
21116B	21/04/2004	2a	1937	
21116B	22/08/2005	2a	2425	
21116B	08/10/2006	2a	2837	
21116B	13/01/2008	2a	3299	
21116B	18/03/2008	2a	3364	
21116B	03/08/2008	2a	3502	
21116B	14/12/2007	2a	3269	
21121A	31/07/2006	2a	2768	
21121A	31/07/2006	3a	2768	
21121A	31/07/2006	9	2768	
21121B	03/08/2006	2a	2771	
21121B	03/08/2006	3a	2771	
21201A	01/04/2001	7a	821	
21202A	23/07/2006	9	2760	
24101A	23/10/2000	2a	661	Cent. 10St.
24101A	06/02/2005	7e	2228	Cent. 10St.
24101A	14/06/2005	7e	2356	Cent. 10St.
24101A	12/12/2005	7e	2537	Cent. 10St.
24101A	09/05/2006	2a	2685	Cent. 10St.
24101A	09/05/2006	7e	2685	Cent. 10St.
24101A	06/08/2006	2a(OB)	2774	Cent. 10St.
24101D	24/07/2006	3a(OB)	2761	Cent. 10St.
24203A	15/03/2005	2a	2265	Cent. 2St. Vert.
24701A	20/01/2004	3b	1845	Cent. 1St.
24701B	07/01/2004	3b	1832	Cent. 1St.
22101 A	25/04/2001	3a	845	
22101 A	25/04/2001	7f	845	

22101 A	13/10/2002	2a	1381	
22101 B	27/11/2000	2a	696	
22101 B	18/04/2001	2a	838	
22201 A	24/01/2001	2a	754	Cent. 5St
22201 A	11/11/2002	2b	1410	Cent. 5St
22201 B	06/01/2001	2a	736	Cent. 5St
22201 B	17/04/2001	2a	837	Cent. 5St
22202 A	25/06/2006	2a	2732	Cent. 1St. High Speed
22202 A	25/06/2006	2b	2732	Cent. 1St. High Speed
22202 A	16/03/2008	2b	3362	Cent. 1St. High Speed
22202 A	16/03/2008	3a	3362	Cent. 1St. High Speed
22202 A	16/03/2008	7c	3362	Cent. 1St. High Speed
22202 B	29/01/2002	2b	1124	Cent. 1St. High Speed
22202 B	14/12/2003	3a	1808	Cent. 1St. High Speed
22202 B	14/12/2003	7c	1808	Cent. 1St. High Speed
22202 B	04/10/2005	2a	2468	Cent. 1St. High Speed
22202 B	09/10/2006	2a	2838	Cent. 1St. High Speed
22202 B	09/10/2006	3a	2838	Cent. 1St. High Speed
22202 B	09/10/2006	3b	2838	Cent. 1St. High Speed
22202 B	09/10/2006	7a	2838	Cent. 1St. High Speed
22202 B	09/10/2006	11	2838	Cent. 1St. High Speed
22204 A	10/06/2001	3a	891	Cent. 1St.
22204 A	17/11/2004	3a	2147	Cent. 1St.
22204 B	26/11/2007	2b	3251	Cent. 1St.
22204 B	26/11/2007	3a	3251	Cent. 1St.
22302 A	22/09/2005	2a	2456	Cent. 1St.
22302 B	13/03/2006	2a	2628	Cent. 1St.
22303 A	20/11/2000	2a	689	Cent. 1St.
22303 A	19/12/2000	2a	718	Cent. 1St.
22303 A	23/12/2000	2a	722	Cent. 1St.
22303 A	06/06/2001	7f	887	Cent. 1St.
22303 B	01/02/2001	2a	762	Cent. 1St.
22303 B	18/02/2001	2a	779	Cent. 1St.
22303 B	23/06/2008	2a	3461	Cent. 1St.
22304 A	11/10/2000	2a	649	Cent. 1St.
22304 A	05/09/2003	2a	1708	Cent. 1St.
22304 A	28/06/2004	2a	2005	Cent. 1St.
22304 A	28/11/2006	2a	2888	Cent. 1St.

22305P1A	27/10/2000	2a	665	Cent. 1St.
22305P1A	07/01/2002	2a	1102	Cent. 1St.
22305P1B	23/07/2000	2a	569	Cent. 1St.
22305P1B	31/07/2000	2a	577	Cent. 1St.
22305P1B	13/08/2000	2a	590	Cent. 1St.
22305P2A	20/08/2000	2a	597	Cent. 1St.
22305P2B	12/08/2000	2a	589	Cent. 1St.
22305P3B	18/02/2008	2a	3335	
22352 A	12/02/2001	3b	773	Cent. 1St.
22352 A	12/02/2001	7a	773	Cent. 1St.
22352 A	22/12/2002	7c	1451	Cent. 1St.
22352 A	07/01/2003	3c	1467	Cent. 1St.
22352 A	04/06/2003	7e	1615	Cent. 1St.
22352 A	13/07/2003	7h	1654	Cent. 1St.
22352 A	07/08/2003	3c	1679	Cent. 1St.
22352 A	25/09/2003	3c	1728	Cent. 1St.
22352 A	07/10/2003	3c	1740	Cent. 1St.
22352 A	07/10/2003	7c	1740	Cent. 1St.
22352 A	25/03/2004	3c	1910	Cent. 1St.
22352 A	25/03/2004	8	1910	Cent. 1St.
22352 A	17/11/2004	3c	2147	Cent. 1St.
22352 B	17/10/2000	3b	655	Cent. 1St.
22352 B	20/10/2000	3c	658	Cent. 1St.
22352 B	06/11/2002	3b	1405	Cent. 1St.
22352 B	06/11/2002	7a	1405	Cent. 1St.
22352 B	06/11/2002	7c	1405	Cent. 1St.
22352 B	12/03/2004	3c	1897	Cent. 1St.
22352 B	12/03/2004	8	1897	Cent. 1St.
22352 B	11/07/2007	3b	3113	Cent. 1St.
22352 B	11/07/2007	7c	3113	Cent. 1St.
22352 B	28/01/2008	3b	3314	Cent. 1St.
22352 B	28/01/2008	7a	3314	Cent. 1St.
22352 B	28/01/2008	7c	3314	Cent. 1St.
22352 B	28/01/2008	12	3314	Cent. 1St.
22352 B	04/09/2008	3b	3534	Cent. 1St.
22352 B	04/09/2008	7b	3534	Cent. 1St.
22352 B	04/09/2008	7i	3534	Cent. 1St.
22401 A	14/06/2001	2a	895	Cent. 1St.

22401 A	19/06/2006	2a	2726	Cent. 1St.
22401 A	04/11/2007	2a	3229	Cent. 1St.
22401 A	04/11/2007	3a	3229	Cent. 1St.
22401 A	04/11/2007	4	3229	Cent. 1St.
22502 A	23/07/2002	2a	1299	Cent. 1St.
22504 A	02/07/2002	2a	1278	Cent. 1St. Vertical
22505 B	03/12/2000	2a	702	Cent. 1St.
22506 A	28/08/2006	3c	2796	Cent. 1St.
22507 A	25/02/2001	2a	786	Cent. 1St. Vertical
22507 A	14/06/2001	2a	895	Cent. 1St. Vertical
22507 A	02/12/2001	2a	1066	Cent. 1St. Vertical
22507 A	19/06/2002	2a	1265	Cent. 1St. Vertical
22507 B	29/11/2001	2a	1063	Cent. 1St. Vertical
22507 B	11/06/2002	2a	1257	Cent. 1St. Vertical
22507 B	11/06/2004	2a	1988	Cent. 1St. Vertical
22507 B	04/03/2005	2a	2254	Cent. 1St. Vertical
22509 A	03/01/2008	2a	3289	Cent. 1St.
22509 A	03/01/2008	7a	3289	Cent. 1St.
22509 A	03/01/2008	7e	3289	Cent. 1St.
22513 A	11/05/2006	2a	2687	Cent. 1St.
22513 A	11/05/2006	3a	2687	Cent. 1St.
22513 A	04/07/2006	10	2741	Cent. 1St.
22513 A	26/03/2007	10	3006	Cent. 1St.
22513 B	21/05/2006	2a	2697	Cent. 1St.
22513 B	21/05/2006	3b	2697	Cent. 1St.
22513 B	21/05/2006	7b	2697	Cent. 1St.
22513 B	21/05/2006	7f	2697	Cent. 1St.
22513 B	21/08/2006	10	2789	Cent. 1St.
22513 B	30/05/2007	2a	3071	Cent. 1St.
22513 B	30/05/2007	3b	3071	Cent. 1St.
22513 B	30/05/2007	7b	3071	Cent. 1St.
22513 B	30/05/2007	7f	3071	Cent. 1St.
22513 B	30/05/2007	10	3071	Cent. 1St.
22514 A	15/01/2003	3a	1475	Cent. 1St.
22514 A	15/01/2003	2b	1475	Cent. 1St.
22514 A	23/03/2003	2b	1542	Cent. 1St.
22514 A	12/03/2008	9	3358	Cent. 1St.
22514 B	31/07/2003	7h	1672	Cent. 1St.

22514 B	27/04/2006	3a	2673	Cent. 1St.
22514 B	27/04/2006	3c	2673	Cent. 1St.
22515 B	22/07/2002	2b	1298	Cent. 1St.
22515 B	22/07/2002	3a	1298	Cent. 1St.
22518 A	11/06/2002	2a	1257	
22518 A	11/06/2002	3a	1257	
22518 B	22/06/2008	3a(IB)	3460	
22519 A	07/01/2001	2a	737	Cent. 1St.
22519 A	13/05/2002	2a	1228	Cent. 1St.
22519 B	16/10/2001	2a	1019	Cent. 1St.
22519 B	04/09/2002	2a	1342	Cent. 1St.
22519 B	25/02/2003	2a	1516	Cent. 1St.
22519 B	02/12/2007	2a	3257	Cent. 1St.
22520 B	30/07/2001	2b	941	Cent. 1St.
22520 B	30/07/2001	3a	941	Cent. 1St.
22521 A	07/04/2003	2a	1557	Cent. 1St.
22521 A	21/02/2005	7c	2243	Cent. 1St.
22521 A	27/12/2005	3a	2552	Cent. 1St.
22521 A	10/12/2006	12	2900	Cent. 1St.
22521 A	02/12/2008	3a	3623	Cent. 1St.
22521 A	02/12/2008	3b	3623	Cent. 1St.
22521 A	02/12/2008	7i	3623	Cent. 1St.
22521 A	02/12/2008	12	3623	Cent. 1St.
22521 B	22/02/2005	2a	2244	Cent. 1St.
22521 B	04/05/2008	3a	3411	Cent. 1St.
22521 B	04/05/2008	7i	3411	Cent. 1St.
22521 B	04/05/2008	12	3411	Cent. 1St.
22522 A	04/05/2000	2a	489	Cent. 1St.
22522 A	04/02/2003	2b	1495	Cent. 1St.
22522 A	21/01/2008	2a	3307	Cent. 1St.
22522 B	24/12/2001	2a	1088	Cent. 1St.
22523 A	12/09/2004	2a	2081	Cent. 1St.
22601 A	10/06/2001	2a	891	Cent. 1St.
22601 A	06/11/2001	3a	1040	Cent. 1St.
22601 A	24/11/2001	2b	1058	Cent. 1St.
22601 A	24/11/2001	3a	1058	Cent. 1St.
22601 A	05/12/2007	2b	3260	Cent. 1St.
22601 A	05/12/2007	3a(OB)	3260	Cent. 1St.

22601 B	05/10/2000	2a	643	Cent. 1St.
22601 B	05/10/2000	2b	643	Cent. 1St.
22601 B	05/10/2000	3a	643	Cent. 1St.
22602	06/09/2001	3a	979	Cent. 1St.
22602	06/10/2005	3c	2470	Cent. 1St.
22602	19/06/2006	3b	2726	Cent. 1St.
22603 B	18/06/2001	2a	899	Cent. 1St.
22603 B	28/09/2001	2a	1001	Cent. 1St.
22603 B	26/01/2006	2a	2582	Cent. 1St.
22603 B	24/11/2007	2a	3249	Cent. 1St.
22603 B	24/11/2007	3a(OB)	3249	Cent. 1St.
22603 C	02/04/2002	2a	1187	Cent. 1St.
22604 B	04/01/2002	2a	1099	Cent. 1St.
22605 B	31/10/2000	2a	669	Cent. 1St. Vertical
22605 B	30/04/2007	2a	3041	Cent. 1St. Vertical
22606 A	25/04/2006	3a	2671	Cent. 1St.
22606 B	10/09/2001	3a	983	Cent. 1St.
22606 B	29/05/2003	3a	1609	Cent. 1St.
22606 B	18/01/2005	3a	2209	Cent. 1St.
22701 A	10/09/2003	3a	1713	
22701 A	10/09/2003	3b	1713	
22701 B	27/03/2003	2b	1546	
22701 B	31/12/2003	2b	1825	
22701 B	31/12/2003	3c	1825	
22701 B	31/12/2003	7i	1825	
22701 B	10/02/2004	2b	1866	
22701 B	19/09/2005	2b	2453	
22701 S	03/12/2000	3a	702	
22701 S	25/03/2003	2b	1544	
22701 S	02/07/2008	3a	3470	
22702 A	10/07/2000	2a	556	Cent. 1St.
22702 A	10/07/2000	7b	556	Cent. 1St.
22702 A	14/08/2000	2a	591	Cent. 1St.
22702 A	13/11/2007	2a	3238	Cent. 1St.
22702 A	13/11/2007	3a(IB)	3238	Cent. 1St.
22702 S	01/10/2001	2a	1004	Cent. 1St.
22702 S	01/10/2001	7e	1004	Cent. 1St.
22702 S	12/12/2007	2a	3267	Cent. 1St.

22702 S	12/12/2007	3a	3267	Cent. 1St.
22703 B	07/05/2002	2a	1222	Cent. 1St.
22706 A	08/01/2001	2a	738	Cent. 1St.
22706 A	01/07/2001	2a	912	Cent. 1St.
22706 A	16/08/2006	2a	2784	Cent. 1St.
22709 B	05/02/2002	3a	1131	Cent. 1St.
22709 B	16/06/2004	3a	1993	Cent. 1St.
22709 B	06/05/2008	3a	3413	Cent. 1St.
22710 A	15/07/2008	3a	3483	Cent. 1St.
22710 A	15/07/2008	2b	3483	Cent. 1St.
22715	09/10/2001	2a	1012	
22715	02/09/2002	2a	1340	
22802 A	25/10/2000	2a	663	Cent. 1St. Vertical
22802 A	18/12/2000	2a	717	Cent. 1St. Vertical
22802 B	09/08/2000	2a	586	Cent. 1St. Vertical
22802 B	07/03/2001	2a	796	Cent. 1St. Vertical
22802 B	05/02/2002	2a	1131	Cent. 1St. Vertical
22802 B	23/09/2002	2b	1361	Cent. 1St. Vertical
22802 B	29/03/2004	2b	1914	Cent. 1St. Vertical
22803 B	07/04/2002	3a	1192	Cent. 1St. Horizontal
22804 A	08/01/2006	2a	2564	Cent. 1St. Horizontal
22804 A	27/06/2007	2a	3099	Cent. 1St. Horizontal
22804 A	27/06/2007	2b	3099	Cent. 1St. Horizontal
22804 A	27/06/2007	3a	3099	Cent. 1St. Horizontal
22804 A	12/07/2007	2a	3114	Cent. 1St. Horizontal
22804 A	12/07/2007	2b	3114	Cent. 1St. Horizontal
22804 B	08/08/2001	2a	950	Cent. 1St. Horizontal
22804 B	08/08/2001	3a	950	Cent. 1St. Horizontal
22804 B	16/08/2001	2a	958	Cent. 1St. Horizontal
22808 A	16/09/2001	2a	989	Cent. 1St. Vertical
22808 A	21/10/2001	2a	1024	Cent. 1St. Vertical
22808 A	23/12/2002	2a	1452	Cent. 1St. Vertical
22808 A	23/12/2002	2a	1452	Cent. 1St. Vertical
22808 A	12/09/2004	2a	2081	Cent. 1St. Vertical
22808 A	28/12/2004	2a	2188	Cent. 1St. Vertical
22808 A	28/12/2004	7j	2188	Cent. 1St. Vertical
22808 B	03/02/2003	2a	1494	Cent. 1St. Vertical
22808 B	03/02/2003	7j	1494	Cent. 1St. Vertical

22808 B	12/03/2007	2a	2992	Cent. 1St. Vertical
22808 B	21/06/2007	2a	3093	Cent. 1St. Vertical
22808 B	15/09/2007	2a	3179	Cent. 1St. Vertical
22901 A	10/03/2002	2a	1164	Cent. Multi stages
22901 A	29/08/2004	2a	2067	Cent. Multi stages
22901 B	08/05/2000	2a	493	Cent. Multi stages
22901 B	22/08/2000	2a	599	Cent. Multi stages
22901 B	29/11/2000	2a	698	Cent. Multi stages
22901 B	29/11/2000	7f	698	Cent. Multi stages
22901 B	18/09/2001	2a	991	Cent. Multi stages
22901 B	24/08/2005	2a	2427	Cent. Multi stages
22901 B	14/12/2005	2a	2539	Cent. Multi stages
22902 B	12/02/2001	2a	773	Cent. 1St. Horizontal
22902 B	28/08/2006	2a	2796	Cent. 1St. Horizontal
22902 B	28/08/2006	3a	2796	Cent. 1St. Horizontal
28356	08/10/2003	2a	1741	
28356	16/01/2004	3c	1841	

APPENTIX II

SUGGESTED MILESTONE FOR FYP I

No	Detail/ Week	1	2	3	4	5	6	7	8	9	10		11	12	13	14	15	16
1	Selection of Project Title	■	■									MID SEMESTER BREAK						
2	Preliminary Research		■	■	■	■	■	■	■	■	■							
	• Research on repairable system		■	■	■	■	■											
	• Research on probabilistic model						■	■	■	■	■							
3	Submission of Preliminary Report				●													
4	Project Work												■	■	■	■	■	■
	• Failure data collection												■	■				
	• Determine failure distribution														■	■	■	■
5	Submission of progress Report								●									
	Seminar									●								
6	Submission of Interim Report Final Draft																	●
7	Oral Presentation																	●

● Suggested milestone ■ Process

APPENTIX III

SUGGESTED MILESTONE FOR FYP II

No	Detail \ Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Doing literature review on Reliability Block Diagram (RBD)	■	■	■	■						**MID SEMESTER BREAK**					
2	Submission of Progress Report 1				●											
3	Using Blocksim to draw the RBD and build the reliability model					■	■	■	■							
4	Submission of Progress Report 2								●							
5	Seminar								●							
6	Touch-up and finalized the report									■		■	■	■		
7	Poster Exhibition											●				
8	Submission of Project Dissertation (soft bound)													●		
9	Oral Presentation														●	
10	Submission of Project Dissertation (Hard Bound)															●

● Suggested milestone ■ Process