Investigation of the Impact

Of Imperfect Repair and Maintenance

To System Availability

By

Ahmad Izzat Bin Rosli

Dissertation submitted in partial fulfilment of

The requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

SEPTEMBER 2013

Universiti Teknologi PETRONAS

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31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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TRONOH, PERAK

SEPTEMBER 2013

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.

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AHMAD IZZAT BIN ROSLI

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ABSTRACT

Reliability engineers use product life data to determine the probability of parts, components, and systems to perform their required functions for desired periods of time without failure, in specified environments. It is an important subject need to be stressed out for quality and productivity improvement by reducing rework and scrap. Availability of repairable system highly depends on the repair effectiveness. Repair effectiveness is a measurement of goodness of one repair. Repair effectiveness closely related to maintainability process which is time taken for repair and maintenance is lesser. The main objective of this paper is to establish a relationship between repair and maintenance effectiveness with the system availability, depending on the numbers of components in the system. Several setup of experimental simulation are done using the BlockSim software and the variables of restoration factors are changed to see its effect to the system availability. The experimental results showed that the imperfect repair and maintenance do give an effect to the system availability. The results clearly show that the imperfect repair and maintenance do gives an impact to the system availability but depending on the event distribution itself whether it is in increasing or decreasing failure rate.

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CHAPTER 1

INTRODUCTION

This chapter will describe the overview of the project which covers the following topics.

- Background of study
- Statement of Problem
- Objectives
- Scope of Study

1.1 BACKGROUND OF STUDY

Since the beginning of history, humanity has attempted to predict the future. All the components and machine part have their own life spend. Same goes to the human itself. How can one determine the end life of certain product? Most of system can be categorized into two basic types, non-repairable which is one time event and repairable system, the reusable consists of many components. Does the imperfect repair for repairable system effects the system availability? Reliability engineers use product life data to determine the probability and capability of parts, components, and systems to perform their required functions for desired periods of time without failure, in specified environments. In this paper, author will investigate more on the impact of imperfect repair and maintenance to system availability.

Nowadays, reliability field become one the most crucial and important subject that need to be focus in one organisation body. It is an important subject need to be stress out since it can improve quality and productivity hence reduce rework and scrap.

1.2 PROBLEM OF STATEMENT

This paper will discuss more on effect of imperfect repair and imperfect maintenance to the system availability. But how can we measure the goodness and the effectiveness of a repair itself? Hence user did not able to measure the system availability. It is significant to conduct a research to study the effects of imperfect repair and maintenance process. The improvement of the effectiveness during repair and maintenance time will result in the reduction of maintenance cost economically and ensure the high in efficiency of machinery operation. Effectiveness of the repair influenced the system availability. However, the impact has not been fully characterized. Therefore, this project is proposed to study the effect of the imperfect repair and maintenance to the system availability.

1.3 OBJECTIVE

The main objective of this paper is to establish a relationship between repair and maintenance effectiveness with the system availability, depending on the numbers of components in one system.

1.4 SCOPE OF STUDY

The effect of imperfect repair and maintenance to system availability will be then illustrated in a graphical chart so that we can predict the availability of one system using different range of repair and maintenance effectiveness start from zero to one, with various number of equipment. The scope of study will focus on the increasing and decreasing failure rate. The design of experiment is also done for different number in components.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses on the general idea of the project based on the following keywords.

- Imperfect repair and maintenance
- System availability
- Relation and Equation Generation

2.1 IMPERFECT REPAIR

2.1.1 WHAT IS REPAIR

A repairable system is a system which, after failing to perform one or more of its functions satisfactorily, can be restored to fully satisfactory performance by any method, rather than the replacement of the entire system [1]. Repair models developed upon successive inter-failure times have been employed in many applications such as optimisation of maintenance policies, decision making and whole life cycle cost analysis

Repair is defined as to restore or to sound condition after failure. Referring to L. Doyen (2004), "imperfect repair is performing standard maintenance which reduces failure intensity but does not leave the system as good as new," [2]. Different technician that performs maintenance on similar machine will give different outcome of maintenance due to their own technical ability and attitude which lead to different repair effectiveness. Other than that, different in part's quality do effect the repair effectiveness itself. Different in repair effectiveness, will drive to different in system availability.

2.1.2 WHY NEED TO REPAIR

The failure rate function will tell us the total time one system or machine can survive on specific time, *t* will fail during the next period of time [3]. In every production line or organization body, there will be a certain time that they need to perform maintenance and repair to the system. The process will involve fixing any sort of mechanical or electrical parts of a machine which keep the device in working order. It is usually known as scheduled maintenance or preventive maintenance. There are many advantages for having a good preventive maintenance program. The advantages apply to every kind and size of plant. From an article written by William C. Worsham (2011), there are several reasons why do we need to perform maintenance on the system and machine [4].

- Reduced production downtime, resulting in fewer machine breakdowns.
- Better conservation of assets and increased life expectancy of assets, thereby eliminating premature replacement of machinery and equipment.
- Reduced overtime costs and more economical use of maintenance workers due to working on a scheduled basis instead of a crash basis to repair breakdowns.
- Timely, routine repairs circumvent fewer large-scale repairs.
- Reduced cost of repairs by reducing secondary failures. When parts fail in service, they usually damage other parts.
- Reduced product rejects, rework, and scrap due to better overall equipment condition.
- Identification of equipment with excessive maintenance costs, indicating the need for corrective maintenance, operator training, or replacement of obsolete equipment.
- Improved safety and quality conditions.

2.1.3 TYPE OF REPAIR

With different repair levels, repair models can be broken down into three categories models for perfect repair, models for normal repair and models for minimal repair [5]. A perfect repair can restore the system as good as new, a normal repair can bring the system to any condition and a minimal repair can restore the system in the state it was before failure. Examples of models for perfect, normal and minimal repair are Homogeneous Poisson Process (HPP), Generalised Renewal Process (GRP) and Non-Homogeneous Poisson Process (NHPP) models, respectively.

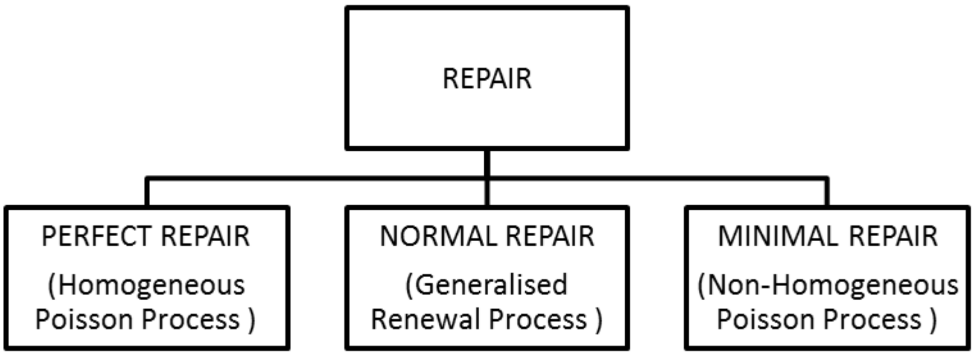


Figure 2.1: Type of Repair

Based on Figure 2.1, repair can be divided into three parts. According to the failure intensity of repair models, repair models fall into three categories: models with constant failure intensity (e.g., HPP models), models with time-dependent failure intensity (e.g., NHPP models) and models with repair-times- dependent failure intensity (e.g., geometric process (GP) models) [6].

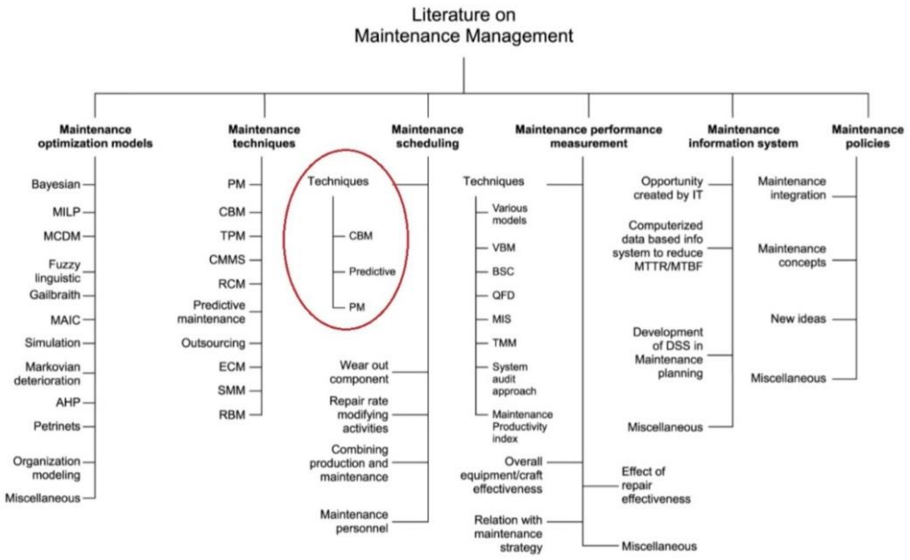
2.1.4 TYPE OF MAINTENANCE

Repair and maintenance need to be performing differently depending on various types of components and time basis. Repair or maintenance can be classified into several types:

(i) Breakdown Maintenance

(ii) Predictive Maintenance

(iii) Preventive Maintenance



Notes: MILP: Mixed Integer Linear Programming; MCDM: Multiple Criteria Decision Making; MAIC: Materially per Apparecchiature de Impiariti Chemiei; AHP: Analytic Hierarchy Process; PM: Preventive Maintenance; CBM: Condition Based Maintenance; TPM: Total Productive Maintenance; CMMS: Computerized Maintenance Management Systems; RCM: Reliability Centered Maintenance; ECM: Effectiveness Centered Maintenance; SMM: Strategic Maintenance Management; RBM: Risk Based Maintenance; VBM: Vibration Based Maintenance; BSC: Balanced Score Card; MTTR: Mean Time to Repair; MTBF: Mean Time Between Failure; QFD: Quality Function Deployment; MIS: Maintenance Information Systems; TMM: Total Maintenance Management; DSS: Decision Support Systems; ECM: Electronic Counter Measures

Figure 2.2: Literature on Maintenance Management [7].

2.1.4 (i) Breakdown Maintenance

Breakdown Maintenance also known as “run it till it breaks” maintenance mode. If we are dealing with new equipment, we can expect minimal incidents of failure. If our maintenance program is purely reactive, we will not expend manpower dollars or incur capital cost until something breaks. Since we do not see any associated maintenance cost, we could view this period as saving money. Referring Deshmukh, S. G. (2006), “this is a process of deteriorating of a single unit system which is based on regenerative and semi-regenerative process theory,” [7]. Table 2.1 show advantages and disadvantages of using condition breakdown maintenance type in maintenance scheduling [8].

Table 2.1: Advantages & Disadvantages of Breakdown Maintenance

ADVANTAGES	DISADVANTAGES
• low cost • less staff	• increased due to unplanned downtime of equipment • increased labor cost, especially if overtime needed • cost involved with repair or replacement of equipment • possible secondary equipment or process damage from equipment failure • inefficient use of staff resources

2.1.4 (ii) Predictive Maintenance

Predictive maintenance consists in deciding whether or not to maintain a system according to its state [7]. This maintenance can also be define as the measurements that detect the onset of system degradation (lower functional state), thereby allowing causal stressors to be eliminated or controlled prior to any significant deterioration in the component physical state. Table 2.2 show advantages and disadvantages of using predictive maintenance type in maintenance scheduling [8].

Table 2.2: Advantages & Disadvantages of Predictive Maintenance

ADVANTAGES	DISADVANTAGES
•Increased component operational life/availability. •Allows for preemptive corrective actions. •Decrease in equipment or process downtime. •Decrease in costs for parts and labor. •Better product quality. •Improved worker and environmental safety. •Improved worker morale. •Energy savings. •Estimated 8% to 12% cost savings over preventive maintenance program.	•Increased investment in diagnostic equipment. •Increased investment in staff training. •Savings potential not readily seen by management.

2.1.4 (iii) Preventive Maintenance

Referring Deshmukh, S. G. (2006), "A series of tasks performed at a frequency dictated by the passage of time, the amount of production, machine condition that either extend the life of an asset or detect that an asset had critical wear and is going to fail or break down constitute cycle known as preventive maintenance," [7]. It also can be define as an actions performed on a time- or machine-run-based schedule that detect, preclude, or mitigate degradation of a component or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level. Table 2.3 show advantages and disadvantages of using preventive maintenance type in maintenance scheduling [8].

Table 2.3 Advantages & Disadvantages of PM

ADVANTAGES	DISADVANTAGES
•cost effective in many capital-intensive processes. •Flexibility allows for the adjustment of maintenance periodicity. • Increased component life cycle. •Energy savings. •Reduced equipment or process failure. •Estimated 12% to 18% cost savings over reactive maintenance program	•Catastrophic failures still likely to occur. •Labor intensive. •Includes performance of unneeded maintenance. •Potential for incidental damage to components in conducting unneeded maintenance.

2.2 SYSTEM AVAILABILITY

2.2.1 WHAT IS AVAILABILITY

Referring Mikell (2008),"availability refer to proportion of the total desired operating time that the machine is actually available and operating," [9]. Availability can be defined as the probability that a system or component is performing its required function at a given point in time or over a stated period of time when operated and maintained in prescribed manner [10]. It is very important for the study the factor of availability. The use of one system or machine can be fully utilized if the availability factor of it can be achieved. There is certain factor that can affect the availability itself. There factor of availability can lead to available time of one system or a machine. For example, we can calculate the available time of automated guide vehicle in production line. The percentage of its available time within one hour, drive from variable factor such as the traffic congestion in production line, efficiency of manual driver who drove it and distance of driver to the vehicle itself. It is impossible to have hundred percent of available time within one hour but the entire factor that lead in decreasing in hundred percent of available time of this machine can be avoid thus maximizing the availability of the machine.

2.2.2 MTBF & MTTR

Mean time to between failures is the average length of unit time the piece of equipment run between the two points of breakdown. Mean time to repair is an average time needed to repair a broke down system or machine and put it back into the system of the operation.

2.2.3 RELATION

There are three types of availability measures. Inherent, achieved, and operational is different type of availability measures [11].

Different types carry different philosophy and factor calculating the availability but end up having same objective which is finding the number of availability of a system. Inherited availability, is common measure of availability which only considering the mean time before failure and mean time to repair. It is a steady state availability which considers only corrective maintenance (CM).

Equation 2.1 shows the relation between system inherent availability, Ai with mean time between failures, $MTBF$ and mean time to repair, $MTTR$

$$Ai = \frac{MTBF}{MTBF+MTTR} \tag{2.1}$$

Second is the achieved availability. Basically it is same with the inherent availability but with the exception that preventive maintenance (PM) downtime are also included and considered because during the maintenance, the system also need to be shut down. Specifically, it is the steady state availability in an ideal support environment. This type of availability referred to availability seen by maintenance and equipment engineering department. This kind of measurement are not included the logistic delay, supply delay and administrative delay.

Equation 2.2 shows the relation between achieved availability, Aa with the mean time between maintenance action, $MTBMA$ and mean maintenance time, MMT

$$Aa = \frac{MTBMA}{MTBMA + MMT} \tag{2.2}$$

Assuming that the constant failure rate $MTBMA$ in the Equation 2.3 can be calculated as:

$$MTBMA = \frac{1}{\lambda + f_{PM}} \tag{2.3}$$

The $MTBMA$ is a relation of failure rate, λ with the assumption of all failure have been repaired and the frequency of preventive maintenance (PM),f_{PM}.

Equation 2.4 shows the main maintenance time, MMT can be further decomposed into the effect of preventive and corrective maintenance as:

$$MMT = \frac{\lambda \, MTTR + \, f_{PM} \, MPMT}{\lambda + f_{PM}} \tag{2.4}$$

Where $MTTR$ is the mean corrective maintenance time and $MPMT$ is the mean preventive maintenance time.

The measurement of availability also can be expressed into another type which is the operational availability as shown in Equation 2.5. Operational availability is a measure of the "real" average availability over a period of time in an actual operational environment. It include all experienced source of downtime, such as administrative downtime, logistic downtime and so on

$$Aop = \frac{MTBMA}{MTBMA + MDT} \tag{2.5}$$

Equation 2.5 show the relationship between the operational availability, Aop with the mean time between maintenance action, $MTBMA$ and the mean maintenance downtime, MDT

Where:

$$MD = MMT + (logistic\ delay\ time) + (administrative\ delay\ time)$$

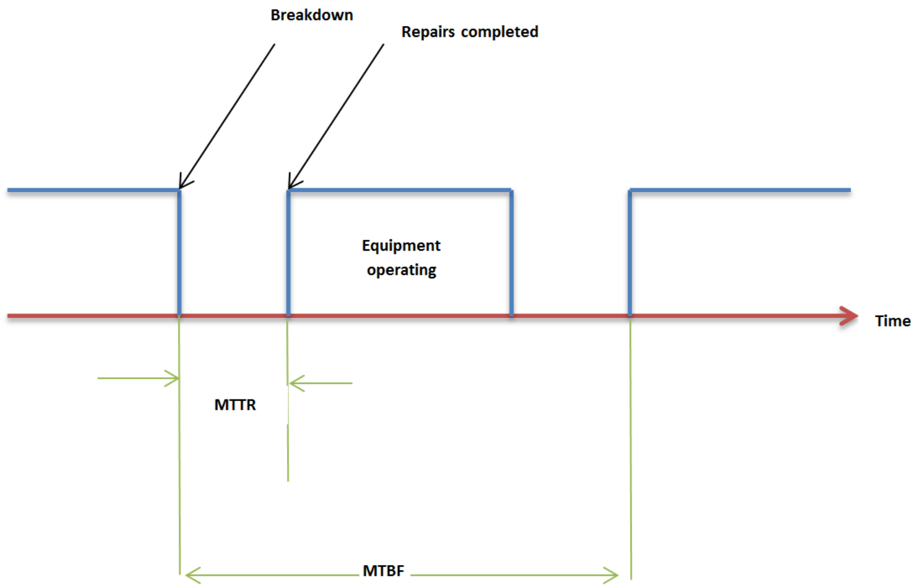


Figure 2.3: Time Scale Showing MTTF and MTTR

Basically the main factor needed in calculating the availability is just the uptime and the downtime of one system. Most organization that uses uptime and downtime as the variable needed in calculating the availability simply not considering any others factor of downtime itself. It will result in lagging in time which they should see future of the system, leading. It is very important to analyze every aspect of machine downtime so that the misinterpretation of data and result will not occur during the data crunching process. Main factor that lead to downtime process can be divided into several type based on the three availability measurement above which are inherent availability, achieved availability and operational availability.

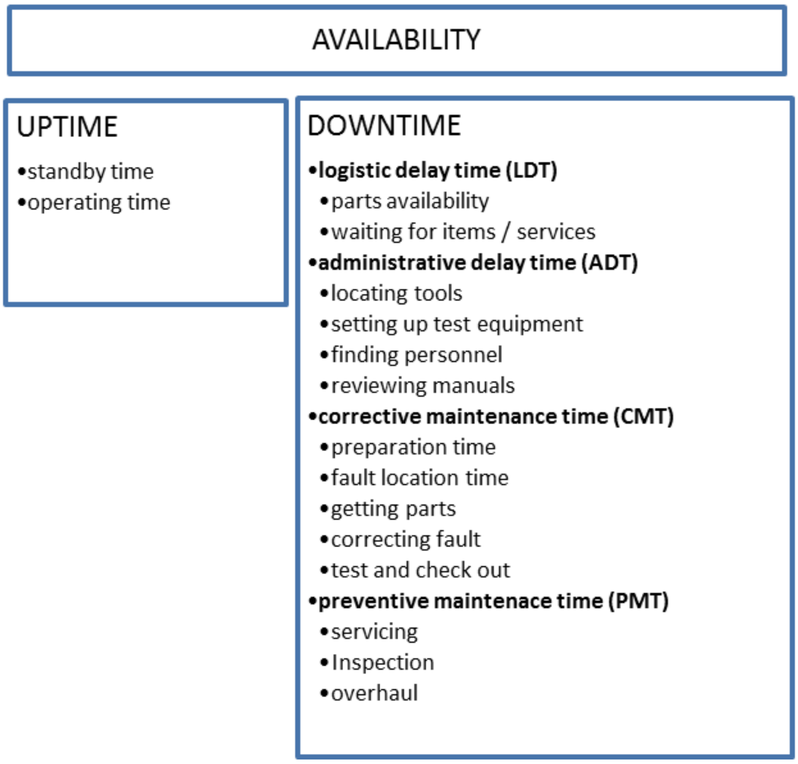


Figure 2.4: Uptime and Downtime

2.3 RELATION AND EQUATION GENERATION

2.3.1 GENERALIZED RENEWAL PROCESS

A repairable system can be divided into five main possible states after a repair process completed:

States of repair	as good as new
	as bad as old
	better than old but worse than new
	better than new
	worse than old

Any kind of failure and downtime are caused by faulty component. After the replacement of the components, the whole system's age will be newer than the old one due to the system replacement. So the system will work better than before replacement.

Recently, Kijima and Sumita have developed a theory of generalized renewal process. According to their research, they found out that the generalized renewal theory from the renewal theory in the context of imperfect repair and applied it to repairable systems with the concept of virtual age. The assumption of virtual age of components after repair related to the repair effectiveness show an important of good repair effectiveness in order to set back virtual age of component back to zero Since this pioneering work, much of imperfect repair modelling literature builds up on Kijima's models based on the Generalized Renewal Process [12]. Kijima Type 1 assumes the repair can only remove the damage incurred from last repair while Kijima Type 2 assumes the repair can remove all cumulative damagea [13]. These statements will be proved in the equation below.

Kijima Type 1

$$v_i = v_{i-1} + qx_i$$
$$v_i = q(x_1 + x_2 + ... + x_i) = qt_i \qquad (2.6)$$

Where:

xi – failure times

vi - virtual age of the system right after *i* repair

q - repair effectiveness factor

Kijima Type 2

$$v_i = q(v_{i-1} + x_i) \qquad (2.7)$$

Where:

xi – failure times

vi - virtual age of the system right after *i* repair

q - repair effectiveness factor

Referring to A.G.Jacopino (2005), he said that Kijima Type 1 can be used for individual components such as compressor, pump and separator while Kijima Type 2 can be illustrated for complex components such as aircraft and car [14].

Kijima introduced the concept of virtual age to be the basis for generalized renewal process. If a system has virtual age $\mathbf{V_{n-1} = y}$ immediately after **(n-1)th** repair, the **nth** failure time **X** is distributed according to the following cumulative distribution function (CDF) [15].

$$G(x) = F(X \mid V_{n-1} = y) = \frac{F(X + y) - F(y)}{1 - F(y)}$$
$$= 1 - \frac{R(X + y)}{R(y)} \quad (2.8)$$

Where:

F(x) is a cdf, the time to first failure (TTFF) of a new system and

R(x) =1-F(x) is the reliability at the respective time

With the assumption that the time to first failure follow a two- parameter Weibull distribution, the probability density function (PDF) is given as

$$f(t_1 \mid \beta, \eta) = \frac{\beta}{\eta}\left(\frac{t_1}{\eta}\right)^{\beta-1} e^{-\left(\frac{t_1}{\eta}\right)^{\beta}} \quad (2.9)$$

$$G(x_i \mid \beta, \eta, q) = 1 - \exp\left\{\left(\frac{qt_{i-1}}{\eta}\right)^{\beta} - \left(\frac{qt_{i-1} + x_i}{\eta}\right)^{\beta}\right\} \quad (2.10)$$

Where:

β – shape parameter

η – scale parameter

q - repair effectiveness factor

2.3.2 BATHTUB CURVE

Three are three basic ways in which the pattern of failure can change with time. The hazard rate may be decreasing, increasing or constant [16]. Decreasing hazard rate is observed in item which becomes less likely to fail as their survival time increase. This is often observed in electronic equipment and parts. 'Burn in' of electronic equipment and parts is a good example of the way in which knowledge of decreasing hazard rate is used to generate an improvement in reliability.

A constant failure rate is the characteristic of failure which the rate of occurrence is constants throughout the time. For example, overstress failures due to accidental or transient circuit overload, or maintenance- induced failure of mechanical equipment. Typically randomly and occur generally constant rate.

Wear out failure mode follows an increasing failure rate. For example, material fatigue brought about by strength deterioration due to the cycle loading is a failure mode which does not occur for a finite time, and then exhibits an increasing probability of occurrence.

The combined effect of all three increasing, decreasing, and constant failure rate produce a bathtub curve which consists of three region of failure which are:

- Infant mortality
- Useful life
- Wear out

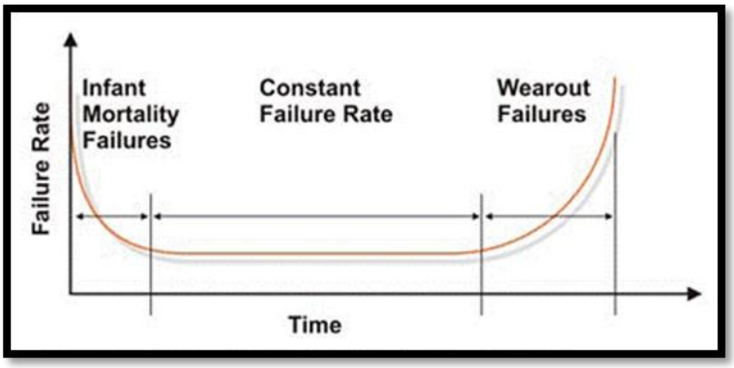


Figure 2.5: Bathtub Curve

2.3.3 WEIBUL DISTRIBUTION

The distribution of Weibul can handle increasing, decreasing or constant failure-rates and can be created for data with and without suspensions (non-failures) [17]. Weibull distribution is flexible and fits to a wide range of data; including Normal distributed data. Weibull distribution can be described in three parameter which are β the shape or slope parameter, η the scale and characteristic life and γ the location parameter [15, 18]. In describing the bathtub curve, value of β will reflect the hazard function or the expected failure rate of the Weibull distribution and interference can be drawn about a population's failure characteristic by considering whether the value β is less than, equal to, or greater than one. The relationship between the value of β and the corresponding section can be clearly seen in Figure 2.4.

If $\beta < 1$ indicates a decreasing failure rate and usually associated with infant mortality [15]. Some literatures describe it as an early failure. It often corresponds to manufacturing related failures and failures records shortly after the production. The first region of the bathtub curve is the region of infant mortality and β value less than 1 or decreasing failure rate region.

If $\beta = 1$ is a constant failure rate and usually related to region of the useful life [15]. Constant failure rate, which often corresponding to the mid-section of a life for a certain product and can be a result of random failure or mixed failure mode. Based on the bathtub curve, useful life is second or middle regions consist of straight parallel line of failure.

If $\beta > 1$ indicates an increasing failure and is usually associated with wear out [15]. If recorded at the beginning of the product life cycle, it can be a sign of a serious design problem. The last region of bathtub curve indicates the increasing failure rate.

CHAPTER 3

METHODOLOGY

3.1 RESEARCH METHOLOGY

In order to complete his project, the author had to do some research on how a pre-commissioning project is executed. Some of the methods conducted were:

1. Primary Data Collection

   During his attachment to the project, the author interacted and discussed frequently with the line production engineers, supervisors and operators regarding the project which related to the system availability and investigate the effect of imperfect repair to the system. Observation been done throughout the time period and see the effect of this factor to the system availability. Frequent discussions with supervisor do help lot during this project attachment. Data collected are analysed and compared with the existing research done by others.

2. Secondary Data Collection

   Certain information was obtained from the Internet since it is a vast repository of information. Theoretical information also had been dig up through research and review of related literature. Gantt chart used in order to make sure that all the project progressions is on time. Uses of key mile stone help author to make some benchmarking and identify the datum.

3. Project attachment

   In the end of this project, author will be able to create a table with three parameters which are different number of system, system availability and factor “q”. Using BlockSim software, author will replicate the system of one real life line production into the software to gather data and information in order to tabulate the three parameter graph.

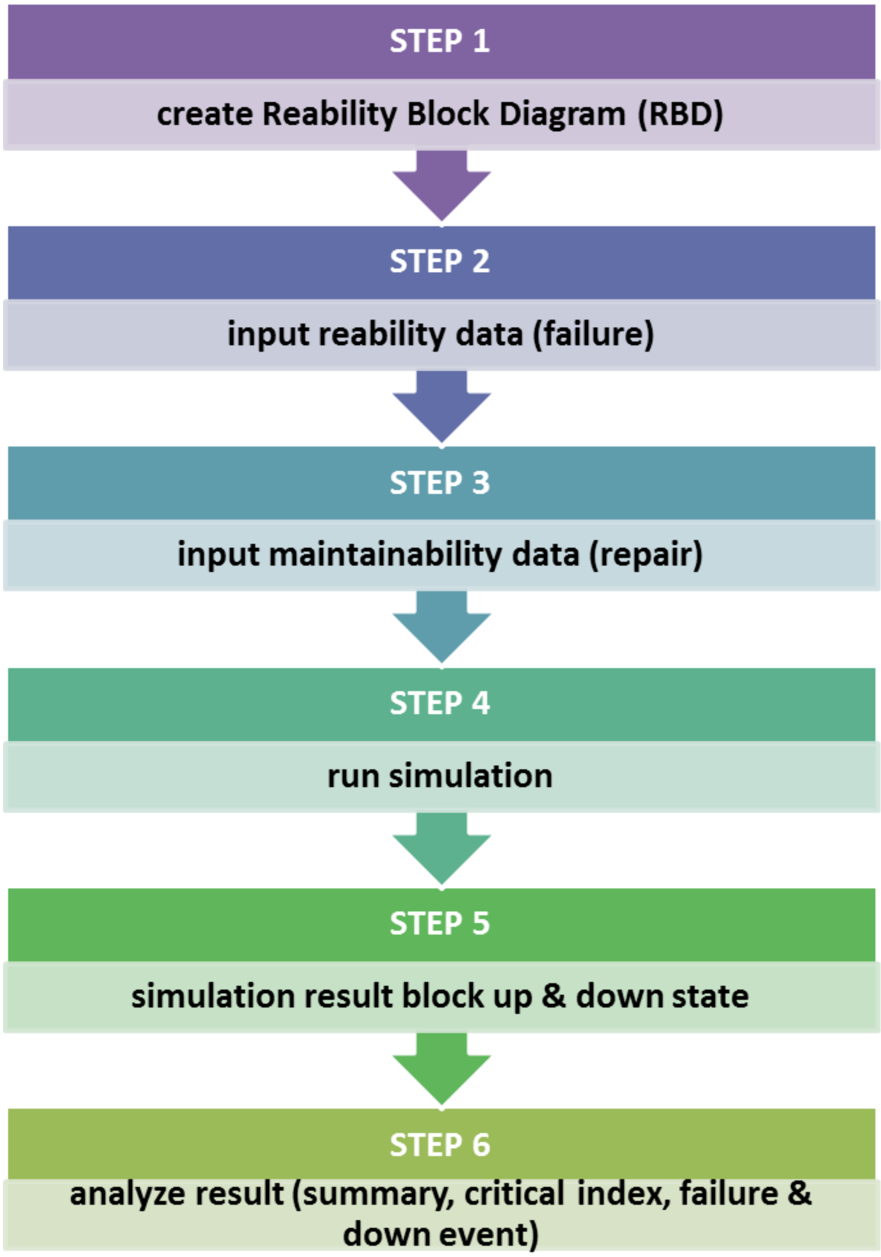


Figure 3.1: Simulation Procedure

Figure 3.1, shows steps for simulation steps for BlockSim software. Firstly, the Reliability Block Diagram was replicated in the software before the reliability and maintainability factors were plug in to the system. Repair effectiveness which is the manipulated variable is changed to see its effect to system availability. After that the simulation results were analysed and translated to graphical chart.

3.2 KEY MILESTONE

Before completing a report, milestones have to be set so that the report can be completed in a timely manner. For this project, the milestones are:

- To become familiar with reliability field.
- Replicate real life situation into software and make analysis
- To be proficient in using the necessary tools such as BlockSim, Microsoft Project, Word and Excel

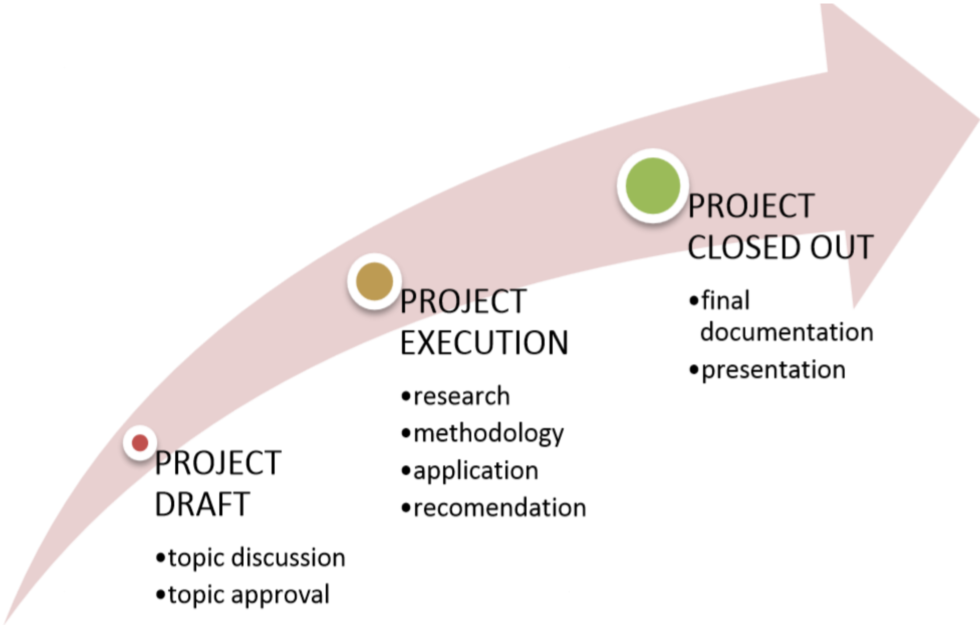


Figure 3.2: Key Milestone

3.3 FLOW CHART

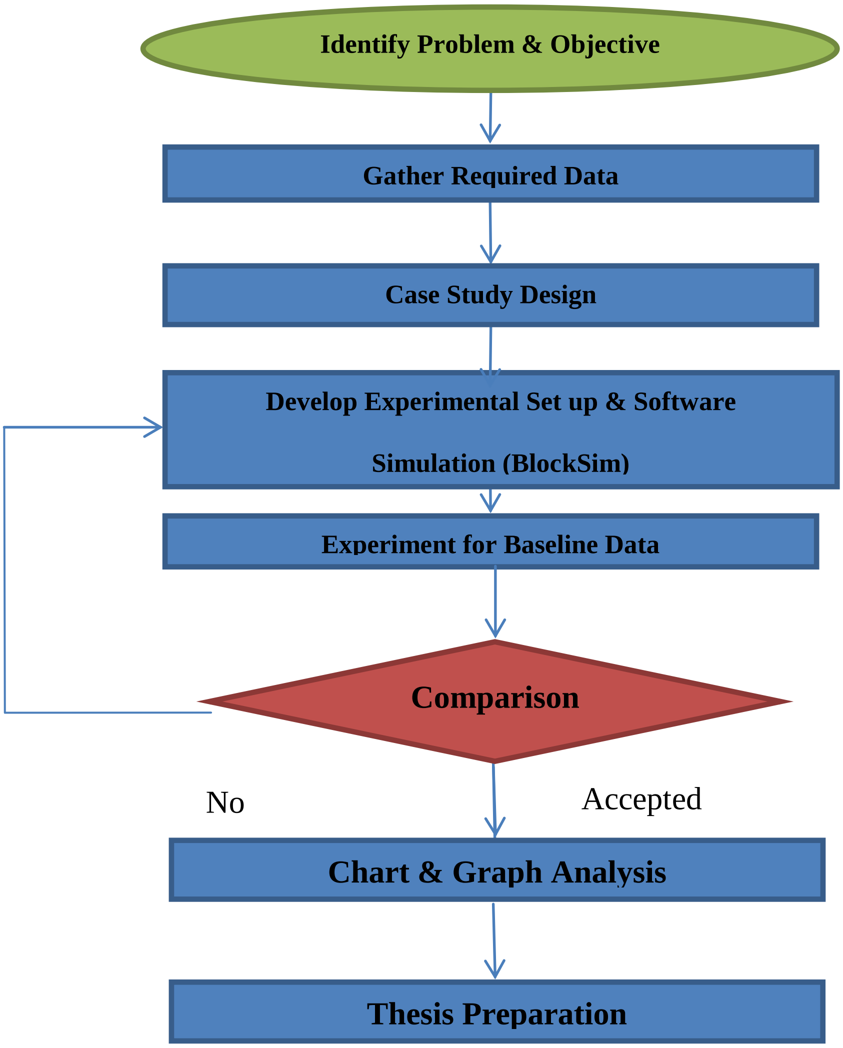


Figure 3.3: Flow Chart of Project General Approach

Figure 3.3 show summary of step for project flow. Project life cycle starting with defining period consists of problem identification and data gathering process. It will define the baseline and goal of end product of study. During the planning period, the development of simulation and concept design were conducted here. After that the simulation and analysis part were done and the comparisons of data were made under the execution period. Delivering period was done on the last part of project for thesis preparation.

3.4 GANTT CHART

Apart from that, a Gantt chart is used to ensure that the author's project is progressing on time. It is also important to increase project efficiency and performance. Gantt chart also provided framework for decision making.

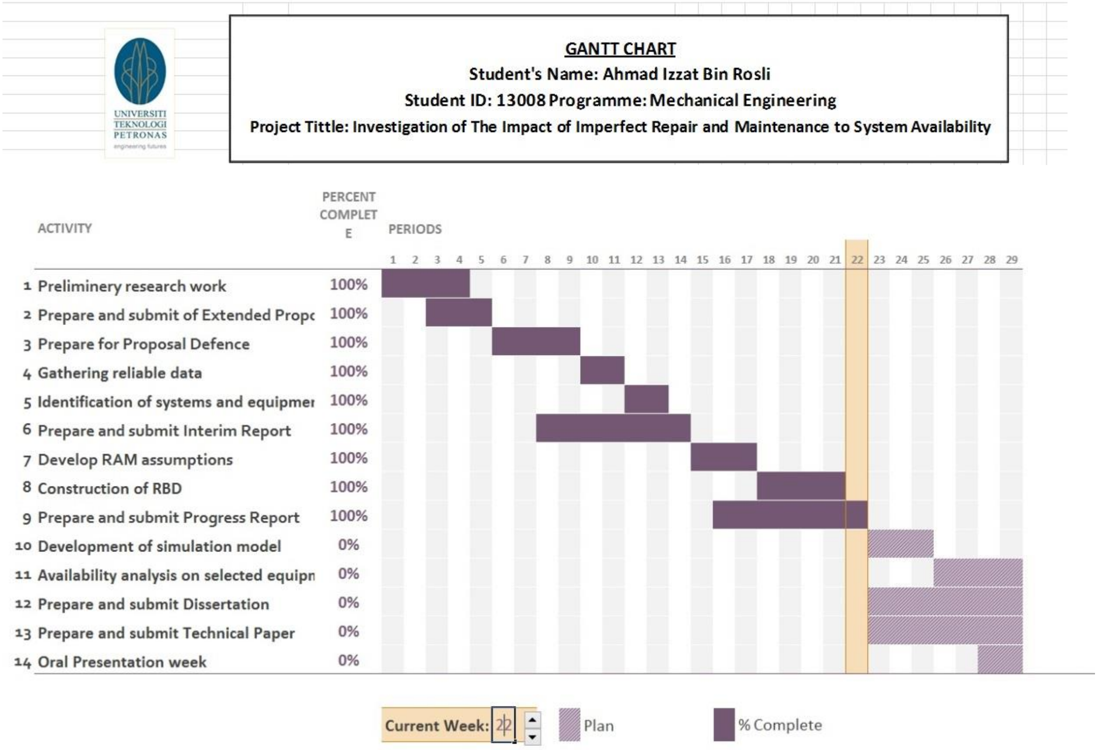


Figure 3.4: Gantt chart

3.4 TOOLS OF PROJECT DEVELOPMENT

To complete this project, a few tools were used extensively. They are:

- Microsoft Word
- Microsoft Project
- Microsoft Excel
- BlockSim

3.4.1 BLOCKSIM

BlockSim supports an extensive array of reliability block diagram (RBD) configurations and fault tree analysis (FTA) gates and events, including advanced capabilities to model complex configurations, load sharing, standby redundancy, phases and duty cycles. Using exact computations and/or discrete event simulation, BlockSim facilitates a wide variety of analyses for both repairable and non-repairable systems. This includes:

- System Reliability Analysis
- Identification of Critical Components
- Reliability Optimization
- System Maintainability Analysis (Determine Optimum Preventive Maintenance Intervals, etc.)
- System Availability Analysis (Calculate Uptime, Downtime, Availability)
- Throughput Calculation (Identify Bottlenecks, Estimate Production Capacity)
- Resource Allocation for Maintenance Planning
- Life Cycle Cost Analysis

BlockSim is a software use in order to perform an analysis of complex system reliability, maintainability and availability analysis and optimization using a reliability block diagram (RBD) approach, a fault tree diagram (FTD) approach or a combination of both. During the project attachment, this software will be use more on system availability analysis focusing on the different in the restoration factor which is repair quality and see does this factor really affecting the system availability.

CHAPTER 4

RESULT AND DISCUSSION

Complex systems consist of several components which work together differently to performing complex system work. It is useful to see each components characteristic in calculating system availability. Different components will have different reliability, different maintenance policy which will contribute to different system availability. The configuration of each component also will affect the total reliability. In this chapter, author will focus on the simulation part and show the effect of imperfect repair to the system availability.

4.1 DESIGN OF EXPERIMENT

Several experimental set up have been made in order to see the effect of the various parameter to the system availability. Design of experiment has been made using BlockSim software in order to simulate the system availability with various manipulated variable. The distribution of the event is assumed in Weibull form since the objective of the paper is to see the effect of imperfect repair and maintenance to system availability. Exponential distribution will not give the effect in availability since it is already in constant failure rate model. Weibull distribution can be described in three parameter which are β the shape or slope parameter, η the scale and characteristic life and γ the location parameter. Batch experiments were conducted varying value of β, η and q which is the restoration factor and see the effect in system availability. The numbers of component and its configuration, series and parallel are also be the variable during the experiment been conducted.

4.1.1 EXPERIMENT 1

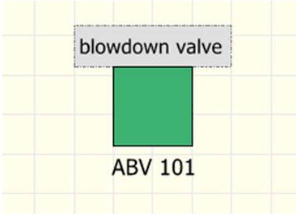


Figure 4.1: Reliability Block Diagram of Experiment 1

Figure 4.1 shows the experimental set up done for single component; blow down valve ABV 101 with different β value which is 0.5 and 3 respectively.

- Manipulated variable : Repair effectiveness
- Responding variable : Availability

Firstly, the experiments run for β value equal to 0.5 which is in region of infant mortality, decreasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 0.5, which is decreasing failure rate, it clearly shows that the availability of the system is reducing with different restoration factor. Figure 4.2 shows the system availability range from 66.820% to 62.900%.

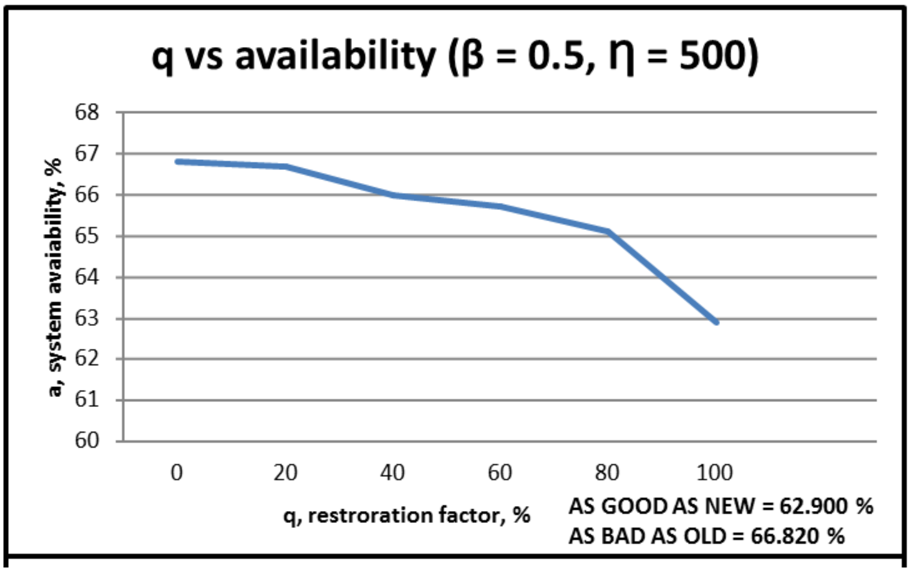


Figure 4.2: Graph of restoration factor versus availability for infant mortality period

Next, the experiments run for β value equal to 3.0 which is in region of wear out period, increasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 3.0, which is increasing failure rate, it clearly shows that the availability of the system is increasing with different restoration factor. Figure 4.3 shows the system availability range from 59.020% to 53.780%.

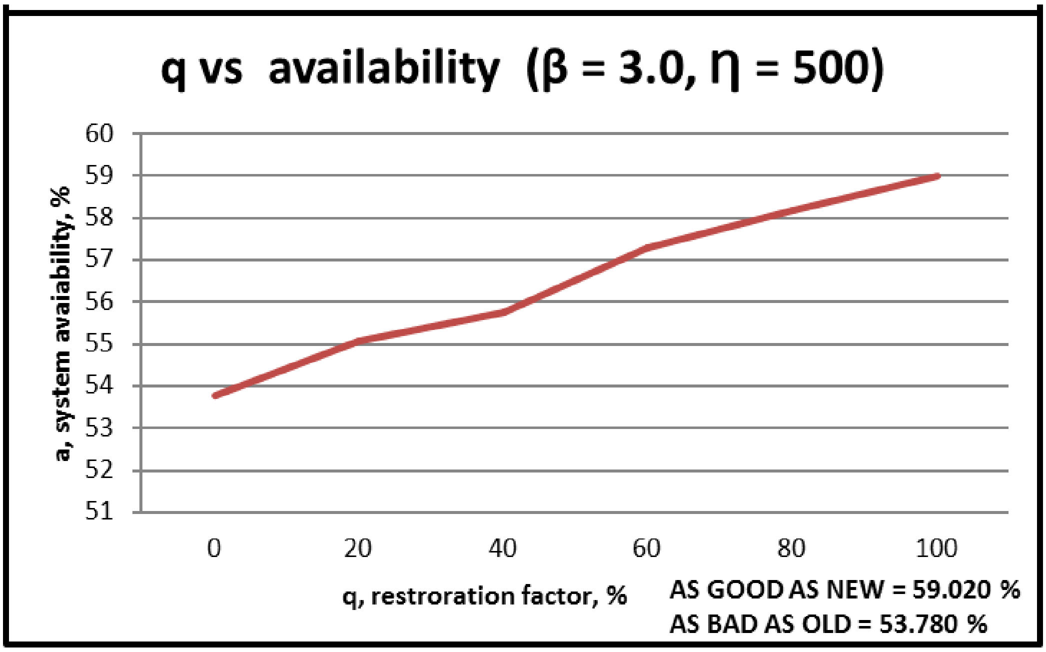


Figure 4.3: Graph of restoration factor versus availability for wear out period

4.1.2 EXPERIMENT 2

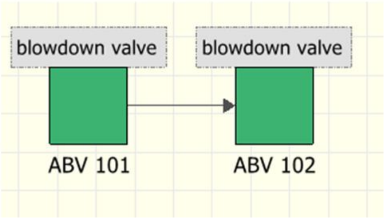


Figure 4.4: Reliability Block Diagram of Experiment 2

Figure 4.4 shows the experimental set up done for two components in series configuration with different β value which is 0.5 and 3 respectively.

- Manipulated variable : Repair effectiveness
- Responding variable : Availability

Firstly, the experiments run for β value equal to 0.5 which is in region of infant mortality, decreasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 0.5, which is decreasing failure rate, it clearly shows that the availability of the system is reducing with different restoration factor. Figure 4.5 shows the system availability range from 46.347% to 41.885%.

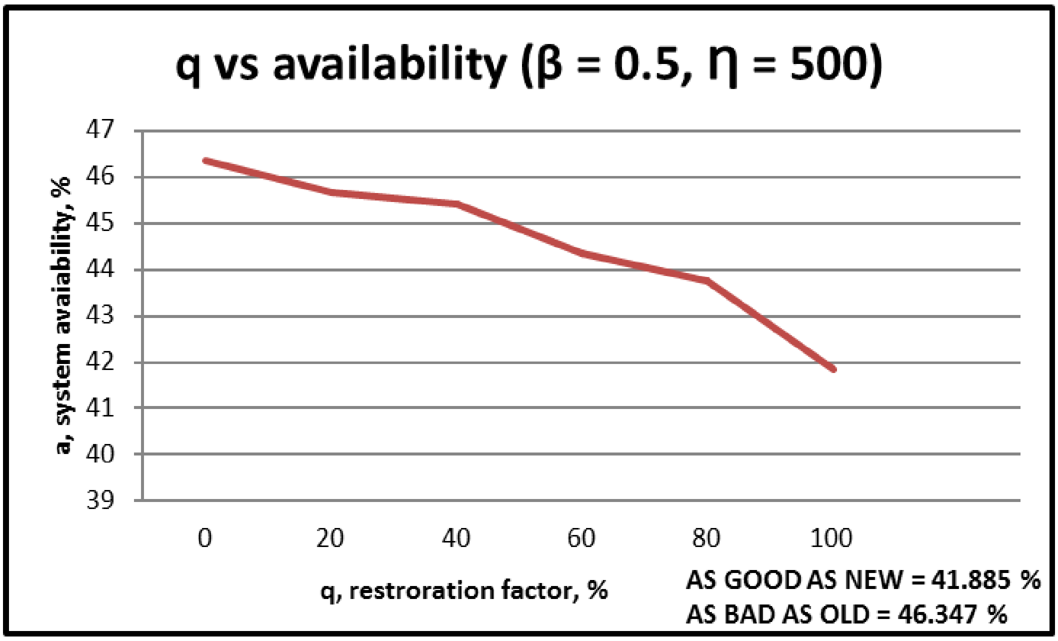


Figure 4.5: Graph of restoration factor versus availability for infant mortality period

Next, the experiments run for β value equal to 3.0 which is in region of wear out period, increasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 3.0, which is increasing failure rate, it clearly shows that the availability of the system is increasing with different restoration factor. Figure 4.6 shows the system availability range from 48.010% to 45.221%.

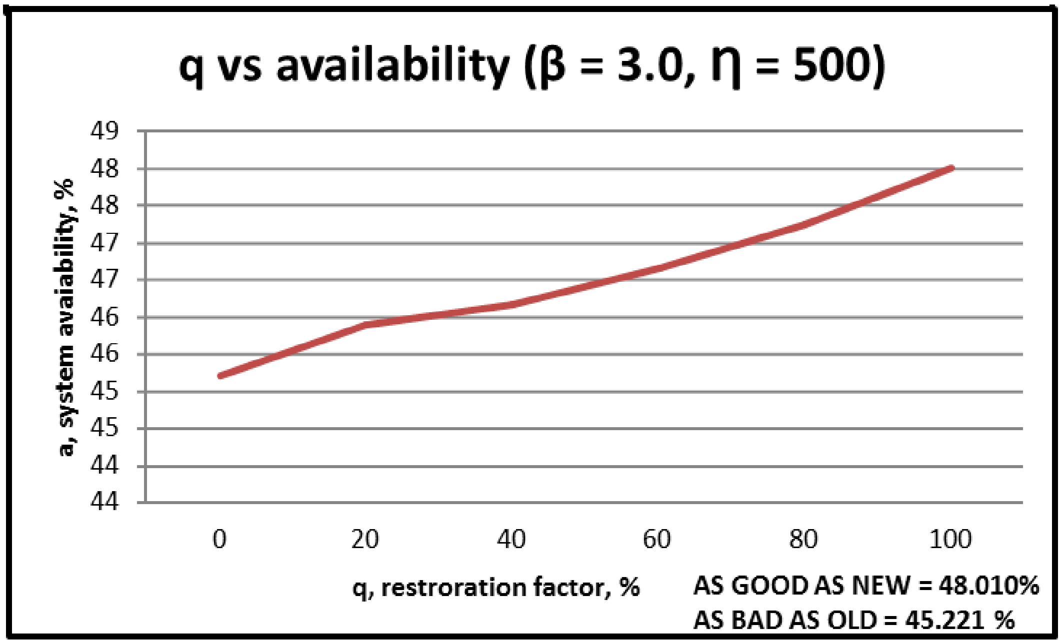


Figure 4.6: Graph of restoration factor versus availability for wear out period

4.1.3 EXPERIMENT 3

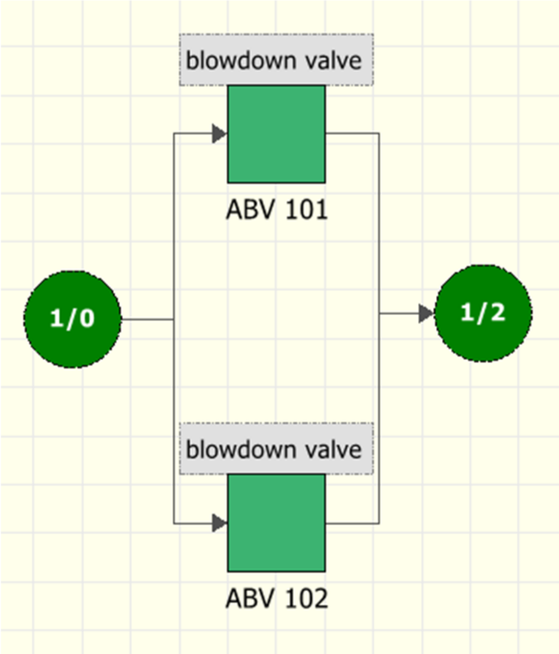


Figure 4.7: Reliability Block Diagram of Experiment 3

Figure 4.7 shows the experimental set up done for two components in parallel configuration with different β value which is 0.5 and 3 respectively.

- Manipulated variable : Repair effectiveness
- Responding variable : Availability

Firstly, the experiments run for β value equal to 0.5 which is in region of infant mortality, decreasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 0.5, which is decreasing failure rate, it clearly shows that the availability of the system is reducing with different restoration factor. Figure 4.8 shows the system availability range from 88.843% to 85.379%.

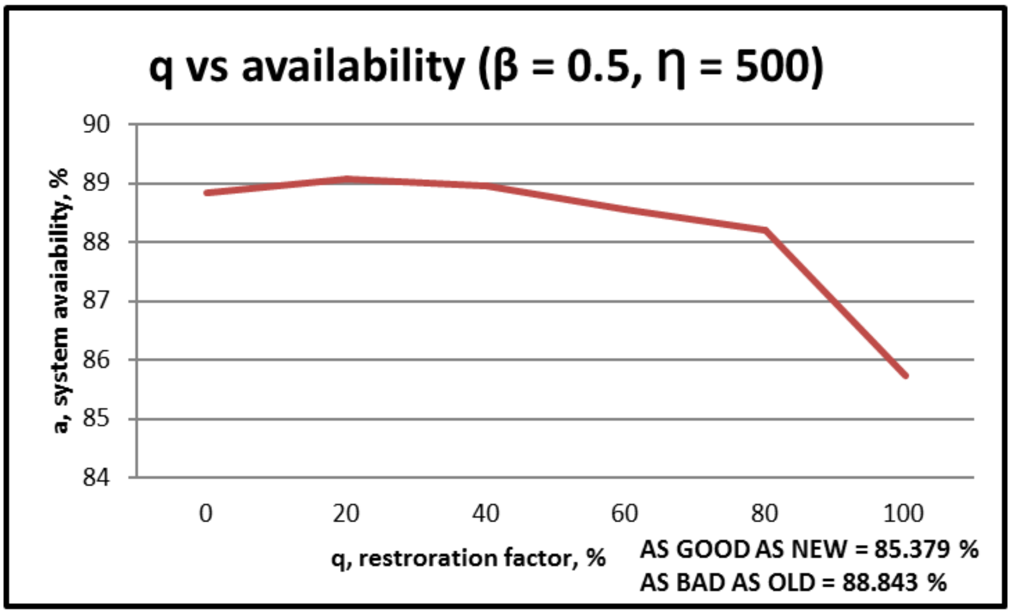


Figure 4.8: Graph of restoration factor versus availability for infant mortality period

Next, the experiments run for β value equal to 3.0 which are in region of wear out period, increasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 3.0, which is increasing failure rate, it clearly shows that the availability of the system is increasing with different restoration factor. Figure 4.9 shows the system availability range from 75.916% to 68.900%.

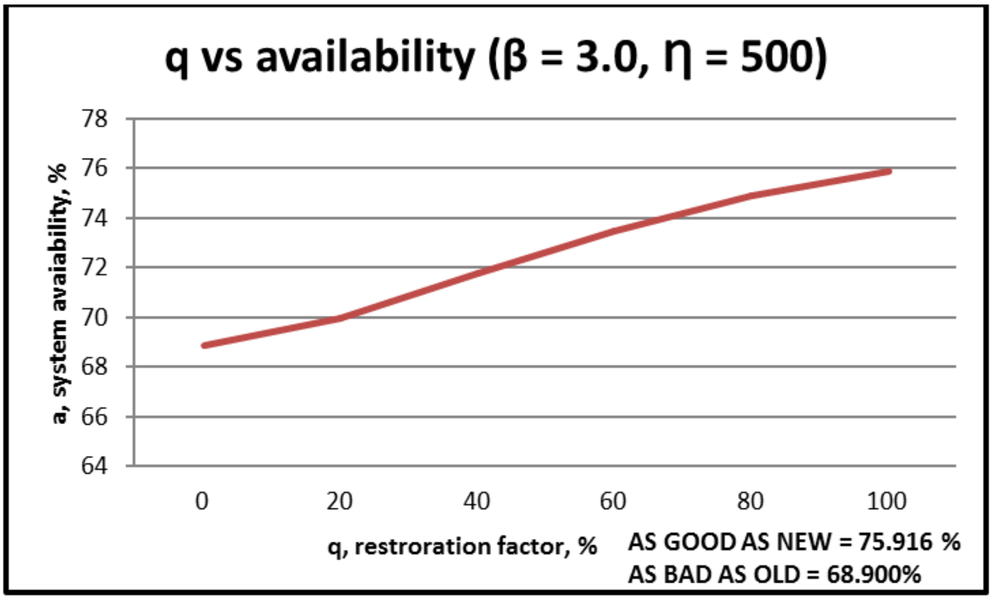


Figure 4.9: Graph of restoration factor versus availability for wear out period

4.1.4 EXPERIMENT 4

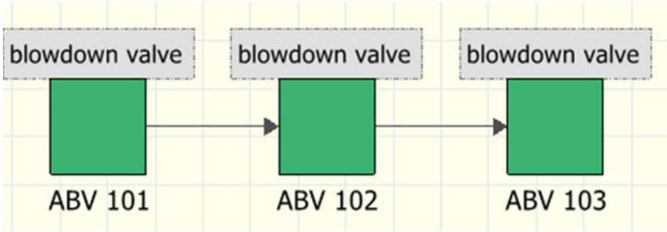


Figure 4.10: Reliability Block Diagram of Experiment 4

Figure 4.10 shows the experimental set up done for three components in series configuration with different β value which is 0.5 and 3 respectively.

- Manipulated variable : Repair effectiveness
- Responding variable : Availability

Firstly, the experiments run for β value equal to 0.5 which is in region of infant mortality, decreasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 0.5, which is decreasing failure rate, it clearly shows that the availability of the system is reducing with different restoration factor. Figure 4.11 shows the system availability range from 31.749% to 29.086%.

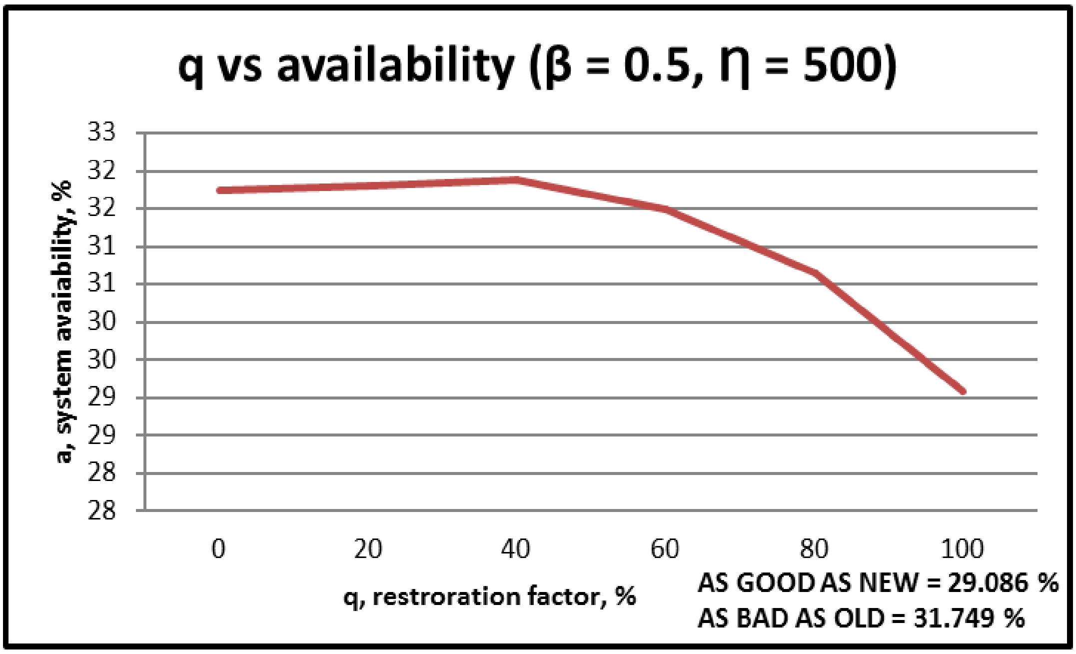


Figure 4.11: Graph of restoration factor versus availability for infant mortality period

Next, the experiments run for β value equal to 3.0 which are in region of wear out period, increasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 3.0, which is increasing failure rate, it clearly shows that the availability of the system is increasing with different restoration factor. Figure 4.12 shows the system availability range from 42.2016% to 40.170%.

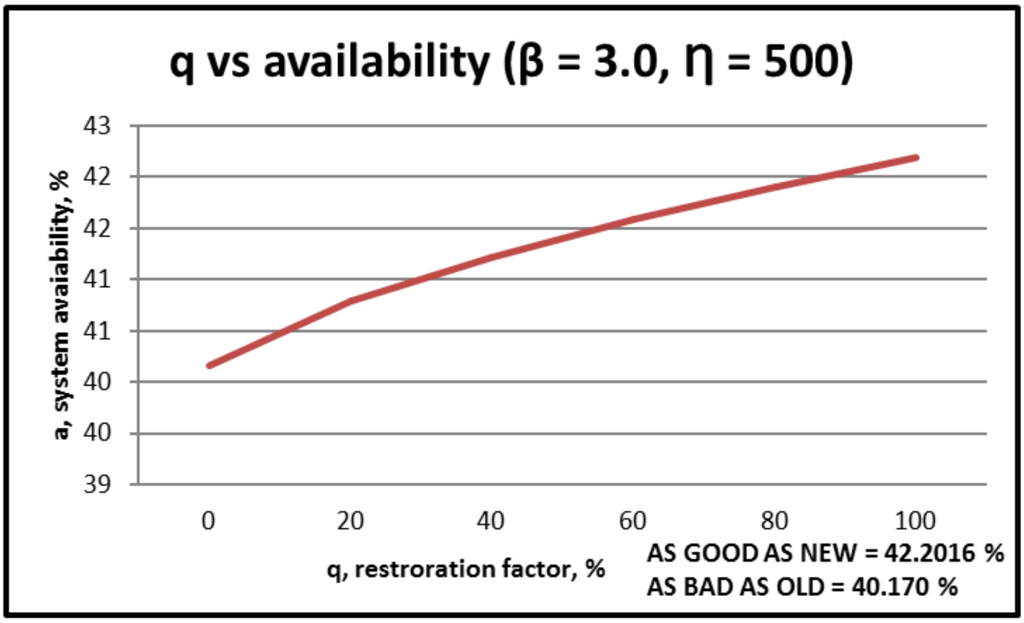


Figure 4.12: Graph of restoration factor versus availability for wear out period

4.1.5 EXPERIMENT 5

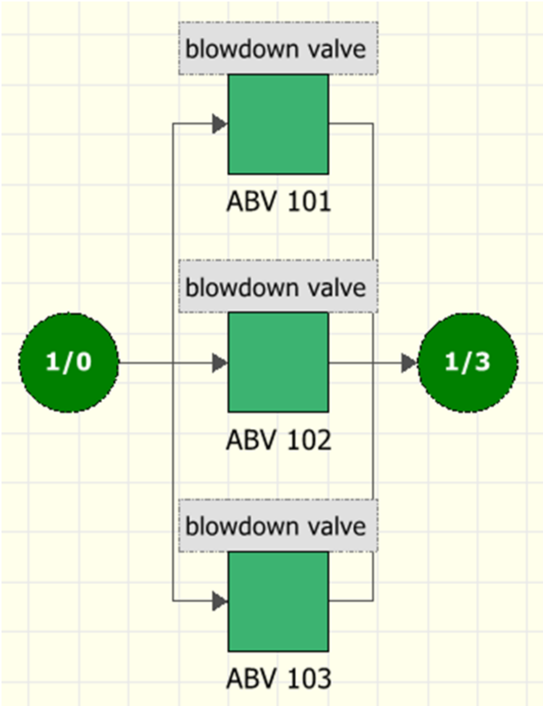


Figure 4.13: Reliability Block Diagram of Experiment 5

Figure 4.13 shows the experimental set up done for three components in parallel configuration with different β value which is 0.5 and 3 respectively.

- Manipulated variable : Repair effectiveness
- Responding variable : Availability

Firstly, the experiments run for β value equal to 0.5 which is in region of infant mortality, decreasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 0.5, which is decreasing failure rate, it clearly shows that the availability of the system is reducing with different restoration factor. Figure 4.14 shows the system availability range from 96.079% to 94.144%.

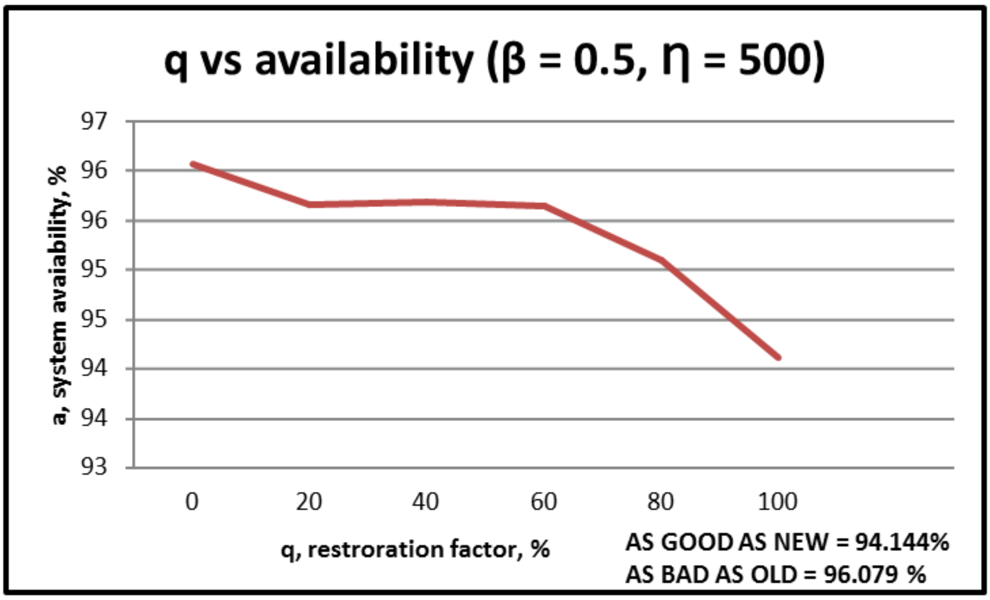


Figure 4.14: Graph of restoration factor versus availability for infant mortality period

Next, the experiments run for β value equal to 3.0 which are in region of wear out period, increasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. For β equal to 3.0, which is increasing failure rate, it clearly shows that the availability of the system is increasing with different restoration factor. Figure 4.15 shows the system availability range from 84.620% to 77.266%.

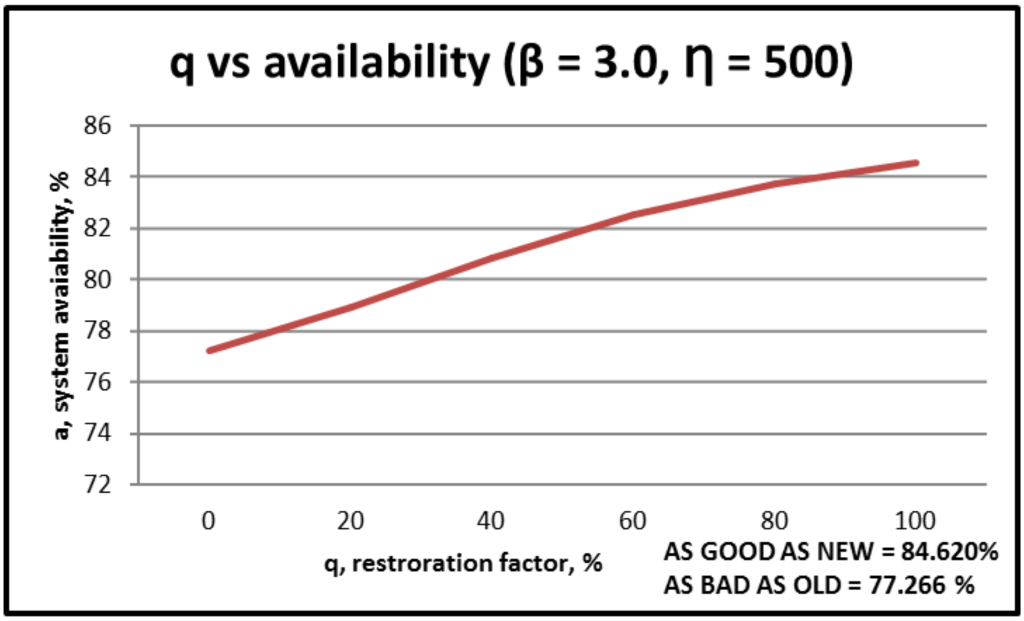


Figure 4.15: Graph of restoration factor versus availability for wear out period

4.1.6 EXPERIMENT 6

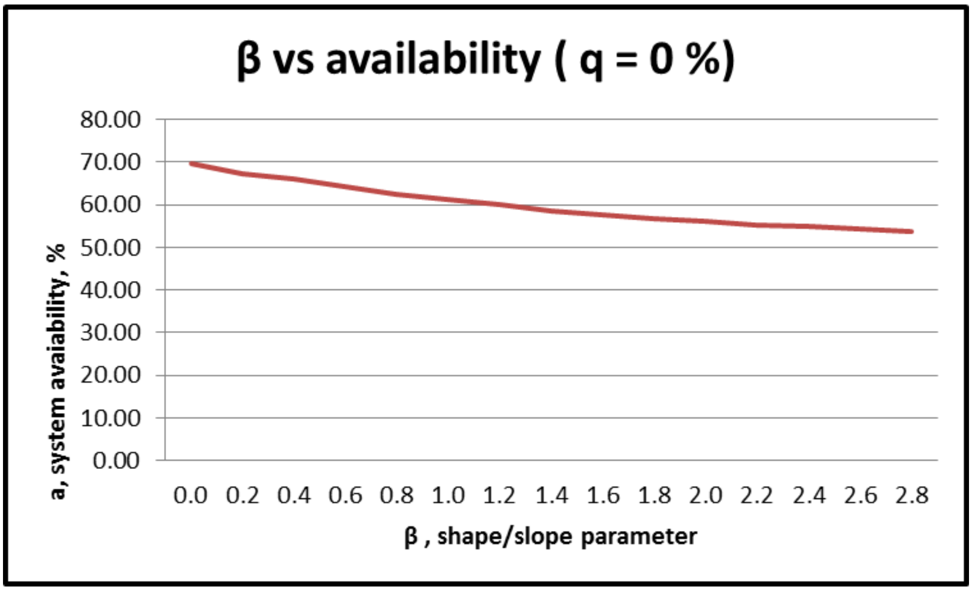


Figure 4.16: Graph of shape parameter versus availability for q = 0 %

Figure 4.16 shows the experimental set up done to see the relationship between the shape parameter, β with the system availability. Figure above show the set up done for the restoration factor which is q = 0 %. Restoration, q = 0 % also can be define as the state of as bad as old assumption. The line clearly show that the availability drop when the shape parameter, β increasing.

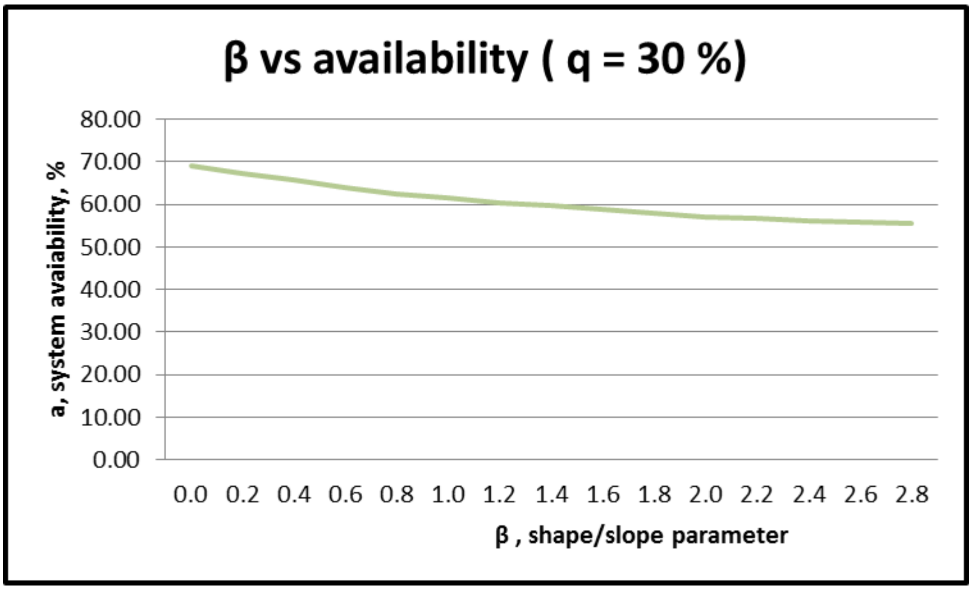


Figure 4.17: Graph of shape parameter versus availability for q = 30 %

Figure 4.17 shows the experimental set up done to see the relationship between the shape parameter, β with the system availability. Figure above show the set up done for the restoration factor which is q = 30 %. Restoration, q = 30 % also can be define as the state of partially restoration. The line clearly show that the availability drop when the shape parameter, β increasing.

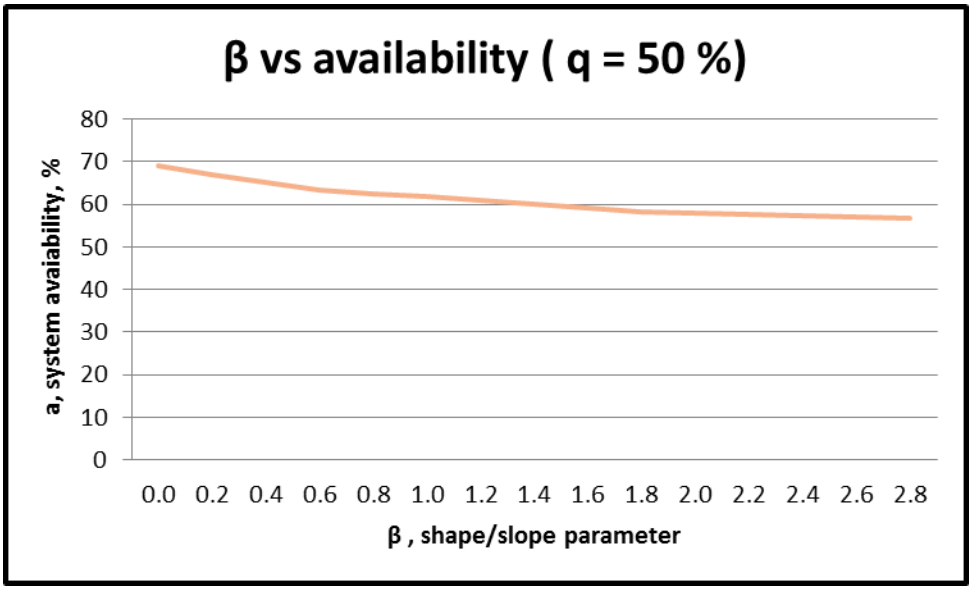


Figure 4.18: Graph of shape parameter versus availability for q = 50 %

Figure 4.18 shows the experimental set up done to see the relationship between the shape parameter, β with the system availability. Figure above show the set up done for the restoration factor which is q = 50 %. Restoration, q = 50 % also can be define as the state of partially restoration or half the restoration. The line clearly show that the availability drop when the shape parameter, β increasing.

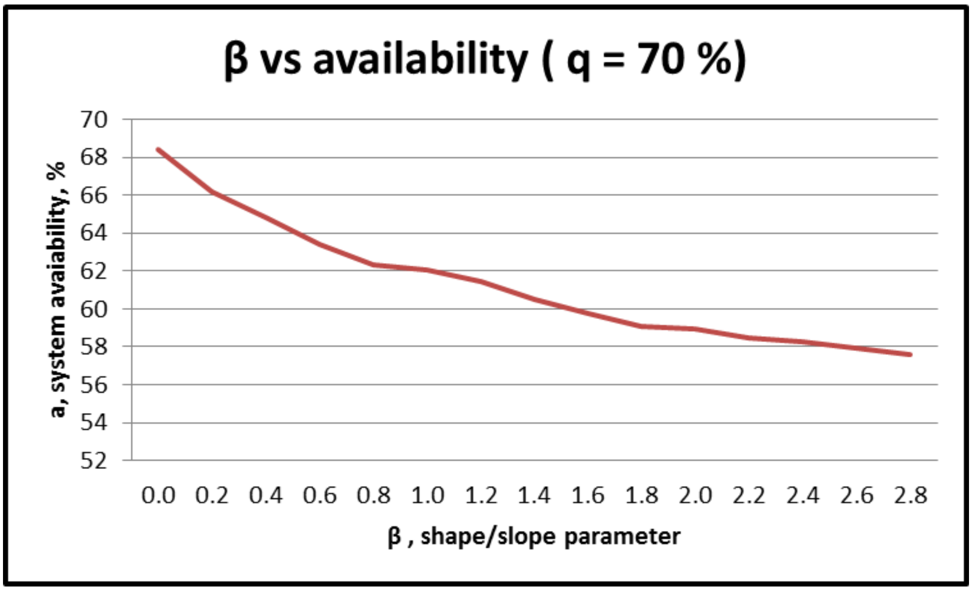


Figure 4.19: Graph of shape parameter versus availability for q = 70 %

Figure 4.19 shows the experimental set up done to see the relationship between the shape parameter, β with the system availability. Figure above show the set up done for the restoration factor which is q = 70 %. Restoration, q = 70 % also can be define as the state of partially restoration. The line clearly show that the availability drop when the shape parameter, β increasing.

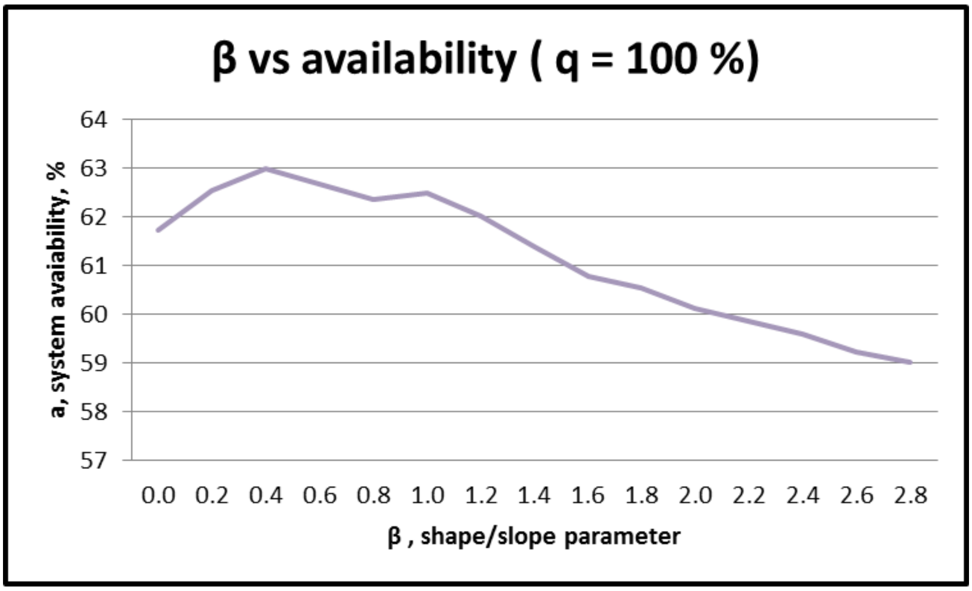


Figure 4.20: Graph of shape parameter versus availability for q = 100 %

Figure 4.20 shows the experimental set up done to see the relationship between the shape parameter, β with the system availability. Figure above show the set up done for the restoration factor which is q = 100 %. Restoration, q = 100 % also can be define as the state as good as new repair. The line clearly show that the availability drop when the shape parameter, β increasing.

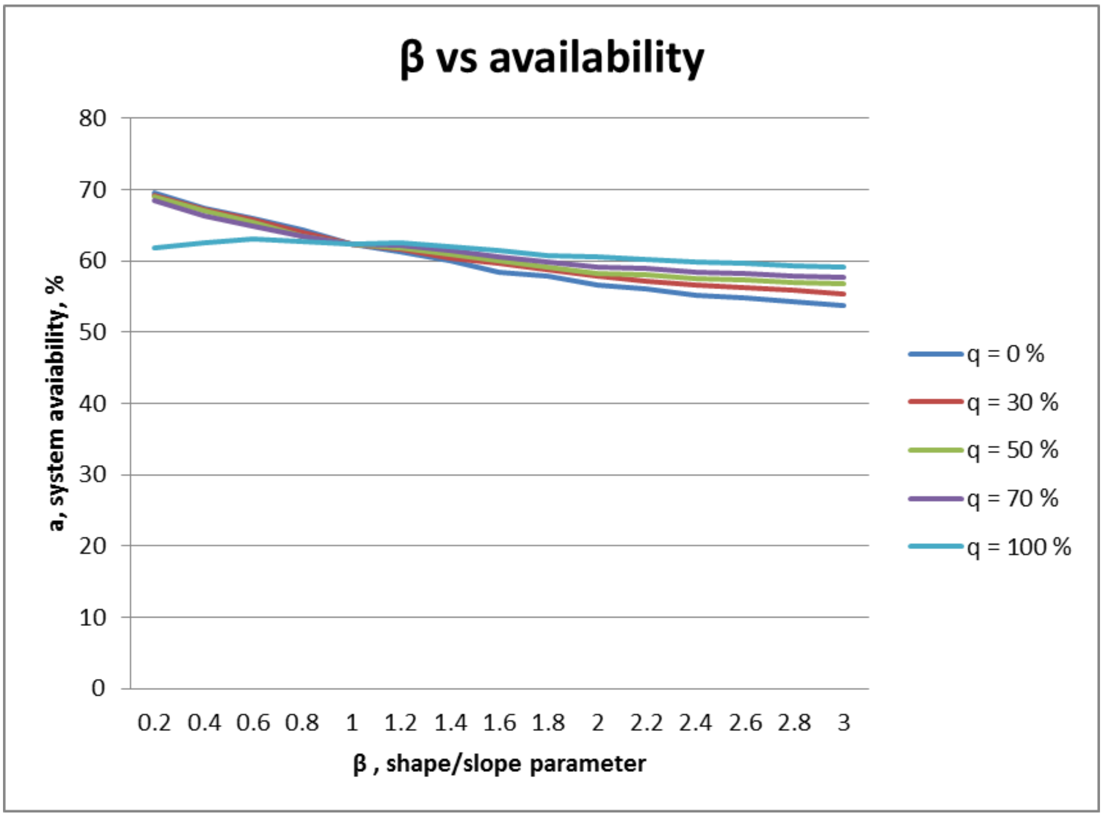


Figure 4.21: Graph of shape parameter versus availability

Based on the Figure 4.21, lines graph show that the availability decrease as the shape parameter, β increase. By increasing the failure rate, the system availability will be increasing in any kind of restoration factor. With the same value of shape parameter, β the value of availability can be improve by increasing the value of restoration factor or improving the repair quality. For example in shape parameter, β of 2.2 for q = 30 % is 57.13 %. But when we increase the restoration factor or improving the repair quality, to q = 70 %, the number of availability is increase to 58.93 %. It shows that the availability is increase with the increasing in the restoration factor.

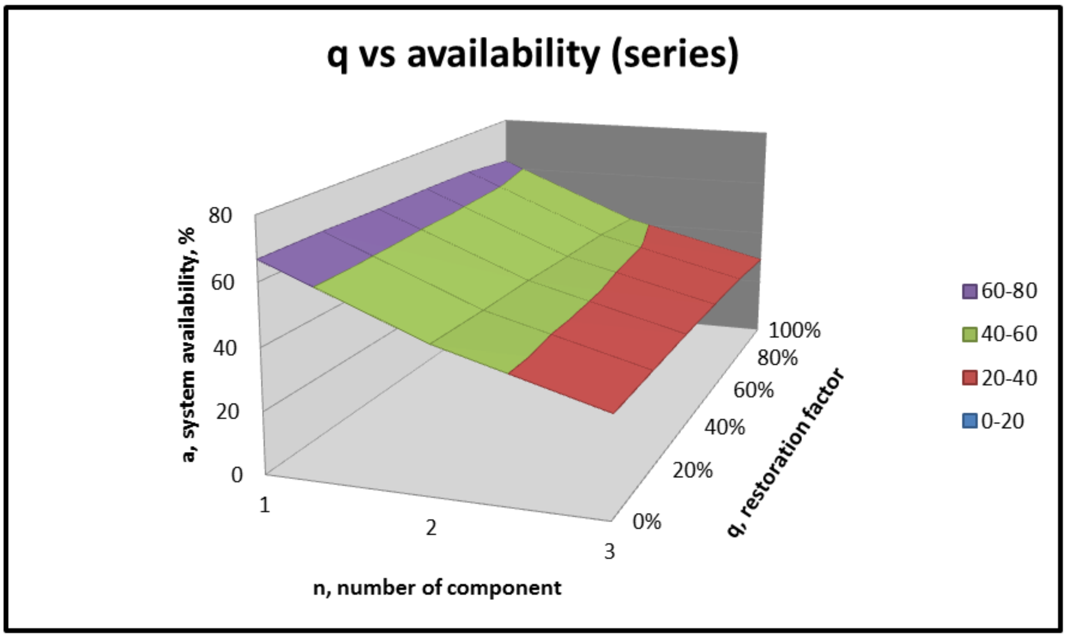


Figure 4.22: Graph of restoration factor versus availability against number of components in series for infant mortality period

Figure 4.22 shows result for the infant mortality period. It shows the effect of increasing the number of component to the system availability when restoration factor are increase. It clearly shows that for series configuration, the availability number is higher when the number of component is decrease while restoration factor are being improved.

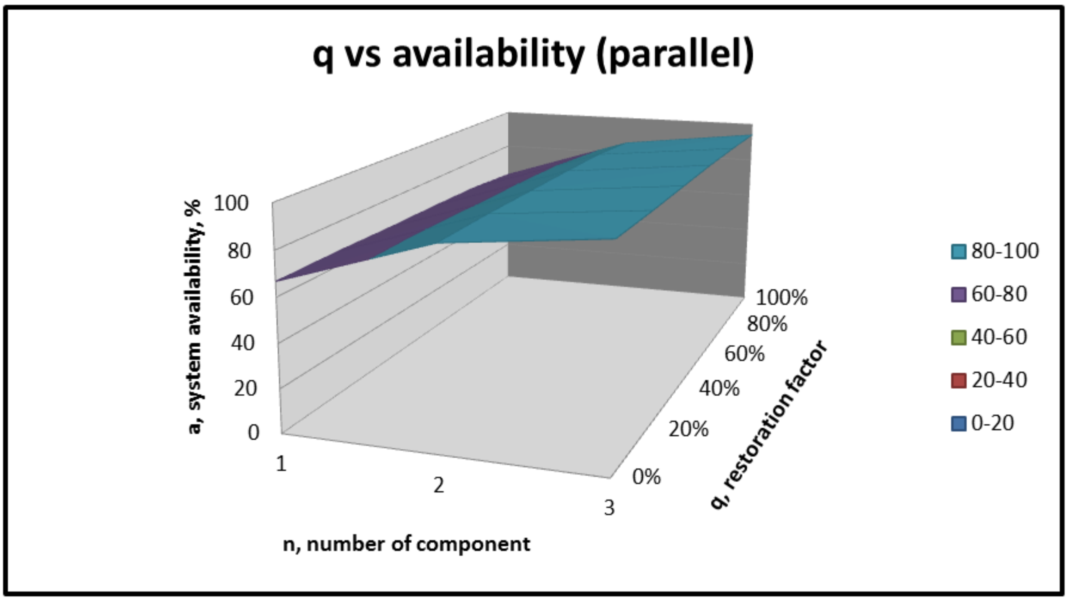


Figure 4.23: Graph of restoration factor versus availability against number of components in parallel for infant mortality period

Figure 4.23 shows result for the infant mortality period. It shows the effect of increasing the number of component to the system availability when restoration factor are increase. It clearly shows that for parallel configuration, the availability number is higher when the number of component is increase while restoration factor are being improved.

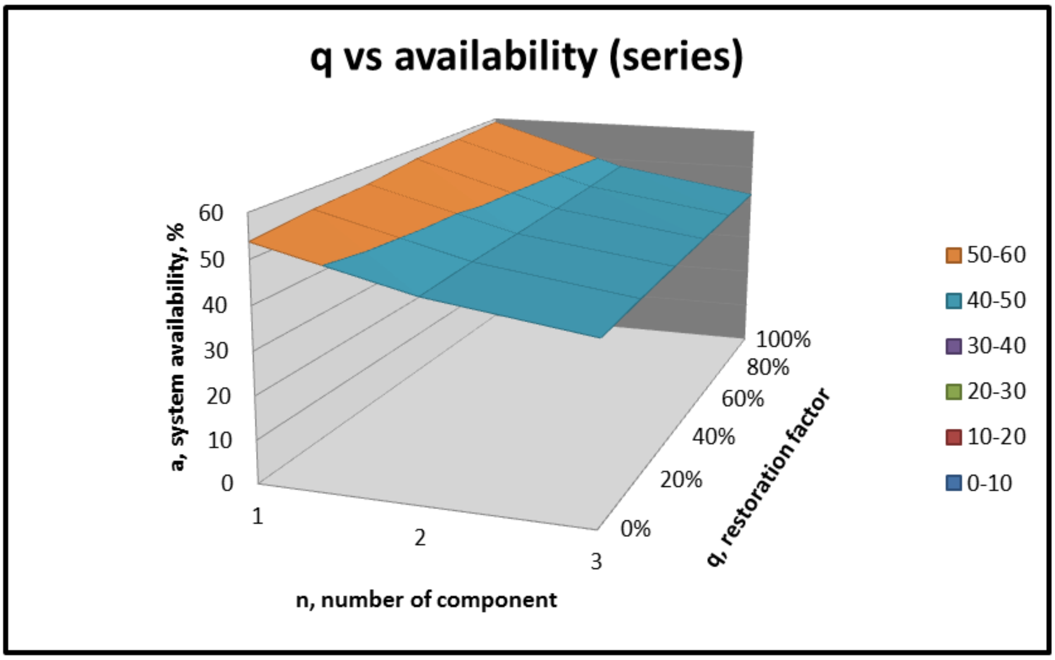


Figure 4.24: Graph of restoration factor versus availability against number of components in series for wear out period

Figure 4.24 shows result for wear out period. It shows the effect of increasing the number of component to the system availability when restoration factor are increase. It clearly shows that for series configuration, the availability number is higher when the number of component is decrease while restoration factor are being improved.

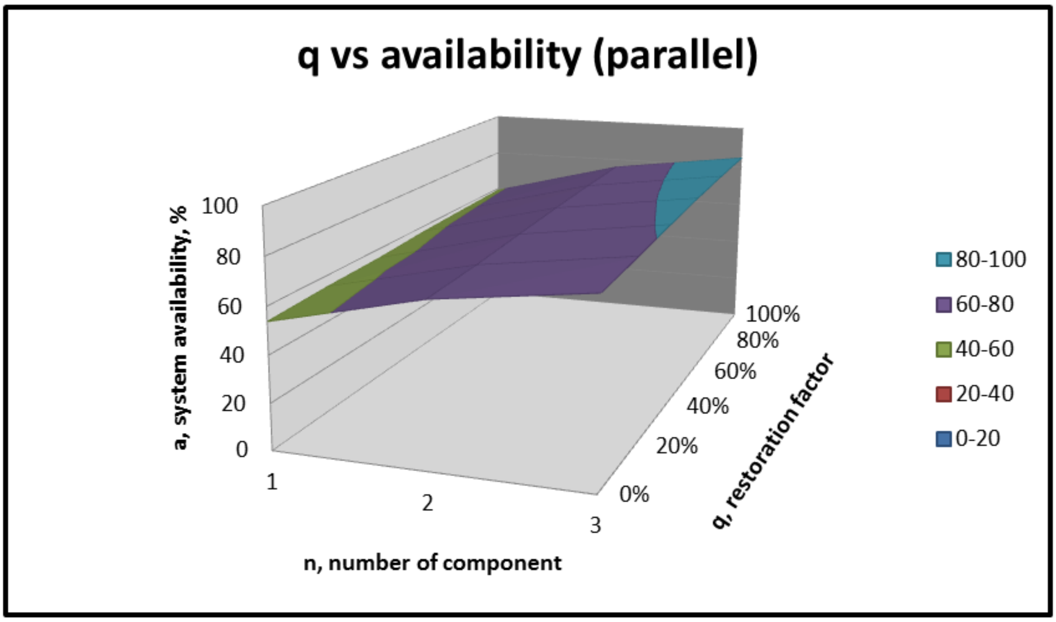


Figure 4.25: Graph of restoration factor versus availability against number of components in parallel for wear out period

Figure 4.25 show result for the wear out period. It shows the effect of increasing the number of component to the system availability when restoration factor are increase. It clearly shows that for parallel configuration, the availability number is higher when the number of component is increase while restoration factor are being improved.

All the results clearly show that the imperfect repair and maintenance do affect the whole system availability. Availability number higher in parallel configuration compared to series configuration. The value of β reflects the hazard function or the expected failure rate of the Weibull distribution and can easily be analyses in bathtub curve.

The first section which is $\beta < 1$, decreasing failure rate is an infant mortality which is the early failure of the system. Availability is decrease with the increase in the repair effectiveness for infant mortality period. Middle part of the bathtub is a section of useful life which value of $\beta \approx 1$ which is a constant failure rate event. Last part of the bathtub also known as the wear out section the increasing failure rate event which $\beta > 1$.

Availability is improved with the increase in the repair effectiveness for wear out period. The distribution of the system need to be considers in order making an analysis of the system availability. The increasing failure rate for instance need a proper maintenance and repair so that the virtual age of the component will be reset back to zero so that the component will last longer and having high in number of availability. The decreasing failure rate model, show that the restoration factor and maintenance will make the availability of the system reduces. It is due to the failure rate line itself. The turn back of virtual age of the component will make the availability to set back in higher failure rate.

4.2 RELIABILITY ANALYSIS ON WEST LUTONG PLATFORM

4.2.1 WEST LUTONG BACKGROUND

West Lutong field choose as the case study for this paper. The West Lutong field is located in the Baram delta area, Offshore Sarawak, East Malaysia about 7 miles (12 km) from Miri Crude Oil Terminal. The water depth varies from 70 feet to 105 feet (21 m to 31.5 m). The facilities comprise of two complexes which are Complex "A" and Complex "C" .The WLP-A production platform receives fluid from the wellheads on the WLDP-B drilling platform and from the WL-123 jacket drilling platform. On WLP-A, the wellhead fluid will be received in the inlet manifold which comprises of high pressure, low pressure and test headers. Next it will go through a gas separation process from the oil through the high pressure and low pressure separators. Auxiliary and utility systems on the platforms include drain systems, wash downs, high pressure, low pressure, and SV vent headers, fuel gas systems, chemical injection facilities and electrical power and instrument air located in WLK-A.

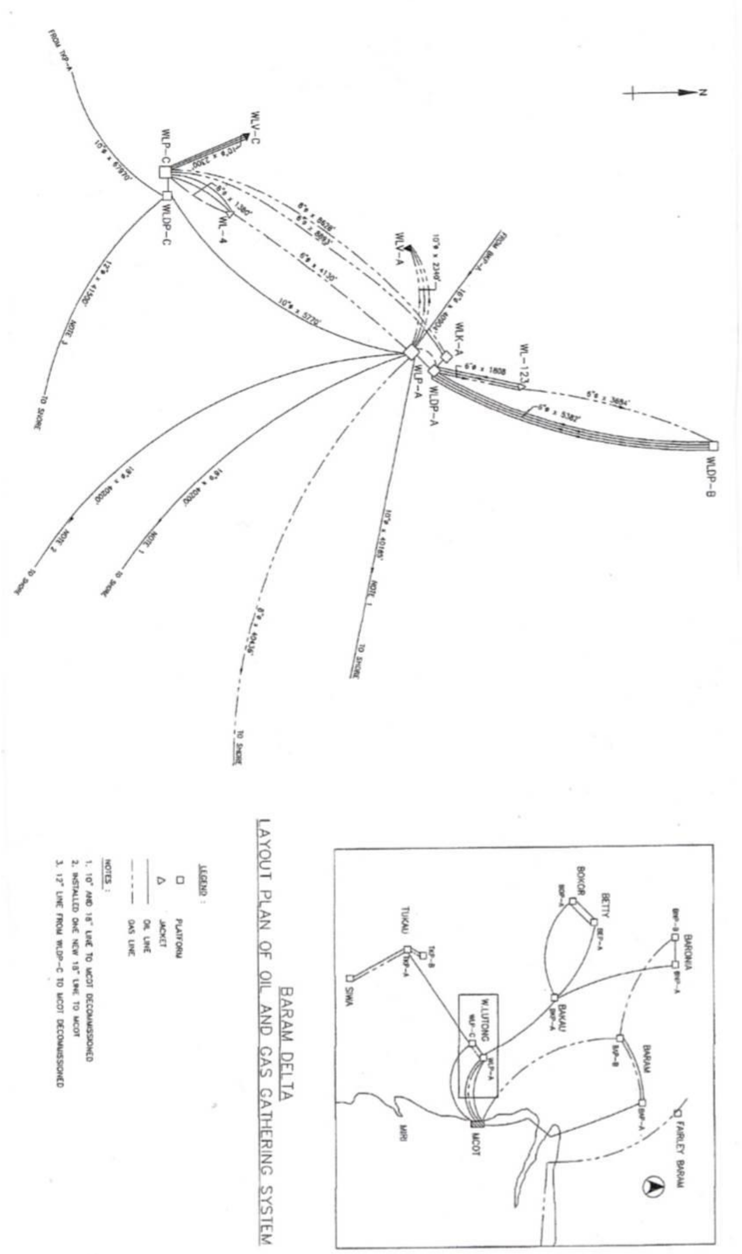


Figure 4.26: Map of West Lutong Field

In this paper, the WLP-A production platform which is one the production platform in West Lutong field will be chose as the case study for the effect of imperfect repair and maintenance to the system availability. The analysis of effect of imperfect repair and maintenance to system availability will be simulated for infant mortality and wear out period. Experimental method of DOE form previous chapter was implemented to WLP-A, separation system for analysis. Only the configuration of the component in WLP-A replicated back in BlockSim software and the analysis had been done on this system.

4.2.2 RELIABILITY BLOCK DIAGRAM GENERATION

The Reliability Block Diagram of WLP-A which is one the separation system of West Lutong created and being analyse. There are ten components in the system with the hybrid configuration having series and parallel configuration in one system. Three main components in the system are valve, separator and vessel. Below is the list of the component use in WLP-A, separation system:

1. Blowdown Valve, ABV 101
2. High Pressure Separator, V – 100
3. Pressure Control Valve, PCV 104
4. Flow Control Valve, LICV 101
5. Blowdown Valve, ABV 201
6. Low Pressure Separator, V – 200
7. Pressure Control Valve, PCV 205
8. Flow Control Valve, LICV 201
9. Surge Vessel, V – 300
10. Flow Control Valve, LICV 201

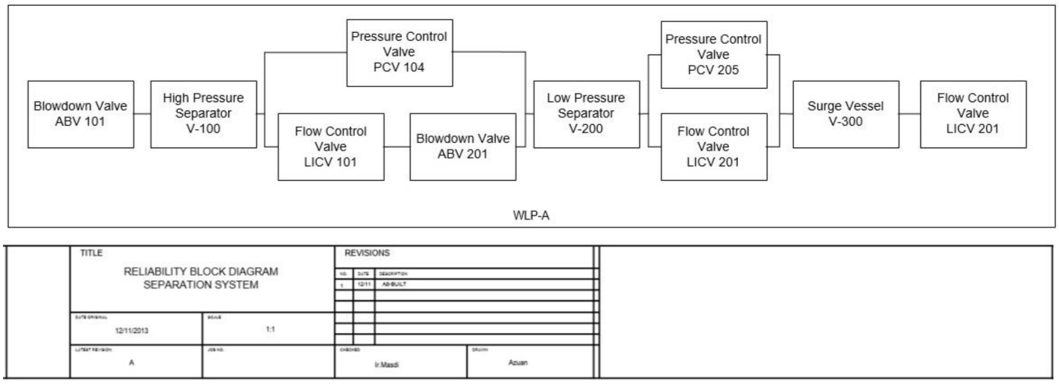


Figure 4.27: WLP – A Separation System

4.2.3 RBD USING BLOCKSIM

WLP-A system in West Lutong are replicated back in BlockSim software for the purpose of simulation. All the data for the failure which is the reliability for each component need to be formulated in this software. Repair assumption which contributed in the maintainability factor need to be considered for this model.

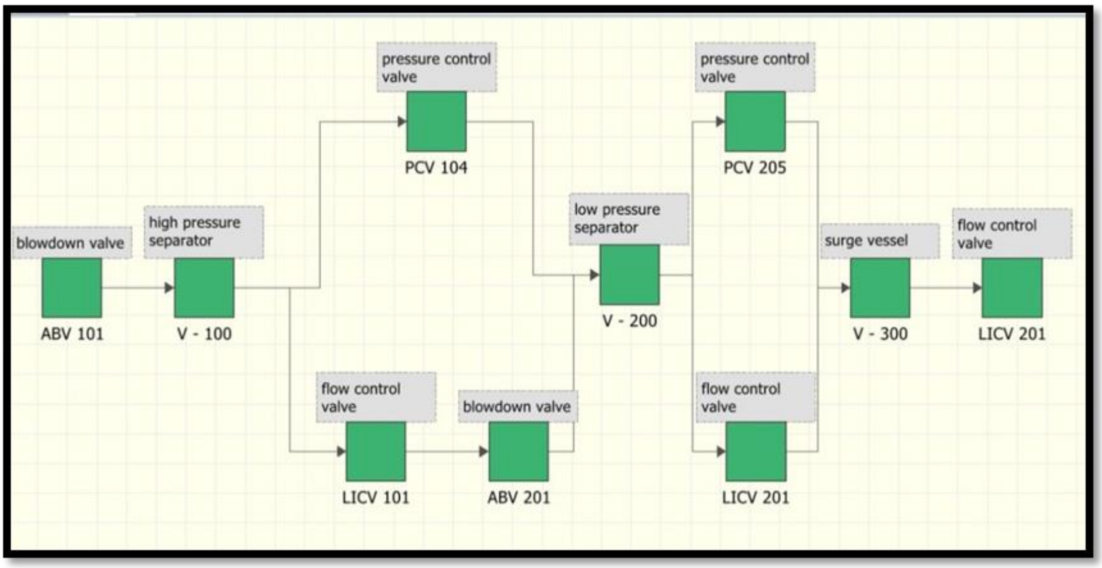


Figure 4.28: WLP – A in BlockSim

Each experimented value for each component being refer from the Van Gough FPSO RAM study assumption. The values of each component were listed in form of MTTR and MTTF. In the study of effect of imperfect repair and maintenance, the failure and repair assumption can't be modelled in exponential form. In case of value given from Van Gough FPSO RAM study assumption, the MTTR and MTTF will directly give the failure rate of each system in exponential form. To study the of effect of imperfect repair and maintenance, Weilbul distribution were choose as the distribution with condition of β, which is the shape or slope parameter should not be in value 1. Based on the Design of Experiment (DOE), the system block diagram is assumed in both increasing and decreasing failure rate with different β value.

Figure 4.28 shows the experimental set up done for WLP-A system in West Lutong with different β value which is 0.5 and 3 respectively.

- Manipulated variable : Repair effectiveness
- Responding variable : Availability

Figure 4.29 shows result simulation for the WLP-A, separation system. Firstly, the case study simulation run for β value equal to 0.5 which is in region of infant mortality, decreasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. It shows the decreasing failure rate which is the first region in bathtub curve, the infant mortality period. Figure 4.29 show the system availability range from 13.387 % to 17.103 %.

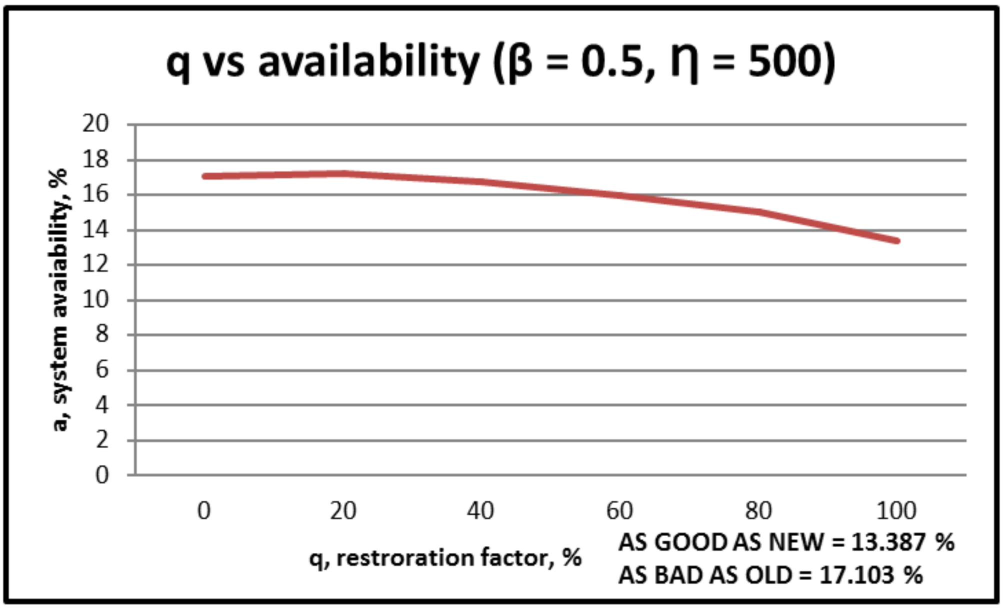


Figure 4.29: Graph of restoration factor versus availability for infant mortality period

Next, the case study simulation run for β value equal to 3.0 which are in region of wear out period, increasing failure rate. The repair effectiveness or restoration factors varied and the changes in availability observed. Based on the bathtub curve, this distribution are in the wear out period. The failure rate of the system is increasing with time. Figure 4.30 shows the system availability range from 34.173 % to 35.361 %.

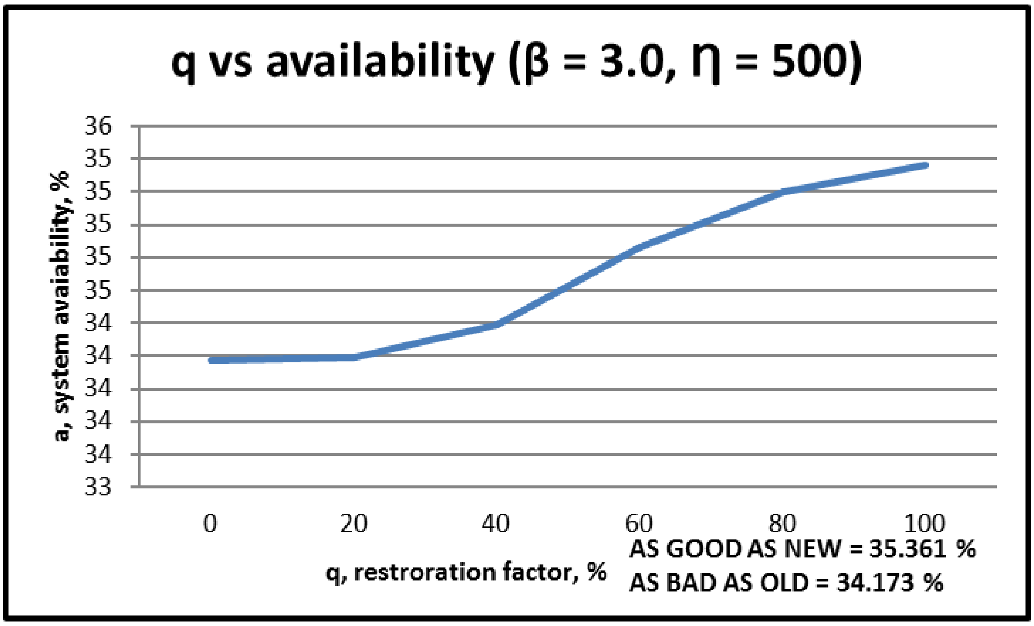


Figure 4.30: Graph of restoration factor versus availability for wear out period

Based on the case study for WLP-A separation system, we can estimate the availability value for the whole system based on the graph provided. If the system in the increasing failure mode and the restoration factor is half which is 50 % of the restoration, we can assume the value of availability is in between 34 % to 35 %. If the value of availability is quite low compared to targeted value, engineers need to figure out ways in achieving higher number and prepared some solution to overcome the downtime effect.

The case study clearly show that the imperfect repair and maintenance to affect the whole system availability. The configuration of the WLP-A separation system taken from the actual separation system but the value of each components and parameter are being tested under the experimental and simulation value. In order to get better result in availability, the actual number and values of parameter should be plug in for real case scenario. The main reason why WLP-A separation system being choose as the case study is because we do like to model real configuration of system into the study of effect of imperfect repair and maintenance. Ranges in value of availability with the repair effectiveness factor in Figure 4.29 and Figure 4.30 clearly show that imperfect repair and maintenance do affect the system availability.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSION

As conclusion, we can say that imperfect repair and maintenance do affect the whole system availability. The β value does give a great contribution for availability effect. Based on the previous chapter, we can classify failure rate into three; decreasing, constant and increasing. As the parameter β value varied, the availability trend does follow the failure factor. Availability is decrease with the increase in the repair effectiveness for infant mortality period. Availability did give no change in even the repair effectiveness vary for useful life region. Availability is improved with the increase in the repair effectiveness for wear out period.

The configuration of the system also does affect the system availability. Parallel configuration is having better number in availability compared to the series configuration if all the other parameters are in constant. Table 5.1 shows the summary of all experimental result for previous chapter.

Table 5.1: Summary of experimental results

Experiment	Summary
1 **(single component)**	Experiment 1 show that in single component configuration, the availability number is increasing respected to the repair effectiveness for wear our period and decreasing in availability number in infant mortality period. Highest availability number is 66.82%.

2 **(two components in series)**	Experiment 2 show that in two components configuration for series, the availability number is increasing respected to the repair effectiveness for wear our period and decreasing in availability number in infant mortality period. Highest availability number is 48.01%. Availability value is higher in Experiment 3 compared to Experiment 2.
3 **(two components in parallel)**	Experiment 3 show that in two components configuration for parallel, the availability number is increasing respected to the repair effectiveness for wear our period and decreasing in availability number in infant mortality period. Highest availability number is 88.84%. Availability value is higher in Experiment 3 compared to Experiment 2.
4 **(three components in series)**	Experiment 4 show that in three components configuration for series, the availability number is increasing respected to the repair effectiveness for wear our period and decreasing in availability number in infant mortality period. Highest availability number is 42.20%. Availability value is higher in Experiment 5 compared to Experiment 4.
5 **(three components in parallel)**	Experiment 5 show that in three components configuration for parallel, the availability number is increasing respected to the repair effectiveness for wear our period and decreasing in availability number in infant mortality period. Highest availability number is 96.07%. Availability value is higher in Experiment 5compared to Experiment 4.
6 **(single component)**	Experiment 6 show that the availability value is decrease as the shape parameter, β increase for each value of repair effectiveness.

The main objectives of the projects had been achieved in the overall phases of its development. Based on the result, it clearly shows that imperfect repair and maintenance do affect the system availability.

5.2 RECOMMENDATION

There are still rooms for improvement to be done in the future for expansion and continuation. The recommended future work derived from author's planning as well as the result from the simulation part. The recommended works in future are as below:-

- Availability starts with redundancy. In order to provide the ability to survive failures, increase number of components hence increasing in redundancy will promise high value in availability.
- Introducing parallel configuration in components configuration rather than series in order to achieve higher number in availability.
- Vary value of parameters in simulation part and fit the event with multiple distributions rather than having only Weibul distribution for specific event.

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CHAPTER 7

APPENDIX

APPENDIX – A: Single Component

EXPERIMENT 1
DOE MANIPULATED : q, restoration factor
RESPONDING : A, avaiability

RELIABILITY	MAINTANABILITY
β = 0.5	β = 0.5
η = 500	η = 500

TO GOOD AS NEW = 62.9 %
AS BAD AS OLD = 66.82 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	66.82	66.71	66.01	65.74	65.11	62.9
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	66.82	66.73	66.12	65.67	65.24	62.9

EXPERIMENT 2
DOE MANIPULATED : q, restoration factor
RESPONDING : A, avaiability

RELIABILITY	MAINTANABILITY
β = 3	β = 3
η = 500	η = 500

TO GOOD AS NEW = 59.02 %
AS BAD AS OLD = 53.78 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	53.78	55.1	55.76	57.33	58.19	59.02
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	53.78	55.08	55.75	57.29	58.187	59.02

APPENDIX – B: Two Component in Series

EXPERIMENT 4 (SERIES)

DOE — MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

β = 0.5	β = 0.5
η = 500	η = 500
RELIABILIT	MAINTANABILITY

TO GOOD AS NEW = 41.855 %

AS BAD AS OLD = 46.347 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	46.347	45.637	45.317	44.395	43.81	41.855
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	46.347	45.665	45.433	44.35	43.753	41.855

EXPERIMENT 5 (SERIES)

DOE — MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

β = 3	β = 3
η = 500	η = 500
RELIABILIT	MAINTANABILITY

TO GOOD AS NEW = 48.010 %

AS BAD AS OLD = 45.221 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	45.221	45.903	46.183	46.671	47.253	48.01
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	45.221	45.9017	46.18	46.671	47.252	48.01

APPENDIX – C: Two Component in Parallel

EXPERIMENT 6 (PARALLEL)

DOE MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

RELIABILIT	MAINTANABILITY
β = 0.5	β = 0.5
η = 500	η = 500

TO GOOD AS NEW = 85.739 %

AS BAD AS OLD = 88.843 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	88.843	89.108	88.806	88.518	87.921	85.739
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	88.843	89.09	88.964	88.572	88.206	85.739

EXPERIMENT 7 (PARALLEL)

DOE MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

RELIABILIT	MAINTANABILITY
β = 3	β = 3
η = 500	η = 500

TO GOOD AS NEW = 75.916 %

AS BAD AS OLD = 68.900 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	68.9	70.006	71.788	73.507	74.915	75.916
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	68.9	70.026	71.79	73.502	74.915	75.916

APPENDIX – D: Three Component in Series

EXPERIMENT 8 (SERIES 3 COMPONENTS)

DOE MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

β = 0.5	β = 0.5
η = 500	η = 500
RELIABILIT	MAINTANABILITY

TO GOOD AS NEW = 29.086%

AS BAD AS OLD = 31.749 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	31.749	31.786	31.808	31.378	30.788	29.086
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	31.749	31.801	31.895	31.499	30.643	29.086

EXPERIMENT 9 (SERIES 3 COMPONENTS)

DOE MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

β = 3	β = 3
η = 500	η = 500
RELIABILIT	MAINTANABILITY

TO GOOD AS NEW = 42.2016 %

AS BAD AS OLD = 40.170%

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	40.17	40.812	41.223	41.588	41.906	42.2016
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	40.17	40.805	41.223	41.588	41.906	42.2016

APPENDIX – E: Three Component in Parallel

EXPERIMENT 10 (PARALLEL 3 COMPONENTS)

DOE — MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

β = 0.5	β = 0.5
η = 500	η = 500
RELIABILIT	MAINTANABILITY

TO GOOD AS NEW = 94.114%

AS BAD AS OLD = 96.079 %

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	96.079	95.664	95.689	95.657	95.099	94.114
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	96.079	95.666	95.542	95.635	95.192	95.114

EXPERIMENT 11 (PARALLEL 3 COMPONENTS)

DOE — MANIPULATED : q, restoration factor

RESPONDING : A, avaiability

β = 3	β = 3
η = 500	η = 500
RELIABILIT	MAINTANABILITY

TO GOOD AS NEW = 84.620 %

AS BAD AS OLD = 77.266%

PARTIALLY RESTORATION	q	0%	20%	40%	60%	80%	100%
ALL ACCUMULATE DAMAGE	A	77.266	78.924	80.928	82.592	83.781	84.62
ALL ACCUMULATE DAMAGE SINCE LAST REPAIR	A	77.266	78.967	80.887	82.562	83.781	84.62

APPENDIX – F: Infant Mortality Period

INFANT MORTALITY PERIOD

series

	0%	20%	40%	60%	80%	100%
1	66.82	66.71	66.01	65.74	65.11	62.9
2	46.347	45.637	45.317	44.395	43.81	41.855
3	31.749	31.786	31.808	31.378	30.788	29.086

parallel

	0%	20%	40%	60%	80%	100%
1	66.82	66.71	66.01	65.74	65.11	62.9
2	88.843	89.108	88.806	88.518	87.921	85.739
3	96.079	95.664	95.689	95.657	95.099	94.114

APPENDIX – G: Wear Out Period

WEAR OUT PERIOD

series

	0%	20%	40%	60%	80%	100%
1	53.78	55.1	55.76	57.33	58.19	59.02
2	45.221	45.903	46.183	46.671	47.253	48.01
3	40.17	40.812	41.223	41.588	41.906	42.2016

parallel

	0%	20%	40%	60%	80%	100%
1	53.78	55.1	55.76	57.33	58.19	59.02
2	68.9	70.006	71.788	73.507	74.915	75.916
3	77.266	78.924	80.928	82.592	83.781	84.62