STUDY OF RELIABILITY, MAINTAINABILITY, AND AVAILABILITY: A CASE STUDY OF A SHUTTLE TANKER PROPULSION SYSTEM

CENTRE FOR NEWFOUNDLAND STUDIES

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Study of Reliability, Maintainability, and Availability: A Case Study of a Shuttle Tanker Propulsion System

by

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Abstract

One aspect in ship propulsion system development is reliability and maintainability analysis. It is concerned with the level of confidence one has in the reliable operation of the plant. Reliability analysis deals with the configuration of the system, testing of components, extending component lifetime and component maintenance.

This research models a ship propulsion system's reliability and maintainability in order to predict and to optimize the effectiveness of the ship propulsion system. A propulsion system of a shuttle tanker, ***M/T Mattea****, is used as a model. The analysis is presented in the form of statistical simulations that are used for determining the reliability level and for measuring the maintainability and availability. The reason a simulation is used rather than a mathematical model is that the latter is too complex to use. The objectives of this research is to review the process of evaluating a shuttle tanker propulsion system's reliability, maintainability, availability, and to investigate the computerised simulation statistical approach to help manage the information that is required in making intelligent maintenance and repair decisions.*

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CHAPTER 1

Introduction

1.1 General

Reliability, according to an International Electrotechnical Commission (IEC) document published in 1974, is defined as the capability of a product or system or a service to perform its expected job under the specified conditions of use over an intended period of time. Thus, in designing for reliability one should consider all elements of the definition of reliability, namely, adequate operation over the specified time and under specified conditions of use. The study of reliability is not only used for predicting the life cycle of a product or a device but it can be used for analysing behaviour of a product between time to failure as a basis for making maintenance decisions. Even when failure cannot be predicted exactly, because it could occur anytime under any conditions, the statistical simulation approach used in this study can be used to significantly improve the quality of maintenance decisions.

Maintainability is the probability that a device or component can be retained or restored into a defined condition under a given time period and under defined procedures (Blanchard et. al., 1995). Thus, the maintainability will show the characteristics of a component. In other words, the maintainability is also defined as a characteristic of a component expressed as the probability that maintenance will not be needed more than x times in a given period of time. The study of maintainability has a strong relationship with the study of reliability. Therefore, the maintainability approach may be said to be analogous to the reliability approach.

Maintenance studies over the past twenty years have changed more than any other management discipline (Mourbay, 1997). The changes are due to a huge increase in the number and variety of physical assets such as plants, equipment and buildings including ships, which should be maintained. Some of these assets are very complex in designs, requiring new maintenance methods and techniques. There have been changing views on maintenance organisation and responsibilities. A maintenance action is to bring devices being maintained towards a state of failure-free operation. Thus, the main objectives of the maintenance function are to keep assets or equipment in a certain condition without neglect or jeopardising safety and overall efficiency (Westerkamp, 1997).

The study of reliability, maintainability, and availability has been conducted for more than thirty years (Bahadir Inozu, 1993) and used to optimize both operational efficiency and design in many industries. In fact, several benefits of implementation of reliability and maintainability studies in industries, for instance, are (Kececioglu, 1995):

- In 1958, The United States satellites were launched successfully about 28% of the time, while recently it has been over 92% of the time.
- One electronics manufacturer reduced operating cost by 70% while sales increased by 25%.
- The improvement of helicopter flight control using a digital system, compared to a mechanical system, can improve safety 600%, reliability 400% and maintainability 250%.

A shuttle tanker, as other devices, needs to be maintained. Maintaining a shuttle tanker may not be as simple as maintaining a vehicle because it operates at sea. Thus, the maintenance manager should have a sound knowledge of maintenance planning, the different types of maintenance and make an appropriate selection of these to deal with each situation. Once there is a failure in planning and unsatisfactory operating results, they stand to lose thousands of dollars or even more. This can be understood by considering failure of the propulsion system of a shuttle tanker at sea. The vessel has to be towed then repaired at a dockyard. The cost is very high. In addition, the company will lose revenues that could have been earned during this off hire time. More over, because the loading schedule from oil production offshore usually has little slack in it, the shipping company may have to charter a replacement vessel. Based on this background, this study is conducted to evaluate the reliability and maintainability of the system, to predict failures, and to avoid ship down time.

1.2 Scope and Objectives

This research focuses on analysing the existing management system of a shuttle tanker propulsion system's maintenance using reliability and maintainability approaches. This research is limited by the availability of collected operational data of the parts of a shuttle tanker's propulsion system. Thus, the collected data are assumed to be correct and the modelling data are also assumed to satisfactorily reflect the real conditions. Therefore, the research has 5 main objectives as follows:

1. Identify the factors that can be approached by reliability, maintainability, and availability studies.
2. Use statistical probability distributions to identify the behaviour of devices based on the data.

3. Promote the application of reliability, maintainability and availability studies and the statistical approach in maintaining the propulsion system of a shuttle tanker.
4. Develop and optimise a comprehensive tool for ship propulsion maintenance management using reliability, maintainability, availability and statistical approaches.
5. Develop methodologies for examining the effectiveness of ship propulsion maintenance operations and adapting the model of study to a real project.

1.3 Research Methodology

This research is designed to achieve the objectives above through the following steps,

1. Review the theory and current research and development in maintenance management in general and in ship propulsion maintenance management in particular.
2. Choose a particular component or system to be modelled and to be evaluated based on the existing data.
3. Study the applicability of reliability and maintainability methods to the real problem especially for maintenance of a shuttle tanker propulsion system.
4. Use the results of simulations.

1.4 Thesis Organisation

Chapter 2 presents a literature review of maintenance management systems in general. In this chapter, reliability and maintainability studies are introduced as a relatively new method to be applied for managing the maintenance of a ship propulsion system. Component reliability and maintainability characteristics, modelling problems and limitations are discussed along with a real life application. This chapter also discusses the existing data acquisition process and analysis method. Furthermore it describes sorting, categorisation, selection, plotting, and formulation. The last section of chapter 2 presents some reliability data banks.

Chapter 3 presents the analysis procedures of the reliability and maintainability studies of the existing maintenance system. The procedures identify each selected component and its integration into the whole system. Block diagram and mathematical modelling are also introduced in this chapter and the simulation logic and process as well.

Chapter 4 presents the simulation results of the system reliability, maintainability, availability, and sensitivity analysis. The results are also discussed in this chapter and compared to a real life experience. The discussion covers the simulation method, data fitting and analysis of the results and their limitations.

The last chapter, chapter 5, is the thesis conclusions and suggestions for possible future studies.

CHAPTER 2

Literature Review

2.1 Introduction

From an engineering point of view, in the past the likelihood of failure was not taken sufficiently into account when designing for the intended service including the required manufacturing and maintenance processes. This is due to the fact that mostly the products were over designed and not very complex. There are many factors that may affect the product reliability (O'Connor, 1992) such as, manufacturing processes, variation in material properties, product weight, dimensions, coefficient of friction etc. Due to the variability of product reliability, the maintenance policies may also vary. Thus, to analyse how the optimum maintenance policy is affected by the product availability, the study of maintainability is conducted.

Assets or products should be maintained in order to keep them operating at a satisfactory level and to avoid damage. Maintenance actions in any industry start to get attention because they create an increase in production and operating cost. The maintenance cost could be up to 40% of production cost (Westerkamp, 1997). Thus to effectively and efficiently maintain a big system which consists of many components one needs to further study the effect of different maintenance policies.

The evolution of maintenance studies can be classified into three periods (Moubray, 1997). The first period started around the 1930's and lasted until the Second World War. During that time, the products were not very complex (easy to maintain) and mostly over designed (reliable). One would fix the devices when they broke. As a result, downtimes were not a big problem and there was no need for systematic maintenance beyond simple cleaning, servicing, and lubrication routines. These activities were taken care of on a daily basis by the onboard crew. For this reason crew complements were larger than is common today. Hence, the functions of maintenance management and development of maintenance skills were also much less important than today.

During the Second World War maintenance management started to mature and led to the idea of preventive maintenance. This period then is included in the second period of the evolution of maintenance management. In the 1960's, this consisted mainly of equipment overhaul done at fixed intervals. The maintenance cost also started to rise considerably relative to other operating costs. The rise in maintenance cost gave the impetus to the growth of maintenance planning and control systems. These have helped greatly in bringing maintenance costs under control, and are now considered an integral part of the practice of maintenance management.

During the third period, which started in the mid-seventies, the process of change in industry gathered even greater momentum. The changes can be classified under the headings of new expectations, new research and new techniques. The new expectations can be described as follows (Moubray, 1993). In the first generation, one fixed the devices only when they were broken. During the second generation the devices were integrated for higher plant availability and had longer equipment life and lower cost. During the third generation, one did not only concern oneself with the availability but also with reliability and safety. In the recent period we have higher plant availability and reliability, greater safety, better device quality, less damage to the environment, much longer equipment life and much greater cost effectiveness.

2.2 Reliability Study

Failures that occur have a cause and we can, by smart anticipation, analysis and studies of reliability, attempt to reduce the chances of their occurrences (Misra, 1992). Anything that might constitute a failure must be identified, studied and analysed. It is therefore imperative to know more about the general characteristics of failures. The following figure shows a general characteristic of failures over various regions of equipment life.

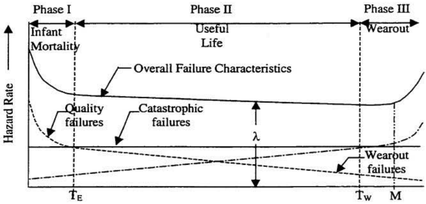
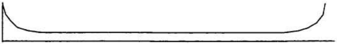


Figure 2.1 Failures Characteristics (Misra, 1992)

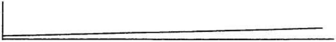
(where, M is the mean wearout)

In general, the full bathtub curve has been known as the failures graph pattern or failures characteristic or hazard function. In the first generation, we had just the right side of the bathtub curve (pattern1 in figure 2.2) while in the second generation we had a full bathtub curve (pattern 2 in figure 2.2). Currently, researchers have been able to investigate up to six failure patterns as these following figures (pattern 1 to 6 in figure 2.2) (Moubray, 1993).

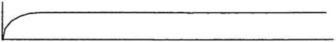
Pattern 1



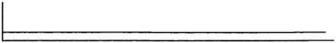
Pattern 2



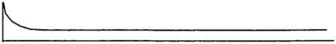
Pattern 3



Pattern 4



Pattern 5



Pattern 6

Figure 2.2 Failure patterns of component (Moubray, 1997)

Studies of those failure patterns have been done in the field of civil aircraft components with the approximate result for electronic and mechanical components given in table 2.1,

Pattern	#
1	2.0%
2	1.4%
3	2.5%
4	3.7%
5	4.14%
6	At least 68%

Table 2.1 Proportion of Failure Patterns Identified in

Civil Aircraft (From Nowlan, 1978)

Those studies have helped to guide us in predicting an appropriate failure model for most components.

The objective of a reliability study is to avoid the risks related to an untrustworthy product. This requirement becomes more stringent in the case of high-risk systems, where the consequences of unreliability can result in considerable financial loss and/or loss of human lives. In the field of marine reliability data modelling and applications, the following studies have been conducted.

Panel M-22 (Reliability and Maintainability) of Ships' Machinery Committee, SNAME, in 1971 developed a model of ship propulsion system reliability. The propulsion system modelled is a steam turbine plant. The result is to provide guidance for the application of reliability modelling technique in the marine industry. The report explains only the basic theory of system reliability modelling, data collection and block diagrams construction procedures.

The Ship Reliability Committee [SRIC], (Inozu, 1993; Tamaki, H., 1990; Sasakawa et. al, 1989), performed analysis on patterns of main engine failures [1983 - 1987], by using equipment surrounding the diesel engine's fuel storage area as the subject. The patterns of failures were investigated using a Weibull analysis. The censored data of main engine failures are assumed to follow a Weibull distribution. Other research has investigated the correlation between maintenance and reliability and vessel age (Birolini, 1985), which investigated the correlation in terms of vessel type, vessel age, and main engine type. The result of this study is, in general, that equipment with high failure rates also had high maintenance rates. Other results are that both failure rates and maintenance rates increase for vessels that are 7 to 8 years of age and their maintenance rates are slightly affected by vessel type, main engine type or engine manufacturer.

Inozu and Kyriacou, evaluated the goodness of fit of marine diesel engine failure distributions in their study (Inozu and Kyriacou, 1993): Selecting Probability

Distribution for Marine Diesel Failures using Multiple Censored Data and Reliability and Replacement Analysis of Great Lakes Marine Diesel Engines. The result is that the diesel engine components failure data can be fitted as a Weibull or Lognormal distribution rather than Gamma or Generalised Gamma distribution. In the study they found that none of the previous studies consider that components form a system. The components of a diesel engine are evaluated individually. Since they considered that the components are evaluated in an integrated system, it can be believed that the result will be more accurate.

2.3 Basic Reliability Theory

One of the underpinnings of reliability and maintainability studies is statistics. Statistics is the art of making conjectures about puzzling questions (Freedman et. al, 1978). More clearly, statistics is defined as a branch of scientific inquiry that provides methods for organising and summarising data, and for using information in the data to solve many problems (Devore, 1991). Many applications of statistics have been adopted to solve real life problems. There are practical problems in applying statistical methods to engineering problems due to uncertainty that may occur in design and operation. One of them is the application of the reliability approach in investigating maintenance management. The basic reliability concept is the main key in the underlying philosophy of reliability-centered maintenance (RCM) and in its implementation (Smith, 1993). The basic reliability concept is highly correlated with the use of probability and statistics in formulating the system. Reliability is defined as the probability that a system or product will perform at a satisfactory level for a given period of time when operated under specified operating conditions (Blanchard et al, 1995). The frequency of maintenance of a system, especially for a repairable system, is affected by its reliability (Morbay, 1993). Basically, system reliability is inversely proportional to the frequency of corrective maintenance actions.

The reliability function, R(t), the proportion of the number of successful events over the total number of events observed is expressed by

$$R(t) = \Pr_{sucsess}(t) = \frac{N_s(t)}{N_s(t) + N_f(t)} \tag{2.1}$$

where,

N_s = number of successes in a period of time

N_f = number of failures in a period of time

$$R(t) = 1 - Q(t) \tag{2.2}$$

where,

Q(t) is the unreliability estimate

Before we go any further, the following terms related to reliability study are required (Davidson, 1994).

1. *Lifetime distribution*: the measure of the reliability of a component is its 'lifetime' that means the time t between the start of a component being used and the component failure. The 'time' used here is actually the operating time but can also be assumed as calendar time for a component operated continually. The lifetime distribution is then expressed as a

probability density function (pdf) that explains the probability of the component functioning during certain time span. The pdf of a component can be given as a graph as shown in figure 2.3,

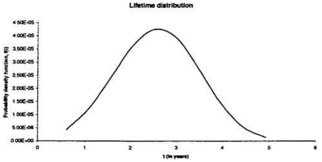


Figure 2.3 Lifetime distribution of a component

The total area below the function line = 1 (i.e. all possible events). Thus, the cumulative distribution function (cdf), F(t), is the area below the line between t = 0 to t = t. For instance, the probability that the component fails in or before year 3 can be given as $\int_0^3 f(t)dt$.

2. *Reliability function*

The reliability function as previously mentioned then can be expressed in another form as, $R(t) = 1 - F(t)$ where F(t) is defined above, i.e., F(t) is the probability of system failure. Thus, the probability that the system can survive must be 1 − F(t) since 1 indicates all possible events that may occur.

3. Hazard rate function

The hazard rate function, known as the failure rate function, is a very useful parameter for identifying component behaviour or component failure characteristics. The failure rate function is defined as a conditional probability of failure given the survival or reliability function. By definition, the hazard rate or failure rate function can be expressed as,

$$\lambda(t) = \frac{f(t)}{R(t)} \text{ or } h(t) = \frac{f(t)}{R(t)} \tag{2.3}$$

For some repairable components the failure rate may be assumed to be a more or less a constant value of the likelihood of a failure. It is independent of the age of the component. However, failures occur as random events in the strict statistical sense. A constant hazard rate is often used to simplify the mathematical model. A non-constant hazard function may also be used in modelling. An increasing hazard function means that the component will be more likely to fail as time progresses. This condition may apply to components that are degraded for instance, due to corrosion, fatigue, and/or wear-out. A decreasing hazard function will apply when a component is initially highly stressed due to incorrect installation such as misalignment, which decreases during operation. A constant hazard function may apply to electrical components.

4. *Availability*

The objective of maintenance is to optimise its in-service life, i.e. to keep the components functioning properly. To optimise a component in-service life there are three objectives: increase the mean time between failures, decrease downtime for repair and maintenance, and achieve those previous two objectives in the most cost-effective manner. These three objectives have a strong relationship with availability. Availability that is defined as the proportion of time a component is capable of performing its function properly. The availability for steady state is given by,

$$A = \frac{\text{Operating time (or Up time)}}{\text{Total Time}}$$

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \tag{2.4}$$

Where:

MTBF : mean time between failure with time measured as operating time and not elapsed time.

MTTR : mean time to repair

2.4 Reliability Block Diagram Modelling

The reliability of a system is affected by its configuration. The physical configuration of the system may not be the same as the reliability block diagram. The reliability block diagram is arranged based on the philosophy of the functions of the components that affect the system reliability. For instance, two generators 500 kW each are physically, arranged as a parallel configuration to generate 1000 kW. The system will succeed when the system generates at least 1000 kW. Thus, in the reliability block diagram, this configuration will be arranged as a series model (see Misra 1993).

When maintenance actions have not been involved in this modelling, an assumption is taken that there is no time required for fixing it after a failure occurs. This acts like a non-repairable system where, when a component fails it is replaced. In this case it is also assumed that replacement time is not necessary. Thus, the MTBF of the system is equal to the MTTR of its non-repairable components.

The following configurations of block diagrams are used in this research (Misra, 1993).

1. **Series Model**

   The idea of a series model is that the system will succeed if all components are successful. In other words, the system will fail when one or more components fail. The block diagram of a series model is given in figure 2.4.

Figure 2.4 Block Diagram of a Series Model

And *the system reliability*, Rs, is expressed as,

$$R_s = P_r(E_1 \cap E_2 \cap E_3 \cap \ldots\ldots \cap E_n) \qquad (2.5)$$

where $E_1, E_2, E_3, \ldots, E_n$ represent the events of the components. By expansion, the equation will be:

$$R_s = P_r(E_1).P_r(E_2 \mid E_1).P_r(E_3 \mid E_1 \cap E_2)\ldots.P_r(E_n \mid E_1 \cap E_2 \cap E_3 \ldots \cap E_{n-1})$$

When we assume that the components are independent, the equation can be simplified as,

$$R_s = P_r(E_1).P_r(E_2).P_r(E_3)\ldots P_r(E_n) \text{ or } R_s = \prod_{i=1}^{n} Pr_i \qquad (2.6)$$

The system MTBF of this model can be formulated as

$$MTBF = \int_0^{\infty} R_s(t)\,d(t) \qquad (2.7)$$

For an exponential R_s function, or for constant failure rate the MTBF can be simplified as (Misra, 1993; Kocecioglu, 1991),

$$MTBF \cong \frac{1}{\sum_{i=1}^{n} \lambda_i} \qquad (2.8)$$

where, λ : failure rate

n : number of components.

For failures that follow the Weibull distribution, we have:

$$f(t) = \left(a_i t^{b_i} e^{\left(\frac{a_i t^{b_i+1}}{b_i+1} \right)} \right) \tag{2.9}$$

and if $b_i = b$ for all components, the MTBF of the system is (Misra, 1993; Ushakov, 1994; See Appendix),

$$\text{MTBF} = \Gamma\left(\frac{1}{b+1} \right) \frac{1}{\left((b+1)\left(\frac{\sum_{i=1}^{n} a_i}{(b+1)} \right)^{\left(\frac{1}{(b+1)} \right)} \right)} \tag{2.10}$$

Where

Γ (t) : gamma function

a and b are constants

2. **Parallel Model**

A parallel reliability model results if all the components in the system must fail for a system to fail. The success of any one or more components in the system implies system success. The probability of success is given by the probability of the union of the success events.

$$R_s = P_r(E_1 \cup E_2 \cup E_3 \cup \ldots \cup E_n) \text{ or}$$

$$R_s = P_r(\overline{E}_1).P_r(\overline{E}_2).P_r(\overline{E}_3)\ldots P_r(\overline{E}_n)$$

$$R_s = 1 - \prod_{i=1}^{m} (1 - P_{ri}) \tag{2.11}$$

And the MTBF of parallel system:

$$\mathrm{MTBF} = \int_0^{\infty} \mathrm{R_s(t)dt}$$

Supposed two units have failures that are exponentially distributed,

$$R_s(t) = e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1+\lambda_2)t} \tag{2.12}$$

The MTBF is given by

$$\mathrm{MTBF} = \int_0^{\infty} \mathrm{R_s(t)dt} \quad = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1+\lambda_2} \tag{2.13}$$

For identical units with exponential failure distribution, MTBF will be

$$\mathrm{MTBF} = \frac{1}{\lambda}\sum_{i=1}^{m}\frac{1}{i} \tag{2.14}$$

and for the Weibull distribution where all $b_i = b$, the MTBF would be (see Misra 1993),

$$\mathrm{MTBF} = \Gamma\left(\frac{1}{b+1}\right)(b+1)^{-\frac{b}{b+1}}\{\left(\frac{1}{a_i^{1/(b+1)}}\right) + \left(\frac{1}{a_i^{1/(b+1)}}\right) + \left(\frac{1}{a_i^{1/(b+1)}}\right)\ldots$$

$$-\left\{\left(\frac{1}{a_1+a_2}\right)^{\frac{1}{b+1}} + \left(\frac{1}{a_1+a_3}\right)^{\frac{1}{b+1}} + \ldots + \left(\frac{1}{a_i+a_j}\right)^{\frac{1}{b+1}} + \ldots + \left(\frac{1}{a_{m-1}+a_m}\right)^{\frac{1}{b+1}}\right\}$$

$$+\ldots+(-1)^{m-1}\left(\frac{1}{\left(\sum_{i=1}^{m} a_i\right)^{\frac{1}{b+1}}}\right)\} \tag{2.15}$$

In this model, the system will fail only when all components fail. The block diagram of the model is,

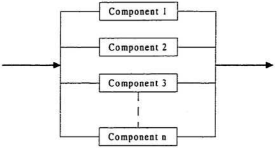


Figure 2.5 Block Diagram of a Parallel Model

3. **Parallel-Series Model**

   The reliability of a combination parallel-series is performed the same way as the calculation for a series model (or parallel model) followed by the calculation for a parallel model (or series model). The block diagram of parallel-series model is shown in figure 2.6,

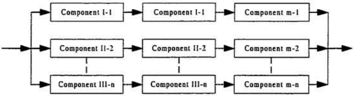


Figure 2.6 Block Diagram of a Parallel-Series Model

Where:

n : number of sub-systems

m : number of components

The system reliability, R_s, of this configuration is given as,

$$R_s = 1 - \prod_{j=1}^{m} \left\{ 1 - \prod_{j=1}^{n_i} \mathrm{Pr}_{ij} \right\} \tag{2.16}$$

And for exponential distribution of the failure rate, the system reliability can be written as,

$$R_s = 1 - \{1 - (e^{-\lambda t})^n\}^m \tag{2.17}$$

$$\text{Hence: MTBF} = \int_0^\infty (1 - (1 - e^{-n\lambda t})^m \, dt \tag{2.18}$$

4. Series Parallel Model

The same as parallel-series model above, the series parallel model is presented as follows,

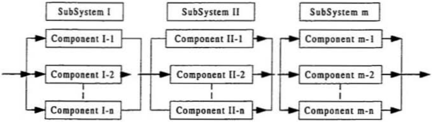


Figure 2.7 Block Diagram of a Series- Parallel Model

The system reliability of this configuration is expressed as,

$$R_s = \prod_{i=1}^{n} \left\{ 1 - \prod_{j=1}^{m_i} (1 - \mathrm{Pr}_{ij}) \right\} \tag{2.19}$$

When it is assumed that the failures of components are exponentially distributed, the MTBF would be written as,

$$\mathrm{MTBF} = \int_{0}^{\infty} \left[1 - (1 - e^{-\lambda t})^{m}\right]^{n} dt \tag{2.20}$$

5. **K-out-of-m**

This system looks like a parallel system model but requires more than one component to function properly. A system functions properly if any k out of m units function properly. If all units are identical, the probability of exactly k successes out of m is given by,

$$P_r(k, m, p) = \binom{m}{k} p^k (1 - p)^{m-k} \tag{2.21}$$

Where p is probability of success of any unit.

Thus, the probability of system success is given by

$$R_s = \sum_{i=k}^{m} \binom{m}{i} p^i (1 - p)^{m-i} \text{ or } R_s = 1 - \sum_{i=0}^{k-1} \binom{m}{i} p^i (1 - p)^{m-i} \tag{2.22}$$

And also if each unit has a known failure distribution,

$$\mathrm{MTBF} = \int_{0}^{\infty} R_s(t) dt$$

This configuration will not be used here because in the ship propulsion system there are only two identical subsystems. We would rather assume a parallel model than this model since the safety of the vessel is only threatened if both fail.

2.5 Component Reliability

A system has several or many sub-systems and a sub-system consists of many components. A component does not connote the smallest part that cannot be divided into several items. A component may consist of several items. Components can be categorised into two groups, non-repairable and repairable components. A non-repairable component is used until it fails. Thus, whenever the component fails, it should be replaced with a new or other replacement unit. Another group, the repairable components, are repaired upon failure and thus the life history will consist of alternating operation and repair periods.

Many studies of reliability methods are mostly dealing with a non-repairable system. This would be simple since a failed component will be replaced with a new one and the system is continuing to operate. The ship propulsion system consists of many components that are repairable. Thus, the analysis of the system reliability should use a repairable reliability approach. More detail about the component reliability is presented in the next chapter.

2.6 Maintainability Study

From the engineering point of view, there are always two elements of management of any physical asset: it must be maintained and/or modified. The idea of maintainability is defined as a process used to determine the maintenance requirements of any physical assets in their operating context. In other words, maintainability could be defined, as a process used to determine what must be done to ensure that any physical asset continues to do whatever its users wants it to do in its present operating context.

Maintainability research has been conducted intensively over the past twenty years. Maintainability is defined as the probability that a product will be brought back to operable condition within a particular downtime. This depends on all component downtimes such as administrative, logistical and active repair or maintenance time.

Maintainability is also an inherent characteristic of a system or product design. It concerns ease, accuracy, safety, and economy in the performance of maintenance activities (Blanchard et. all, 1995) and it can be expressed in terms of a maintenance frequency factor, maintenance times and man-hour factors, and maintenance cost. The maintainability is associated with the following factors (Blanchard, 1995),

1. Mean time between maintenance (MTBM), which covers preventive maintenance (scheduled) and corrective (unscheduled) maintenance, and considers the reliability to be given as the mean time between failures.

2. Mean time between replacement (MTBR) of the products or devices that should be done.
3. Mean maintenance downtime (MDT), or total time consumed to restore the product to a particular condition that is operable. This consists of mean active maintenance time ($\overline{M}$), mean logistic delay time (LDT), and mean administrative delay time (ADT). Where mean active maintenance time ($\overline{M}$) consists of two parts: mean preventive maintenance time ($\overline{M}pt$) and mean corrective maintenance time ($\overline{M}ct$) that is equal to mean time to repair (MTTR).
4. Mean Turnaround time (MTT) is the mean time of maintenance time needed to service, repair and or check out a product for commitment.
5. Maintenance labor-hours or maintenance man-hours per item of product or system operating hours.
6. Maintenance cost per product or system operating hour. This maintenance cost should be considered in terms of total life-cycle cost.

The formulation of maintainability can be written in a similar fashion as the reliability approach. The following formulation will show the similarity between the reliability approach and the maintainability approach (Kececioglu, 1995).

The probability density function (Pdf) of time to maintain, g(t), is given as,

$$g(t)=\mu(t).[1-M(t)] \tag{2.23}$$

$$g(t)=\mu(t).e^{-\int_0^t \mu(t)dt} \qquad (2.24)$$

where $\mu(t)=\frac{g(t)}{1-M(t)}$ and

$\mu(t)$: maintenance rate

M(t) : probability of successfully completing maintenance activity

Thus the probability of maintenance completion by time t_1, $M(t_1)$, can be given as,

$$M(t_1) = P\ (t < t_1) \qquad (2.25)$$

$$M(t_1) = \int_0^{t_1} g(t)\,dt \qquad (2.26)$$

$$Q(t_1) = 1-\frac{g(t_1)}{\lambda(t_1)} \qquad (2.27)$$

$$Q(t_1)=1-e^{\int_0^{t_1}\mu(t)dt} \qquad (2.28)$$

Where, Q : Unreliability index

And the Mean Time to Maintain or Mean Time To Repair, MTTR = $\bar{t}$

$$\text{MTTR} = \int_Y^{\infty} t\ g(t)\ dt \qquad (2.29)$$

$$\text{MTTR} = \int_0^{\infty} [1-M(t)]\ dt \qquad (2.30)$$

For a given MTTR value that can be generated from known distribution of both maintenance rate and failure rate, the following formulation are used to find the system MTTR.

$$\mathrm{MTTR} = \frac{\sum_{i=1}^{N} \lambda_i \bar{t}_i}{\sum_{i=1}^{N} \lambda_i} \tag{2.31}$$

where N : total number of repairable component

$\bar{t}_i$: time required for repairing

λ_i : failure rate of component I

and $\lambda_i = \dfrac{1}{\mathrm{MTBF}_i}$

2.7 Reliability and Maintainability Studies in Marine Industries

Even though the studies of reliability, availability and maintainability have been conducted for more than thirty-five years in many industries, they are relatively new to being fully applied in marine industries. One of the first conferences on this topic was held in February 1963 in the US. It did not stimulate any major use of reliability methodology by marine industries. It only created an awareness of the reliability applications and techniques and helped to focus attention on the limitations due to lack of data (Inozu, 1993).

The uses of the reliability approach in marine industries are to improve the operational safety of ship operation and to improve maintenance on existing ships or new ships. Besides that, the reliability approach may be able to improve the quality of the configuration of system designs in marine industries. There are many previous studies of reliability and maintainability in the field of marine industries. These have been discussed in previous sections.

2.8 Reliability Data Banks

In the reliability approach, one will try to become wiser from the past mistakes and the whole effort is to avoid failures for which causes have become known. Therefore, failure information is a must for a reliability improvement program. The success of the reliability effort depends on the availability of good failure data, which is complete and accurate (Misra, 1992). This would enable measures to improve design, plan production processes, properly operate or even plan maintenance strategies well in advance. Therefore, the collection and storage of failure data is central to the entire reliability management program.

One basic difficulty restricting the growth of the reliability approach has always been scarcity and inaccuracy of reliability data. Although a number of reliability data banks have been established, the quality of reliability data is far from satisfactory to support the more sophisticated theoretical models that are available now.

In 1965, the society of Naval Architects and Marine Engineers organised panel M-22 for reliability and maintainability (see SNAME, 1971). This panel initiated two major tasks: preparation of a practical guide in reliability and maintainability, and development of a practical shipboard data reporting system for data banks. The guide was prepared but the data was not collected.

There are three types of data especially important for evaluating product reliability. These are operational failure data, service life data without failure, and result from engineering tests (manufacturer's test) (Misra, 1992). Operational failure data constitute meaningful data since they represent experience from real life. However, the exact operational and environmental conditions before and at the time of failure may not be fully and exactly known. Service life data is necessary in assessing the time characteristic of reliability. It would be helpful to know how many units are in service, for what period of time, or under what conditions of use. Moreover, it will be useful when the two types of information mentioned above are completed including the result of manufacturer's tests or engineering tests.

Many countries and associations have their own reliability data banks. They collected the data from past experiences and research in their kind of environment and condition. The following data banks will be described briefly (Inozu, 1993; Davidson 1994).

- **OREDA** (Offshore Reliability Database) is formed by Norwegian operators of the offshore industry since 1983 (Inozu, 1993). The main objective of OREDA is to encourage the use and exchange of reliability studies among the participating marine industries. This database is performed to enhance safety, risk, reliability, availability and maintainability studies of offshore systems and equipment by providing a sound base of generic reliability data gathered from maintenance systems, testing records, operational logbooks and other technical information systems (OREDA-92, 1992). Therefore, the database covers main components of offshore equipment in process systems, safety systems, electrical systems, utility system, crane system, and drilling equipment, which are broken down into detailed parts. The following list are covered in OREDA (OREDA-92, 1992):
  - ✓ Process Systems: vessels, valves, pumps, heat exchangers, compressors, gas turbines and pig sphere launching/receiving stations.
  - ✓ Safety Systems: gas and fire detection systems, process alarm sensors, fire-fighting systems,
  - ✓ Electrical Systems: power generation, power conditioning, protection and circuit breakers.
  - ✓ Utility Systems: slop and drainage systems
  - ✓ Crane Systems: diesel hydraulic driven and diesel friction driven.
  - ✓ Drilling Equipment: drawworks, hoisting equipment, diverter systems, drilling risers, blow off production systems, mud systems, rotary tables and pipe handling systems.

- **Credo** (Centralized Reliability Data Organization) is the result of co-operation between the US and Japanese and has been co-sponsored by the US Department of Energy's (DOE) office of Technology Support Programs and Japan's Power Nuclear Fuel Development Co-operation (PNC) (Inozu, 1993). This database focuses on the components of advanced nuclear reactor facilities: assessing reactor safety, design and licensing. This data bank does not cover marine equipment.

- **SRIC data bank** was established in 1981 by the Japan Foundation for Shipbuilding Advancement which formed the Ship Reliability Investigation Committee (SRIC) (Inozu, 1993). The main objective of SRIC is to investigate equipment and system reliability of MO (Machinery Zero Ship that is designed for unmanned engine room) ships. The data are collected from 1982 to 1991 and about 100,000 ship machinery failures and alarms have been investigated including failure classification and corrective maintenance. The failure classification has been established as the following failure causes: vibration, fatigue, corrosion and pitting, deterioration, overheat and high temperature, contamination and bad contacts, age, leakage, noise, and other unknown reasons. For more detail, SRIC has also established the following failure details as, cracking, breaking, tearing change, distortion, peeling, loosening and falling, wear and tear, abnormal wearing, corrosion, leakage, contamination, sticking, clogging, burning, melting, electrical line failure, and electrical failure. Related to the failure classification the following causes of failures also have been established, design defect, material defect, installation defect, construction defect, mishandling, calculation problem, ageing, lubricating, and other unknown reasons.

The problem of acquiring data is not an easy one. Although sufficient failure data has been collected and is available for electronic components, very little published information is available on the failure of mechanical components (Morbray, 1997). The OREDA database so far collected reliability data on marine equipment and operation and maintenance, thus this research will use the OREDA data bank as the main data for maintenance. In addition, the components that are not covered in OREDA will use the reasonable approximation value and distribution based on the previous studies and experiences. And for the diesel engine main components the data from Inozu will be used.

CHAPTER 3

Ship Machinery Reliability and Maintainability Data Modelling

3.1 Introduction

As is well known, machinery components used for marine application have very high quality. This means they tend to have a very high reliability as well. The components may be over designed compared to land used components due to the harsh environment and to minimize the risk and losses caused by idle times. The designer and the owner ought to consider that the level of component reliability should be traded off against rising cost. Therefore, choosing machinery, equipment, and arrangement for a ship are based on their reliability, maintainability and availability indices besides the performance purposes for the operating conditions. The reliability engineering studies will result in meaningful information which the ship operators or designers can use to establish risk of failure. The most important number is the mean time between failures of important components or operational breakdown of the ship as a system. The reliability analysis is only a study on paper and is not necessarily an expensive effort when compared to the possible costs of rework and fault correction (SNAME, 1971).

Prediction of the reliability, maintainability, and availability indices with associated confidence values is the quantitative information that reliability and maintainability engineering will supply. This information can lead to better quality decisions that in turn will lead to increased profits during operation. Hence, the operators or designers can evaluate and improve prediction on (SNAME, 1971):

1. Frequency of inspection periods.
2. Frequency and cost of repair periods.
3. Future repair parts demand.
4. Voyage success.
5. Ship scheduling and minimising turn around times.

In order to review the design from a reliability and maintainability point of view, simulation studies will be conducted to predict reliability and maintainability indices and to find the uncertainty factors and analysing the risks that may occur. Many obstacles are faced in modelling of the ship propulsion system reliability and maintainability. The main obstacle is the lack of data. Without any data and information the analysis cannot be done. However, because of the limitation of component failure distribution data published, the reasonable distributions are taken from previous studies and assumed to be satisfactory. Another factor that may be faced in modelling is the determination of machinery components to simulate. All components that are important regarding their effect on the overall system performance should be analysed. However, after some considerations and assumptions and given the time and funding limitations, the main machinery components are chosen for the purposes of this study.

3.2 Reliability and Maintainability Modelling Methodology

This section discusses the methodology of the reliability and maintainability modelling of a ship propulsion system. Again, the important thing in the modelling is the machinery characteristics data. The simulation will be successful and accurate only if the data used is accurate data believed appropriate for the model we have. The availability of published failure-rate and distribution data for ship propulsion machinery are very limited. It is often restricted for reasons of company competitiveness considerations, or national security. The development of accurate prediction equations may also be used from valid operational data or from previous studies taken from other vessels. The availability of the ship propulsion data is also not very complete. Thus, for some machinery components one may use data that is assumed and reasonable.

Another effort for establishing the reliability and maintainability data in modelling is from technical specifications of the product, e.g., from engineering specifications or from contract specifications. One should explore all clauses concerning reliability and maintainability in such documents. It is also a good idea to try to find data on similar parts from other sources. This data can be corrected for differences in operating conditions etc. In addition, consulting all applicable company, classification and military standards and requirement may be very useful. Before starting the simulation, the system reliability block diagrams should be determined based on their functions (Kececioglu, 1991) and define the probability distributions associated with the reliability and maintainability of each component.

Therefore, the methodology of reliability modelling may be summarised as follows,

- Choose the ship propulsion configuration
- Identify the components involved in the analysis
- Find the component characteristics
- Determine each component's function in the configuration
- Construct the system block diagram
- Define the mathematical model
- Run simulation

3.3 The Ship Propulsion Machinery Configuration

A shuttle tanker, which transports oil or gas needs to have a very good over all performance. The down time that may occur will reduce the company profit and may even cause loss of trust from customers. As a case study, the research will evaluate the shuttle tanker, M/T Mattea. The M/T Mattea is a shuttle tanker operated for Hibernia and fields on the Grand Banks of Newfoundland. This vessel is owned and operated by Canship Ugland Limited. The ship was built in 1997 and has been in operation without any serious problems. The ship has 12 cargo tanks, 2 slop tanks, 13 segregated ballast tanks and a bow loading system on the forecastle deck. The vessel is twin skeg with twin screw propellers and twin diesel engines. The propellers and shafts are attached directly to the main slow speed engines. The propulsion system machinery of M/T Mattea consists of:

Main engines

- *Two(2) HYUNDAI MAN B&W, Type 7S50MC*
- *MCR: 12,700 BHP * 118.8 RPM (Each); CSR: 11,430 BHP 90 % of MCR (Each)*
- *7 cylinders 2 stroke, single acting, non-reversible, crosshead, turbo-charged*

Propeller and Propeller components

- *Two (2), Ulstein Controllable Pitch Propellers, four (4) blades, with a diameter of 6,000 mm*
- *Direction of rotation - Outboard*

- *Material: Ni-Al-Bronze*
- Propeller cap
    - *Two (2) sets*
    - *Material: Ni-Al-Bronze*
- Propeller hub
    - *Two (2) sets*
    - *Material: Ni-Al-Bronze*

Shafting devices

1. **Propeller shaft**
    - *Two (2) sets*
    - *Material: SF590, T.S* ≥ 590 *N/mm*^{2} *(60 Kg/mm*^{2}*)*
2. **Aft intermediate shaft**
    - *Two (2) sets*
    - *Material: SF590, T.S* ≥ 590 *N/mm*^{2} *(60 Kg/mm*^{2}*)*
3. **Forward intermediate shaft**
    - *Two (2) sets*
    - *Material: SF590, T.S* ≥ 590 *N/mm*^{2} *(60 Kg/mm*^{2}*)*

The general arrangement of the propulsion system machinery is given in figure 3.1,

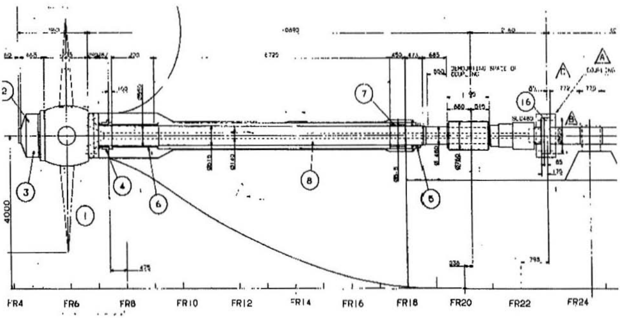


Figure 3.1 The Ship Propulsion System General Arrangement of MT Mattea

And the Power Transmission components that will be analysed are (from General Arrangement of M/T Mattea),

Propeller
Propeller cap
Propeller hub
After Stern Tube Seal
Forward Stern Tube Seal
After Stern Tube Bushing
Forward Stern Tube Bushing
After Intermediate Shaft
Forward Intermediate Shaft
Intermediate Shaft
Earthing Device
Propeller Side Hydraulic Coupling B/N
Intermediate Side Hydraulic Coupling B/N
Engine Side Hydraulic Coupling B/N
Dismounting Ring
Shaft Locking Device

And the main diesel components are,

Cylinder pistons
Cylinder heads
Connecting rod bearings
Cylinder jackets
Cylinder liner and Piston rings
Turbocharger
Fuel cams

3.4 Component Failure Rate Distribution

Difficulties may arise in reliability modelling in finding a suitable statistical distribution for each component. Much reliability data are published but only a limited amount is useful for repairable systems or mechanical components. Studies of reliability data fitting are conducted and published by OREDA, EuroDat, SRIC, etc (Inozu, 1993). Since the Weibull distribution is commonly used in ship propulsion reliability modelling (Sasakawa et. al., 1989), we assume that for components whose failure distribution is not published, it will follow the Weibull distribution. The parameters of distributions of shafting and propeller components are taken from discussion and communication with experienced maintenance personnel. All diesel engine components results are based on Inozu and Kyiriacou's research. The data are obtained from testbed trials and from calibration measurements from sea trials. For each component, a fault probability is obtained based on prior fault probabilities, historical data of operation and the current engine condition (see Inozu, 1993). In that research, the data was then fitted to the failure data to find the best fit distribution. Table 3.1 gives the list of estimation of Time Between Failures distribution with the parameters used in the simulations.

#	Component	Parameter	
		α	β
	Shafting and Propeller		
1	Propeller	$6.25\ 10^4$	1.8
2	Propeller cap	$7.38\ 10^4$	1.8
3	Propeller hub	$5.28\ 10^4$	1.3
4	Forward Stern Stern Tube	$5.25\ 10^4$	2.2
5	After Stern Tube Seal	$3.24\ 10^4$	2.7
6	Tube Seal	$7.30\ 10^4$	2.2
7	After Stern Tube Bush	$5.01\ 10^4$	2.1
8	Forward Stern Tube Bush	$5.88\ 10^4$	2.0
9	After Intermediate Shaft	$2.16\ 10^5$	0.8
10	Forward Intermediate Shaft	$2.16\ 10^5$	0.8
11	Intermediate Shaft	$2.16\ 10^5$	0.8
12	Earthing Device	$6.89\ 10^4$	2.7
13	Propeller Side Hydraulic Coupling B/N	$6.37\ 10^4$	1.4
14	Intermediate Side Hydraulic Coupling B/N	$6.66\ 10^4$	1.4
15	Engine Side Hydraulic Coupling B/N	$7.87\ 10^4$	2.1
16	Dismounting Ring	$8.28\ 10^4$	2.8
17	Shaft Locking Device	$5.46\ 10^4$	2.6
	Main Diesel Engines		
18	Cylinder pistons	$2.1\ 10^5$	1.221
19	Cylinder heads	$6.98\ 10^4$	1.544
20	Connecting rod bearings	$3.17\ 10^4$	3.432
21	Cylinder jackets	$7.48\ 10^4$	2.196
22	Cylinder liners and Piston rings	$8.38\ 10^4$	1.425
23	Turbocharger	$3.18\ 10^4$	1.521
24	Fuel cams	$6.04\ 10^4$	0.71

Table 3.1 Component's Time Between Failures Distribution

Where, α and β are parameters for Weibull distribution (defined by skewness of the function)

In figure 3.2 through 3.25 are presented the determination of component probability density functions and overview plots of the components in the propulsion model. The overview plots of components are results derived from Minitab version 12 with each component analysed using the following functions: (1) the probability density function, (2) the data fitting on the distribution, (3) the reliability or survival function, and (4) the hazard function (Minitab ver 12 Guide, 1998).

1. The probability density function shows the component lifetime characteristic that is expressed as the failure time distribution. Thus, from the graph we can predict the most likely time that the component will fail and the probability the component will be in good condition.
2. Fitting the data on the distribution informs us how well the data fits the selected distribution. The data may also be checked with other distributions to find the best fit of the data to a distribution. (For more detail, see Davidson, 1994).
3. The Survival (or reliability) function displays the survival probabilities versus time. Each plot point represents the proportion of units surviving at time t. The survival curve is surrounded by two outer lines—the 95% confidence interval for the curve, which provides reasonable values for the "true" survival function.
4. The hazard function presents the instantaneous failure rate for each time t. Often, the hazard rate is high for short time periods, low in the middle of the plot, then high again at the end of the plot. Thus, the curve often resembles the shape of a bathtub. The early period with high failure rate is often called the infant mortality stage. The middle section of the curve,

where the failure rate is low, is the normal life stage. The end of the curve, where failure rate increases again, is the wear out stage.

In addition, the parameters of distributions given by Minitab 12 are approximate values caused by the behaviour of the random data since the data used for the Minitab analysis are from generated random data. For instance, to analyse the reliability of the propeller, we generate 10,000 time between failures random numbers that follow a Weibull distribution with parameters $\alpha = 62.5\ 10^3$ and $\beta = 1.8$. The 10,000 random numbers are then analysed and plotted.

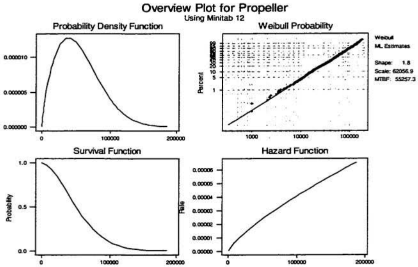


Figure 3.2 Overview Plot for Propeller

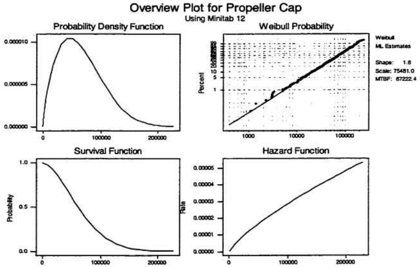


Figure 3.3 Overview Plot for Propeller Cap

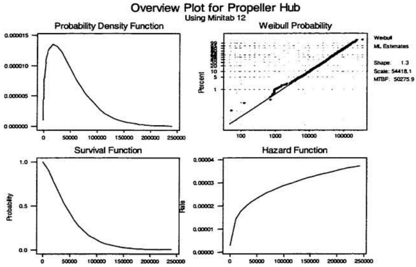


Figure 3.4 Overview Plot for ropeller Hub

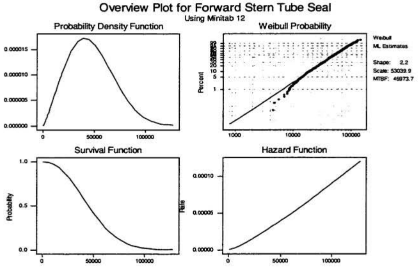


Figure 3.5 Overview Plot for Stern Tube

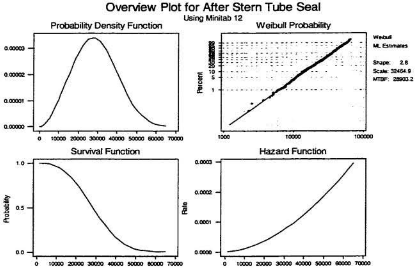


Figure 3.6 Overview Plot for After Stern Tube Seal

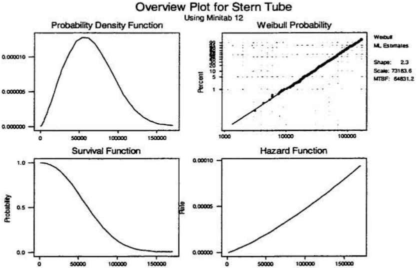


Figure 3.7 Overview Plot for Forward Stern Tube Seal

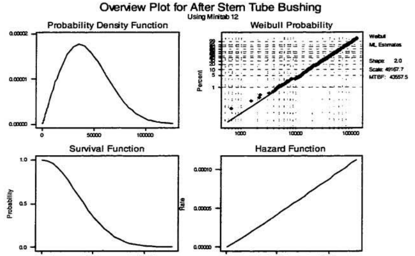


Figure 3.8 Overview Plot for After Stern Tube Bushing

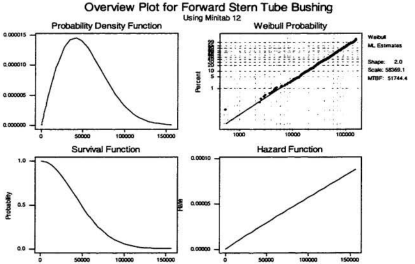


Figure 3.9 Overview Plot for Forward Stern Tube Bushing

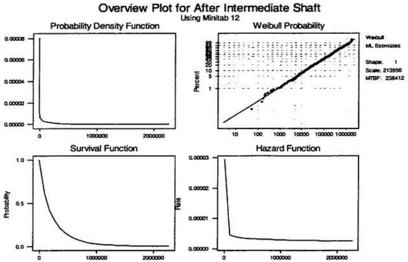
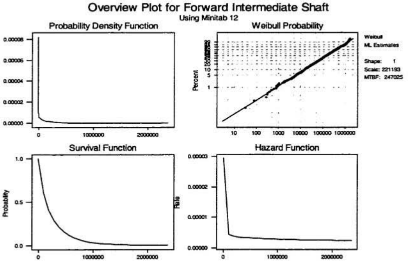


Figure 3.10 Overview Plot for After Intermediate Shaft



Fiure 3.11 Overview Plot for Forward Intermediate Shaft

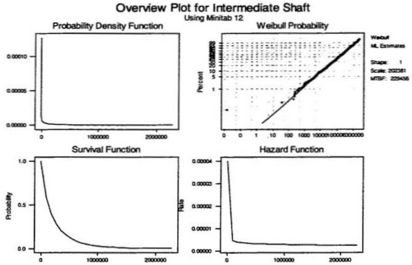


Figure 3.12 Overview Plot for Intermediate Shaft

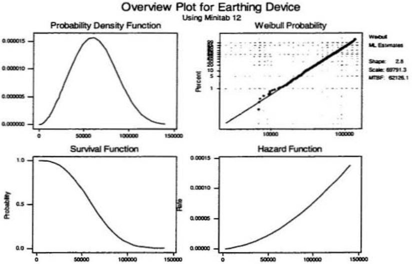


Figure 3.13 Overview Plot for Earthing Device

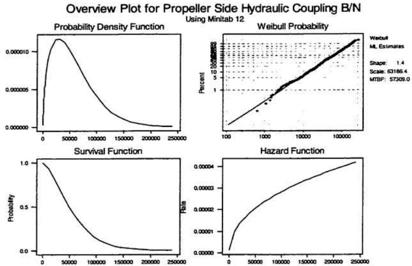


Figure 3.14 Overview Plot for Propeller Side Hydraulic Coupling B/N

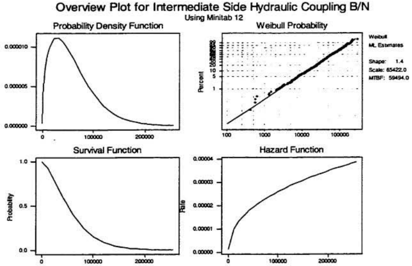


Figure 3.15 Overview Plot for Intermediate Side Hydraulic Coupling B/N

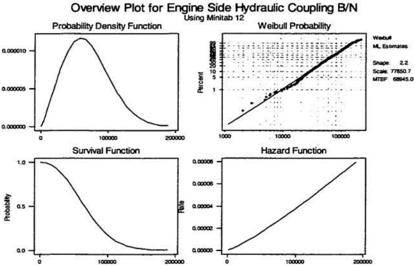


Figure 3.16 Overview Plot for Engine Side Hydraulic Coupling B/N

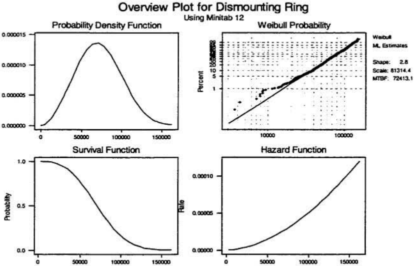


Figure 3.17 Overview Plot for Dismounting Ring

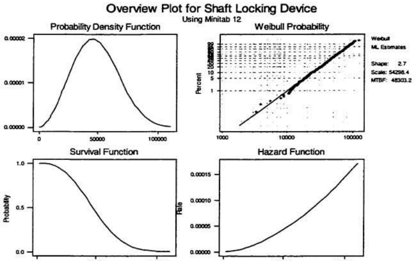


Figure 3.18 Overview Plot for Shaft Locking Device

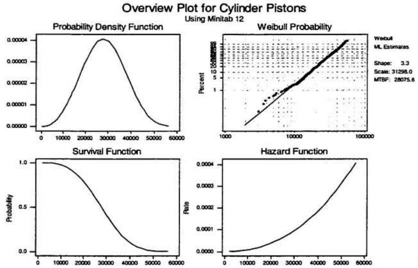


Figure 3.19 Overview Plot for Cylinder Pistons

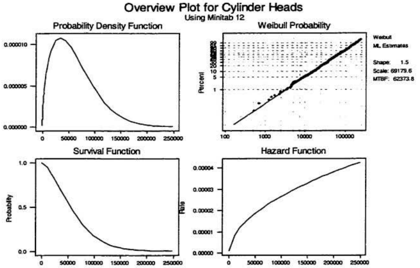


Figure 3.20 Overview Plot for Cylinder Heads

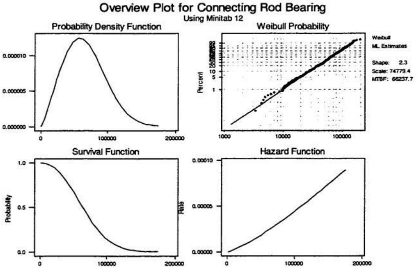


Figure 3.21 Overview Plot for Connecting Rod Bearing

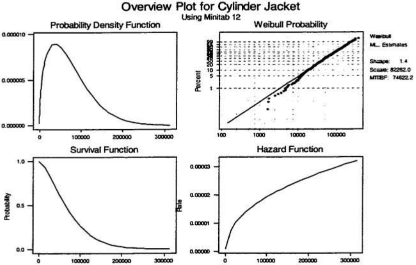


Figure 3.22 Overview Plot for Cylinder Jacket

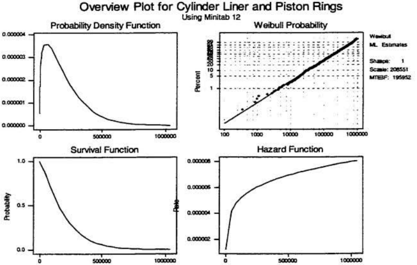


Figure 3.23 Overview Plot for Cylinder Liner and Piston Rings

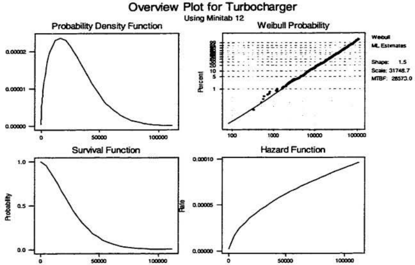


Figure 3.24 Overview Plot for Turbocharger

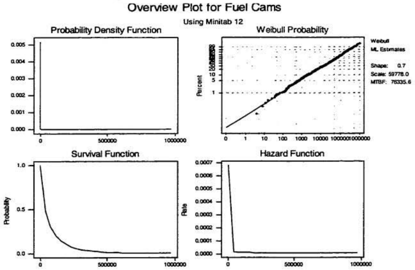


Figure 3.25 Overview Plot for Fuel Cams

3.5 Construction of Ship Propulsion System Block Diagram

The system configuration that in this case is the general arrangement of the propulsion system may not be identical to the reliability block diagram. The reliability block diagrams are arranged based on the component function that causes the overall system to work successfully or not. Since we take only the main components that may have critical failure that causes the system to become inoperable, all blocks in the reliability block diagram are arranged as a series system in each of the two sets of propulsion system configurations. In this case, both sets of propulsion system components are configured serially.

In modelling of the reliability system block diagram, we can assume that the ship uses a full load of power or only the half of full load (SNAME, 1971). Even when the ship has twin engines and twin propellers, we may be satisfied when the system generates half of the total capacity. When a full-load model is considered, the subsystems then will be configured as a series model and for a half-load model would be a parallel model. Thus, the Time Between Failures of the system is considered using a series model, and is equal to one half of the Time Between Failures of the sub-system. The Time Between Failures of system considered using a parallel model, is equal to 3/2 of Time Between Failures of the sub-system (see Misra, 1992; Kececioglu, 1991). Hence,

$$MTBF_{parallel} = 3 * MTBF_{series}$$

Therefore, the block diagrams of the propulsion system can be given as shown in figures 3.26 and 3.27.

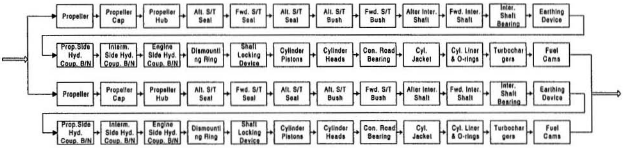


Figure 3.26 Half-Load Block Diagram (Considered as a Parallel Model)

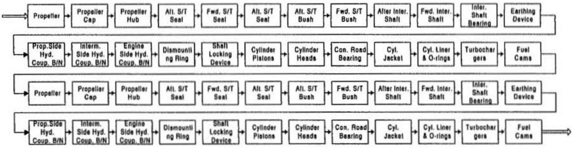


Figure 3.27 Full-load Block Diagram (Considered as a Series Model)

3.6 Simulation

Dealing with a complex system and complicated failure patterns, the mathematical analysis would be extremely difficult or sometimes even impossible to solve. For instance, the normal distribution and the Weibull distribution are two types of distributions that are widely used but are difficult to analyse mathematically (Ushakov, 1995; Misra, 1993; Bain L.J., 1991). In the case of analysing a complex system, a simulation method may be the best or only way to find a solution.

Simulations, which usually are aided by computer, are used to predict the behaviour of components that in the operating processes are difficult or may impossible to represent with analytical relationships. Simulation methods are also known to be valid methods (Ushakov, 1995). Simulations may also be used if the mathematical relationships are known but would require a lot of time for a solution. In simulation, there are three steps that may be followed such as, (1) development of a formal model, (2) creation or selection of the software being used and (3) simulation itself (Ushakov, 1995).

A reliability simulation model ordinarily is a discrete model with a governing sequence of discrete events, such as failures, repair or switching. The simulation method used in this study is Monte Carlo simulation. Monte Carlo simulation is a method whose solution is able to approach that of the mathematically complex analytical solution. Monte Carlo simulation is a powerful technique that is able to give an answer to any problem faced by reliability engineers, (Davidson, 1994). One advantage of using Monte Carlo simulation is that, unlike Markov analysis, it is not restricted to using exponential distribution but can also simulate any distribution such as Weibull, log-normal, normal, uniform, etc (see Davidson, 1994). Therefore, we can choose the best distribution fit for each component. As a result, Monte Carlo simulation may be more accurate than Markov analysis.

In Monte Carlo simulation, a large number of replicas of the system are simulated by mathematical models (Ireson, 1988). The value of variables and parameters are selected based on their best-fit probability distribution. The technique is to generate random numbers that follow the best distribution and then formulated in the mathematical form required for the given block diagram arrangement. The outputs from the mathematical model give the simulation result. In formulating the mathematical model, the random numbers represent Time Between Failures. These can be converted to failure rates, which are assumed to be constant (see Kececioglu, 1991). These procedures are repeated many times. The average value (expected value) of the resulting Time Between Failures distribution gives the MTBF for the simulation operation.

The Monte Carlo simulation method is actually very simple in concept and flows naturally from the sampling distribution concept. The only aspects to implementing Monte Carlo simulation are

(a) Writing the computer program code to simulate data condition chosen and

(b) Interpreting the estimated sampling distribution (Mooney, 1997).

The problem now may be solved since the development of general-purpose simulation software simplifies the task considerably. One such piece of software is the package Minitab. It can be used for Monte Carlo simulation.

The simulations were carried out using Minitab version 12. The Minitab package is a very powerful software package for Monte Carlo simulation. The macro facility makes its use more flexible and easy for implementation of the real problem. In addition, the software can simulate up to 18 distributions: Chi-square, normal, F, t, Uniform, Bernoulli, Binomial, Discrete, Integer, Poisson, Beta, Chaucy, Exponential, Gamma, Laplace, Logistic, Lognormal and Weibull. Thus, we can fit the component failure patterns to up to 18 distributions. This enables one to choose the best distribution. The macros used follow the flow chart given in figures 3.28 and 3.19. They are based on the block diagrams of the systems (figure 3.26 and 3.27). The macros are tested using a simple configuration to insure that they are well constructed and contain no error. The macros for this simulation are also attached in the appendix on a 3½" floppy disk.

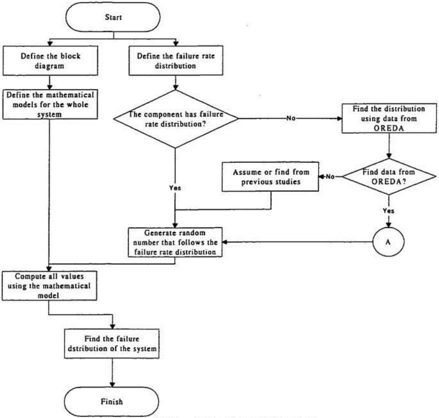


Figure 3.28 Simulation Logic Flowchart

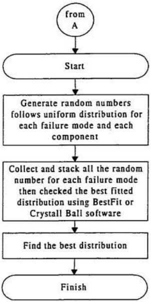


Figure 3.29 Simulation Logic Flowchart, Finding Component Distribution

In this reliability modelling, the following assumption are used (Birolini, 1985):

1. The components alliterate continuously from the operating state (uptime) to the repair state (downtime) and vice-versa.
2. Preventive maintenance is not considered.
3. After each repair activity, the component is as good as a new component.
4. Switching effect can be negligible.
5. Failure–free and repair times are statistically independent.
6. The failure-rates of components are statistically independent as well.

In addition, assumption #1 actually is not restrictive if we consider operating time instead of calendar time, and if the concept bad-as-old can be used in the case of interruption without repair or maintenance. Assumption #3 is applied if the component is completely renewed at each repair activity. This is to simplify the model, which will not change the probability distribution.

3.7 Sensitivity Analysis

In addition to the whole system simulation, we also try to simulate the system by reducing each component Time Between Failures by 1% to 100%. This is in order to identify the behaviour of the system and the effect of one component on the system's reliability. The flow chart in figure 3.30 presents the logic of the simulation used for sensitivity analysis. We assume here that the data is already available. Each trial of a component is reduced by n% and is run a hundred times with 10,000 random numbers for each point. The result of the sensitivity analysis for full-load is presented and discussed in the next chapter. The reason only one model is analysed in the sensitivity analysis is that between full-load and half-load we have the same behaviour and a linear relationship, for instance, MTBF of Full-load = 1/3 of MTBF of half-load model (see Misra, 1992).

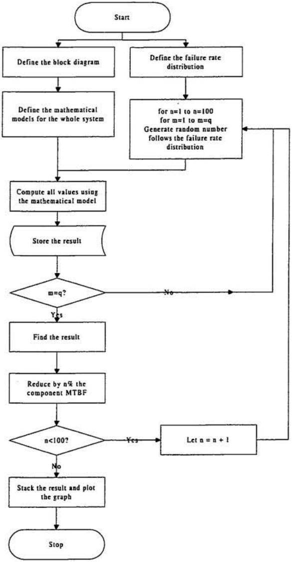


Figure 3.30 Flow chart of one component simulation by decreasing its Time Between Failures

3.8 Maintainability Modelling

The maintainability modelling cannot be independent of the reliability modelling since for each failure that occurs a maintenance action is taken. There is no maintainability data that we have found so far for the propulsion system. Therefore, the simulation will use data from other similar equipment and assumed to be satisfactory. The time to maintain/repair data of components are estimated from OREDA-92 and OREDA-97, and from discussions and communications with experienced maintenance personnel. In addition, the probability density function of the time to maintain will mostly be one of the following distributions: normal, log-normal or exponential distribution (see Blanchard, et. al, 1995). Here, we assume that the data are normally distributed.

The following table is the estimation of distributions with parameters for each component investigated.

#	Component	Distribution	Parameter	
			Mean	STD
	Shafting and Propeller			
1	Propeller	Normal	25	5
2	Propeller cap	Normal	1	0.2
3	Propeller hub	Normal	25	5
4	Forward Stern Tube Seal	Normal	5	2
5	After Stern Tube Seal	Normal	5	2
6	Stern Tube	Normal	15	5
7	After Stern Tube Bush	Normal	5	2
8	Forward Stern Tube Bush	Normal	7	2
9	After Intermediate Shaft	Normal	5	1.5
10	Forward Intermediate Shaft	Normal	5	1.5
11	Intermediate Shaft	Normal	5	1.5
12	Earthing Device	Normal	4	1
13	Propeller Side Hydraulic Coupling B/N	Normal	2	0.3
14	Intermediate Side Hydraulic Coupling B/N	Normal	2	0.3
15	Engine Side Hydraulic Coupling B/N	Normal	2	0.3
16	Dismounting Ring	Normal	0.5	0.1
17	Shaft Locking Device	Normal	5	1
	Main Diesel Engines			
18	Cylinder pistons	Normal	5	1
19	Cylinder heads	Normal	5	1
20	Connecting rod bearings	Normal	4	1
21	Cylinder jacket	Normal	5	1
22	Cylinder liners and O-rings	Normal	5	1
23	Turbocharger	Normal	28	6
24	Fuel cams	Normal	8	1.5

Table 3.2 Time To Maintain Distribution List

In order to find the mean time to repair of the system, a Monte Carlo simulation is also conducted. The technique is, similar to the reliability simulation. Random numbers are generated for the maintenance time. These follow the selected maintenance time and are used in the distribution and formulated in a mathematical model as described in chapter 2. The output of the simulation is the final result, which is the system MTTR. The results are discussed in the next chapter and the macros used in the simulation are attached in the appendix on a 3 ½ floppy disk.

3.9 Availability Modelling

Modelling of the availability function of the system is a further task to be done. By using the result of the simulation of the system reliability function and the system maintainability function, the system availability can be easily solved. The simulation will use the relation between availability, reliability and maintainability that can be described as,

$$\text{Availability} = \frac{\text{Time Between Failues}}{\text{Time Between Failures} + \text{Time to Re pair}}$$

The result of this simulation is also presented and discussed in chapter 4 for both full-load and half-load configurations.

CHAPTER 4

Result and Discussion

4.1 Introduction

The simulation results give sets of mean time between failures for each trial. For investigating the reliability of a system, maintainability of a system, and availability of a system, the simulation ran 20 times with each trial generating 10,000 random numbers, for each component, which were used as inputs into the mathematical model. For the sensitivity analysis, the simulation ran 100 times for each point decreasing Time Between Failures with 10,000 random numbers as inputs into the mathematical model (see Appendix). The results are stacked in a column for each trial and each simulation. They are then fitted to various distributions to identify, which is the best fit. Thus, after running all the simulations the system Time Between Failure distribution, Time to Repair distribution, and Availability index distribution can be found by using Bestfit and Crystal Ball software. The method used to rank the distribution is the Chi-Square Test.

4.2 Simulation Result

The simulation results discussed are divided into three parts: Reliability of system, Maintainability of system and Availability of system.

4.2.1 Reliability of System

The simulation results for the system reliability consist of the full-load model, half-load model and the sensitivity analysis.

4.2.1.1 Full-load Model

The result of the simulation for the full-load model Time Between Failures after fitting to its distribution is shown table 4.1.

Trial #	Distribution	Parameter		Rank
		Mean	SD	
Trial 1	Normal	256.06	101.77	#1
Trial 2	Normal	258.91	102.13	#1
Trial 3	Normal	258.20	101.23	#1
Trial 4	Normal	256.60	101.02	#1
Trial 5	Normal	256.59	101.28	#1
Trial 6	Normal	257.85	101.44	#1
Trial 7	Normal	256.51	102.42	#1
Trial 8	Normal	255.88	101.24	#1
Trial 9	Normal	256.49	102.21	#1
Trial 10	Normal	256.02	101.89	#1
Trial 11	Normal	256.38	101.88	#1
Trial 12	Normal	257.66	101.07	#1
Trial 13	Normal	256.74	101.50	#1
Trial 14	Normal	256.74	101.50	#1
Trial 15	Normal	256.93	100.87	#1
Trial 16	Normal	255.29	102.02	#1
Trial 17	Normal	256.80	100.74	#1
Trial 18	Normal	257.86	101.37	#1
Trial 19	Normal	256.86	100.93	#1
Trial 20	Normal	256.98	101.48	#1
Average		256.87	101.5	

Table 4.1 Reliability Simulation Result – Full-load Model

From the above table, we can conclude that the pdf of the propulsion system follows a Normal distribution with parameters:

mean = 256.87 and

standard deviation = 101.5

Or it can be expressed as,

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2}$$

where:

μ : mean value

σ : standard deviation

Thus,

$$f(t) = \frac{1}{\sqrt{2\pi}\,101.5} e^{-\frac{1}{2}\left(\frac{t-256.87}{101.5}\right)^2}$$

From the fitting data above, even if all components have a Weibull distribution, the overall system is normally distributed. The overview of the full-load system reliability can be shown as the graphs in figure 4.1,

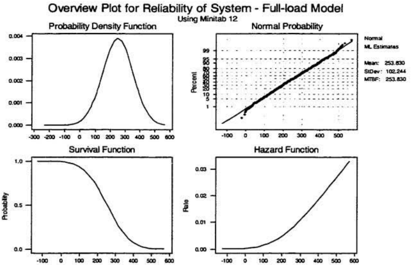


Figure 4.1 Overview Plot for Simulation Result Reliability of Full-load Model

4.2.1.2 Half-load Model

The result of reliability simulation for the Half-load model for Time Between Failures after fitting to its distribution is presented in table 4.2.

Trial #	Distribution	Parameter		Rank
		Mean	SD	
Trial 1	Normal	772.63	302.91	#1
Trial 2	Normal	764.13	305.86	#1
Trial 3	Normal	766.59	302.46	#1
Trial 4	Normal	772.91	301.83	#1
Trial 5	Normal	776.12	303.04	#1
Trial 6	Normal	769.36	308.15	#1
Trial 7	Normal	774.58	307.15	#1
Trial 8	Normal	769.87	302.21	#1
Trial 9	Normal	773.61	306.01	#1
Trial 10	Normal	768.64	301.05	#1
Trial 11	Normal	769.32	306.27	#1
Trial 12	Normal	770.32	303.89	#1
Trial 13	Normal	770.81	301.88	#1
Trial 14	Normal	772.22	304.66	#1
Trial 15	Normal	771.78	305.52	#1
Trial 16	Normal	764.98	302.28	#1
Trial 17	Normal	768.43	310.27	#1
Trial 18	Normal	771.34	302.84	#1
Trial 19	Normal	771.30	305.71	#1
Trial 20	Normal	773.62	305.50	#1
Average		**770.63**	**304.47**	

Table 4.2 Reliability Simulation Result – Half-load model

From the table, we can conclude that the pdf of the propulsion system follows a Normal distribution with parameters:

mean = 770.63 and

standard deviation = 304.47

Or it can be expressed as,

$$f(t) = \frac{1}{\sqrt{2\pi}\,304.47} e^{-\frac{1}{2}\left(\frac{t-770.63}{304.47}\right)^2} \text{ and plotted as shown in figure 4.2.}$$

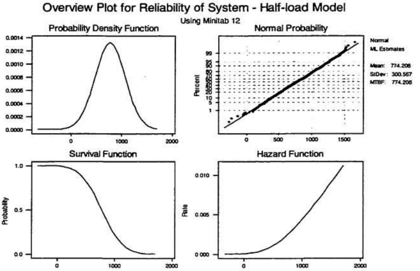


Figure 4.2 Overview Plot for Simulation Result Reliability of Half-load Model

4.2.1.3 Sensitivity Analysis

To identify the behaviour of the system affected by each component, a sensitivity analysis is conducted. The analysis uses a Monte Carlo simulation. The method is to generate random numbers of each component that follows its distribution and calculated using mathematical equations developed from the system block diagram. For the next run of the simulation, the component Time Between Failures are decreased 1% from previously and the simulation returns to find the resulting the overall reliability of the system. These procedures are repeated until the reduction of component Time Between Failures is 100%, i.e., zero Time Between Failures. The graphs in figure 4.3 and 4.4 show the results of the simulation that present the effect of the failure of each component.

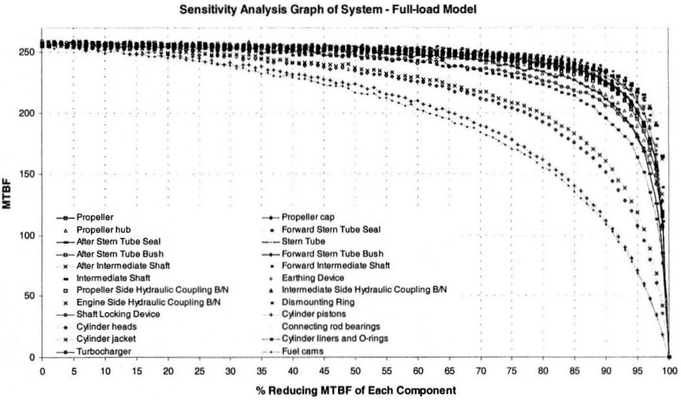


Figure 4.3 Sensitivity Analysis Graph of System -Full-load Model

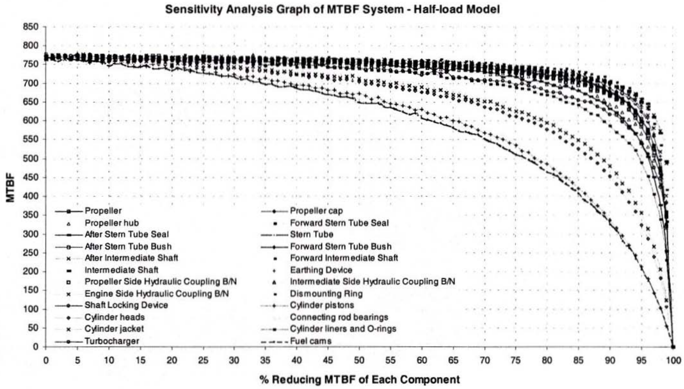


Figure 4.4 Sensitivity Analysis Graph of System -Half-load Model

4.2.2 Maintainability of System

The result of the simulations for both full-load model and half-load model Time To Repair are the same since the components involved in the simulations are the same. Hence, they have identical failure distributions and Time To Repair distributions. The system's Time To Repair is also independent of its configuration (see Blanchard, 1995; Kececioglu, 1991). Therefore, after fitting it to its best distribution the result for both full-load model and half-load model can be shown as follows,

Trial #	Distribution	Parameter		Rank
		Mode	Scale	
Trial 1	Extreme Value	6.58	1.78	#1
Trial 2	Extreme Value	6.58	1.73	#1
Trial 3	Extreme Value	6.63	1.81	#1
Trial 4	Extreme Value	6.60	1.74	#1
Trial 5	Extreme Value	6.59	1.78	#1
Trial 6	Extreme Value	6.60	1.77	#1
Trial 7	Extreme Value	6.59	1.76	#1
Trial 8	Extreme Value	6.58	1.74	#1
Trial 9	Extreme Value	6.59	1.77	#1
Trial 10	Extreme Value	6.58	1.77	#1
Trial 11	Extreme Value	6.57	1.78	#1
Trial 12	Extreme Value	6.58	1.76	#1
Trial 13	Extreme Value	6.61	1.79	#1
Trial 14	Extreme Value	6.58	1.77	#1
Trial 15	Extreme Value	6.58	1.78	#1
Trial 16	Extreme Value	6.60	1.77	#1
Trial 17	Extreme Value	6.60	1.83	#1
Trial 18	Extreme Value	6.56	1.74	#1
Trial 19	Extreme Value	6.60	1.78	#1
Trial 20	Extreme Value	6.56	1.77	#1
Average		**6.59**	**1.77**	

Table 4.3 Maintainability Simulation Result

Therefore, we conclude that the time to maintain (pdf) of the propulsion system follows an Extreme Value distribution with parameters:

mode (μ) = 6.59 and

scale (σ)= 1.77

Or it can be expressed as,

$$f(t) = \frac{1}{b} e^{-\left(\frac{t-a}{b}\right)} e^{-e^{\left(\frac{t-a}{b}\right)}}$$

where:

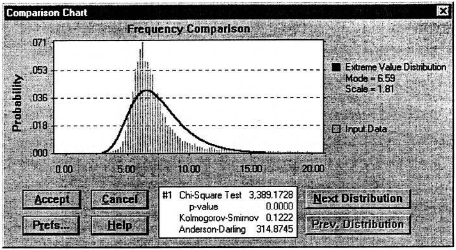
b : mode value

a : scale

Thus,

$$f(t) = \frac{1}{6.59} e^{-\left(\frac{t-1.77}{6.59}\right)} e^{-e^{\left(\frac{t-1.77}{6.59}\right)}}$$

From the fitting of the above data, it can be seen that even though each component has a normal distribution, the overall system follows the Extreme Value distribution. In some cases, the best-fit distribution may not really fit the results well. To show the comparison between the simulation result and the fitted value, figure 4.5 is presented.



#1		
	Chi-Square Test	3,389.1728
	p-value	0.0000
	Kolmogorov-Smirnov	0.1222
	Anderson-Darling	314.8745

Figure 4.5 Comparison Chart Between The Result and Fitted Data

4.2.3 Availability of System

Another simulation conducted is the availability of system. The two following tables, table 4.3 and table 4.4, are the results of the simulations for full-load model and half-load model. In general, the results all follow the Extreme Value distribution although each component distribution is normal.

4.2.3.1 Full-load Model

Trial #	Distribution	Parameter		Rank
		Mode	Scale	
Trial 1	Extreme Value	0.97	0.02	#1
Trial 2	Extreme Value	0.97	0.02	#1
Trial 3	Extreme Value	0.97	0.02	#1
Trial 4	Extreme Value	0.97	0.02	#1
Trial 5	Extreme Value	0.97	0.02	#1
Trial 6	Extreme Value	0.97	0.02	#1
Trial 7	Extreme Value	0.97	0.02	#1
Trial 8	Extreme Value	0.97	0.02	#1
Trial 9	Extreme Value	0.97	0.02	#1
Trial 10	Extreme Value	0.97	0.02	#1
Trial 11	Extreme Value	0.97	0.02	#1
Trial 12	Extreme Value	0.97	0.02	#1
Trial 13	Extreme Value	0.97	0.02	#1
Trial 14	Extreme Value	0.97	0.02	#1
Trial 15	Extreme Value	0.97	0.02	#1
Trial 16	Extreme Value	0.97	0.02	#1
Trial 17	Extreme Value	0.97	0.02	#1
Trial 18	Extreme Value	0.97	0.02	#1
Trial 19	Extreme Value	0.97	0.02	#1
Trial 20	Extreme Value	0.97	0.02	#1
Average		**0.97**	**0.02**	

Table 4.4 Availability Simulation Result – Full-load Model

From the table, the availability of the system can be expressed by,

$$f(t) = \frac{1}{0.97} e^{-\left(\frac{t-0.02}{0.97}\right)} e^{-e^{\left(\frac{t-0.02}{0.97}\right)}}$$

The parameters of the distribution are taken from the average values of trials.

4.2.3.2 Half-load Model

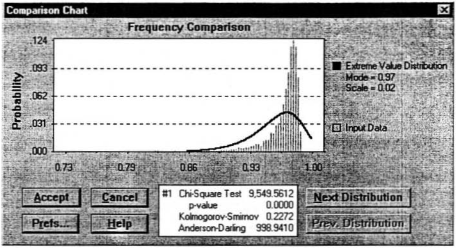
Trial #	Distribution	Parameter		Rank
		Mode	Scale	
Trial 1	Extreme Value	0.99	0.01	#1
Trial 2	Extreme Value	0.99	0.01	#1
Trial 3	Extreme Value	0.99	0.01	#1
Trial 4	Extreme Value	0.99	0.01	#1
Trial 5	Extreme Value	0.99	0.01	#1
Trial 6	Extreme Value	0.99	0.01	#1
Trial 7	Extreme Value	0.99	0.01	#1
Trial 8	Extreme Value	0.99	0.01	#1
Trial 9	Extreme Value	0.99	0.01	#1
Trial 10	Extreme Value	0.99	0.01	#1
Trial 11	Extreme Value	0.99	0.01	#1
Trial 12	Extreme Value	0.99	0.01	#1
Trial 13	Extreme Value	0.99	0.01	#1
Trial 14	Extreme Value	0.99	0.01	#1
Trial 15	Extreme Value	0.99	0.01	#1
Trial 16	Extreme Value	0.99	0.01	#1
Trial 17	Extreme Value	0.99	0.01	#1
Trial 18	Extreme Value	0.99	0.01	#1
Trial 19	Extreme Value	0.99	0.01	#1
Trial 20	Extreme Value	0.99	0.01	#1
Average		**0.99**	**0.01**	

Table 4.5 Availability Simulation Result – Half-load Model

By taking the average value of parameter from the table above, the availability of half-load model can be expressed by equations,

$$f(t)=\frac{1}{0.99}e^{-\left(\frac{t-0.01}{0.99}\right)}e^{-e^{\left(\frac{t-0.01}{0.99}\right)}}$$

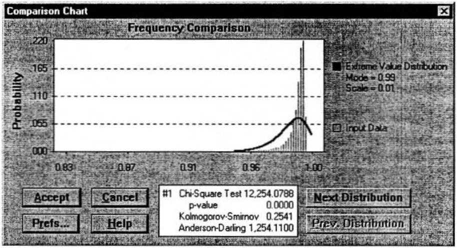
Similar to the maintainability result fitting, the availability results do not really fit the Extreme value distribution well as shown in figure 4.6 and figure 4.7.



Extreme Value Distribution
Mode = 0.97
Scale = 0.02

```
#1  Chi-Square Test  9,549.5612
        p-value          0.0000
    Kolmogorov-Smirnov   0.2272
    Anderson-Darling   998.9410
```

Figure 4.6 Comparison Chart Between The Availability Simulation Result Full-load Model and Fitted Line



Extreme Value Distribution
Mode = 0.99
Scale = 0.01

```
#1  Chi-Square Test 12,254.0788
        p-value           0.0000
    Kolmogorov-Smirnov    0.2541
    Anderson-Darling  1,254.1100
```

Figure 4.7 Comparison Chart Between The Availability Simulation Result Half-load Model and Fitted Line

4.3 Discussions

4.3.1 The Monte Carlo Simulation

When we deal with a Monte Carlo simulation there are two interpretations that can be followed:

- In generating the random numbers, we can generate one random number for each component to follow a statistical distribution. The random numbers are then used as input into the mathematical model. The steps are repeated many times. More clearly, for a simulation of the system using 10,000 random numbers for each component, can be shown in the following flow chart,

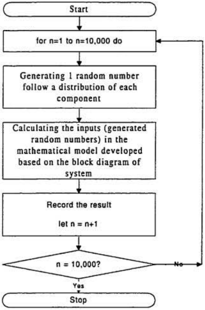


Figure 4.8 Flow Chart of The First Interpretation of Monte Carlo Simulation

The flowchart seems to represent the real problem since the failure occurs once for each trial. But, if we try to collect all the generated random numbers for each component (1,000 points or less) and we fit the result, it may not give the same mean as expected, and possibly not even the same distribution (in this example, a normal distribution). Thus, sometimes the random number distribution does not represent the desired component distribution. This may occur because when the computer generates one random number, say, following a normal distribution, which is immediately used in complex mathematical equations, the seed number for the random number generator may give a bias which will give the above mentioned effect. This may also make it impossible to achieve simulation repeatability. To reduce this effect, the amount of random numbers each component involved in the simulation should be approximately 10,000. We should be able to achieve repeatability in our simulation results if the random numbers follow the required distribution since for each trial we have approximately:

- ✓ 600,000 random numbers for each trial reliability and maintainability simulation,
- ✓ 1,200,000 random numbers for availability simulation, and
- ✓ 6 million random numbers to do the sensitivity analysis simulation.

- Another method for doing the Monte Carlo simulation is to generate each component random numbers to follow the desired distribution (say 10,000 for one component) before we compute the mathematical model. This is all very simple and more accurate than the first method. This means that when we repeat the simulation, the results are most likely the same or of the same order of magnitude. This method will not require a very fast computer to do the simulation even for a complex simulation since the computer generates the random numbers in chronological sequence without any delay. In addition, this technique can reduce the simulation time required. With this method, we may use a spreadsheet to do the simulation unless required special features or functions are not provided by that program.

4.3.2 Reliability of System

From the data of component Time Between Failures distributions presented in table 3.1, can be seen that the components have very low failure rates or long Time Between Failures. In other words, the quality of the components is very high. In contrast, the overall system has a very low Mean Time Between Failures, 250 hours for the series model and 750 hours for the parallel model. There is real life experience in the US that the overall MTBF of a ship propulsion system (a Full-load model), USS Halfbeak, is approximately 359 hours at 25,518 hours operation (see Crowder, M.J. et. al, 1991). The reason why the simulation result and the real life experience are different is because the components used in the two ships are not the same. Another reason is that in real life, preventive maintenance is also done but is not included in the simulation since the correlation between component time between failures, the preventive maintenance and the quality and frequency of maintenance is unknown. The preventive maintenance can increase the reliability of a system as a function of frequency of maintenance and the quality of maintenance (Endrenyi, 1978).

4.3.3 Sensitivity Analysis

Figure 4.3 and figure 4.4 are the sensitivity analysis result graphs for the Full-load model and the Half-load model, respectively. The graphs present the overall Time Between Failures by decreasing the Time Between Failures of each component. It can be seen from the graphs that the overall Time Between Failures is not affected by the change in individual components unless the component MTBF decreases to 85% or even less. This is displayed by the slope of the line corresponding to the change due to an individual component. In this case study, the fuel cams are the most sensitive component of the diesel engine components that affects the overall system Time Between Failures. This can be caused by either the mean of Time Between Failures and/or the type of distribution of fuel cams and also the configuration of the system block diagram. Figures 4.3 and 4.4 show that the most sensitive components are,

Diesel Engine:

Fuel Cams
Cylinder Pistons
Cylinder Heads

Shafting and Propeller:

Aft Stern Tube Seal
Propeller Hub
Fwd Stern Tube Seal

4.3.4 Maintainability of System

Since the full-load model and half-load model have the same components, the analysis of maintainability will give the same result as well. The result of the simulation is presented in table 4.3. In the maintainability simulation process, the most difficult part is the determination of the proportion of time to repair of one in a set of components since people recorded the time to repair a set of components instead of the time for individual components. Therefore, we needed a short discussion with an experienced maintenance manager to define it. The results of the maintainability simulation may surprise us, for a component with a long Time Between Failures needs only about 6 hours repair time. From our correspondence and discussions with maintenance management personnel, this is due to the fact that they do the repair or maintenance in a very professional and well planned manner.

As presented in table 4.3, the best fit of the Time To Maintain is the Extreme Value distribution although the distribution is not really a good fit to the result. The comparison between the result and the fitted data is presented in figure 4.5 in the previous section. That is one limitation of the software. Thus, the maintainability simulation result may have a better distribution (better goodness-of-fit) that is not provided by the software, Minitab package or Crystal Ball.

4.3.5 Availability of System

In the simulation of the availability of the system we do not use the simulation result distribution of the reliability and the maintainability but we prefer to use the *original* component distribution since the reliability and maintainability results do not fit the distribution well. For instance, in the previous section of discussion of the maintainability of the system, the result is not really appropriately represented by the Extreme Value distribution.

The result of the availability simulation seems very good for such a complex system. The mean of the availability index for unlimited operation time is approximately 0.98 for a Full-load model and 0.99 for a series model. Therefore, the system will perform with high effectiveness.

CHAPTER 5

Conclusion

In this study, the Monte Carlo method is utilised to develop the reliability, maintainability and availability prediction model for a ship propulsion system. The study presents the benefits of using a statistical simulation when the mathematical model may not be able to solve the problems. This is because the mathematical approach is not able to solve the infinite integral of some distributions, e.g. normal distribution.

An investigation of the process of data and system modelling, and simulation, lead to the conclusion that,

In general,

- The Monte Carlo simulation was found to be an appropriate tool for predicting the reliability, maintainability and availability of ship propulsion systems.

- The simulation results can approach the real problem in predicting the reliability, maintainability, and availability of a ship propulsion system. Therefore, to use the simulation result, we have to be very careful since the simulation did not include the preventive maintenance factor that in fact can improve the system reliability and availability. Neither does it consider the influence of machinery health monitoring systems, which may be installed.

- The simulation results are limited to only a certain system with certain components. However, the simulation result can be used for guidance in predicting the lifetime and behaviour of components and the particular system. The sensitivity analysis graphs can help to determine the priority of maintenance activities preventive and corrective.

- The model and the simulation are limited by the availability of data. Therefore, the accuracy of the results can only be improved by improving the accuracy of data or failure rate and required maintenance and repair times.

- The simulation is a way to predict the reliability, maintainability and availability indexes but it cannot represent exactly the real condition of the system.

In particular,

- Even if the individual component has a 'long' mean time between failures, it does not mean that the system will perform as long as the mean time between failures for the component. In this case study, the minimum of the mean time between failures of a component is 30.000 hours, but the overall system's mean time between failures is just around 250 hours for the full-load model and 750 hours for the half-load model. Thus, it can be pointed out that even when we have very high quality components configured as a system, the time between failures of the system would be much shorter than the individual component's mean time between failures.

- When choosing the 'best' implementation of the Monte Carlo simulation, the requirement of a very fast computer can be traded off against run time and accuracy. The level of accuracy has to be sufficient to ensure that good maintenance decision can be made. The run time of the reliability simulation for 20 trials (with 10,000 random numbers for each component) using the first interpretation is more than 7 x 24 hours and using the second method is less than 5 minutes. However, the results are approximately the same. On the other hand, when the simulations using 1,000 random numbers for each component, the simulation result almost always changes from each trial by around ± 5% from the expected value using the first method while for the second method it is only ± 0.25%.

- The graph of reliability sensitivity analysis can be used to lead us to make a priority maintenance schedule of some 'critical' components to avoid disabling the system due to failures of the critical components. The critical components are shown in the graphs with the more sensitive components having the lower lines in the graphs.

- To increase the availability of the system, we can increase the reliability of each component and/or decrease the maintenance time for each component. To increase the reliability of a component, only the manufacturers can increase the quality (lifetime) of the component. This can be done in design, manufacturing processes and material selection. In operation, the operator should also do preventive maintenance in order to reduce the failure rate of components. In addition, the preventive maintenance can be performed at a close to optimum time by the implementation of a good machinery health monitoring system. A system that is geared to detecting deterioration in those components that the overall reliability of the system is the most sensitive to will go a long way toward optimising the overall system availability.

- The existing maintenance policy is mostly based on the manufacturers' manuals and classification rules. This is sometimes too early to do maintenance since the manufacturer's manual and the classification society tend to err on the conservative side in order to avoid failures. The manufacturer's recommendations are made based on laboratory tests not on real condition tests. The classification society recommendations tend only to be changed to a more infrequent maintenance frequency when there is ample evidence that applies to all ships, or a given distinguishable class of ships. Therefore, when we have enough reliable component operating data, the maintenance policy can be made based on the prediction of failure rate or survival function. The best time to do maintenance is when the failure rate dramatically increases or the survival function decreases dramatically. This can be found in the graph of overview plots for components shown in chapter 3 (figure 3.2 to 3.25). For instance, from figure 3.19 the failure rate of pistons starts to increase at around 10.000 operating hours. Thus, they should be given maintenance after 10.000 hours of operation. On the other hand, the manufacturer and classification society rules advice to maintain them at 8.000

operating hours. The real condition data is more accurate than the manufacturer's manual for representing the real condition of the system. The classification society should also accept the maintenance period based on the reliability study for that ship, or that class of ships.

- ➢ To maintain some components would be better if it is done at the same time for several components in order to save on total time to repair. For instance, it is better to maintain a cylinder head, piston and piston rings at the same time. Decreasing the time to repair leads to an increase in system lifetime and also in the availability index of the system. Increasing the lifetime and availability of the system would lead to the potential for earning more revenues.

Possible future studies that improve the understanding of these problems:

- ✓ Having more detailed data and more complete information on the components involved will result in a more accurate investigation of the reliability, maintainability and availability indexes of the propulsion system. Involving other systems to perform, as an integrated system may also be possible to do if the data are available. This would be very useful.

- ✓ Other techniques of simulation and optimisation may also be tried to determine the most appropriate technique for predicting the reliability, maintainability and availability of a ship propulsion system or an integrated ship system.

- ✓ Preventive maintenance is also an important factor that is commonly used in real life. By involving the preventive maintenance in the simulation, the result may more closely approach the real problem. The important part to involve the preventive maintenance in this simulation is to find the correlation between the preventive maintenance and the failure rate of the component after it has been maintained. The maintenance cost may also be an interesting topic to be traded off against the total revenue that may be earned due to greater availability increase and in ship lifetime.

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Appendix A

MT Mattea Data

M/T Mattea Specification:

FLAG: CANADIAN
PORT OF REGISTRY: ST JOHN'S, NEWFOUNDLAND
CALL SIGN: VCSR
OFFICIAL NO.: 819115
IMO NO.: 9131888
COMMUNICATION: SATELLITE <B>
SATELLITE <C>
OWNER: PENNEY UGLAND INC.
MANAGER: CANSHIP UGLAND LTD.
P.O. BOX 8274, STN <A> 1289 TOPSAIL ROAD,
ST JOHN 'S, NEWFOUNDLAND, CANADA AI B 3N4
Telephone: (709) 782 3333 Telex: (709) 782 0225
E-mail: cul@canship.com
BUILDER: SAMSUNG HEAVY INDUSTRIES CO., LTD., HN 1189
BUILT: 1997
DESCRIPTION: The vessel is a twin skeg, twin screw SHUTTLE TANKER with 12 cargo tanks, 2 slop tanks, 13 segregated ballast tanks and bow loading system on the forecastle deck.

SHIP EQUIPMENT

HOSE HANDLING CRANES (NORLIFT)

- Two (2) Hydraulic type, each capacity of S.W.L. 15 tonnes max. Working radius 16.8 m and max outreach 6.4 m from the ship's side.

BOW MOORING/LOADING EQUIPMENT (PUSNES)

• Chain Stopper	One (1) Hydraulic self-locking type, Max. tension force 500 tonnes, chain dim. 83 mm
• Mooring Winch	One (1) Twin drum traction type. Pulling capacity of 70 tonnes at 7 m/min
• Storage Unit	Storage Capacity of 500 m 100 mm dia. Rope
• Loading Manifold	One (1) Single Probe type 20"
• Hose Handling winch	One (1) Double Drum, Pulling capacity of 25 tonnes
• Service Crane	One (1) Hydraulic jib type, Capacity of 5.0 tonnes, Working radius 9 m

STEERING GEARS (PORSGRUND - AKER)

- Two (2) Electro - Hydraulic, Rotary Vane type

RUDDERS

- Two (2) sets Becker Flap type

BOW THRUSTER (ULSTEIN)

- Two (2) sets C.P.P. type, Capacity of 2,100 kW each

WINDLASSES(PUSNES)
- Two (2) Hydraulic high pressure type, Combined with 2 Mooring Drums, Capacity of 45 tonnes 9 m/min

WINCHES (PUSNES)
- Eight (8) Hydraulic high pressure type, Capacity of 20 tonnes, 15 m/min. each 2 drums

HELICOPTER DECK
- One (1) Designed for a "EH1 01 " type Helicopter

PROVISION CRANES (NORLIFT)
- One (1) Electro - Hydraulic, Capacity of 5 tonnes * 10 m radius
- One (1) Electro - Hydraulic, Capacity of 2 tonnes * 10 m radius

PUMPS

CARGO PUMPS (SHINKO)
- Two (2) Two speed electric motor driven and one(1) steam driven vertical centrifugal type, Capacity of 4,000 m^3/h x 150 MLC(S.G.: 0.82)

BALLAST PUMPS (SHINKO)
- Two (2) Electric motor driven vertical centrifugal type, Capacity of 2,500 m^3/h x 25 mWC

CRUDE OIL WASHING PUMP (SHINKO)
- One (1) Electric motor driven vertical centrifugal type, Capacity of 1,000 m^3/h x 150 mLC(S.G.:0.82)

CARGO STRIPPING PUMP (SHINKO)
- One (1) Steam driven vertical reciprocating type, Capacity of 300 m^3/h x 135 mLC(S.G.:0.82)

MACHINERY

MAIN ENGINES
- Two(2) HYUNDAI MAN B&W, Type 7S50MC
- MCR: 12,700 BHP * 118.8 RPM (Each)
- CSR: 11,430 BHP 90 % of MCR (Each)
- 7 cylinders 2 stroke, single acting, non-reversible, crosshead, turbo-charged

AUX. ENGINE
- Two (2) Ulstein Bergen, Type BRG-8, 4,389 PS * 720 RPM, 3,000 kW Alternator - ABB
- Two (2) Ulstein Bergen, Type KRG-9, 2,169 PS * 720 RPM, 1,500 kW Alternator - ABB

EMERGENCY DIESEL ENGINE
- One (1) MAN-DEMP type D2842LE, 544 BHP * 1,800 RPM, 400 kW Alternator

PROPELLERS

- Two (2) sets, Ulstein Controllable Pitch Propeller, four (4) blades
- Diameter, 6,000 mm
- Direction of rotation - Outboard
- Material: Ni-Al-Bronze

OIL FIRED BOILER

- Two(2) MITSUBISHI type MAC-258
- Each capacity of 25,000 kg/h - 16 kg/cm^2

EXHAUST GAS ECONOMIZER

- Not provided

INERT GAS PLANT

- One (1) set Aalborg Sunrod, Boiler flue gas type with (2) inert gas fans, each capacity 16,250 Nm^3/h

FRESH WATER GENERATOR

- Two (2) sets Nirex, Plate type, Each capacity of 30 tonnes/day

NAVIGATION AND COMMUNICATION EQUIPMENT

RADAR PLANT

- One (1) set, S-Band with ARPA, Sperry VT340 CDA314P
- One (1) set, X-Band with ARPA, Sperry VT340 CDA027P
- One (1) X-Band scanner on foremast, Sperry

MARINE NAVIGATION SYSTEM

- Two (2) sets, GPS, Trimble NT 200D
- One (1) set, LORAN-C, North Star, 800X
- One (1) set, Integrated Navigation System, Sperry

GYRO COMPASS

- Two (2) sets, Sperry, MK37VT

ECHO SOUNDER

- One (1) set, Sperry, LSE 135
- One (1) set, Sperry, LSE 297

AUTO PILOT

- One (1) set, Sperry, ADG 6000

DYNAMIC POSITIONING SYSTEM

- One (1) set, dual (redundant) Cegelec DPS 902

The DP system is interfaced to the following environmental sensors:

- Two (2) Gyrocompasses, Sperry MK37VT
- Two (2) Vertical reference units
- Two (2) Anemometers
- Four (4) Draft sensors

DP Position Reference Systems available for use are:

- One (1) Artemis MK IV (Antenna located in top of fore mast)
- One (1) Simrad OLS 410 HPR System
- Two (2) Seatex DGPS/DARPS units

(DGPS - Differential Global Positioning System)
(DARPS - Differential Absolute and Relative Positioning System)

The DP system controls the following propellers/rudders

- Two (2) CPP tunnel thrusters in bow (ULSTEIN)
- Two (2) CPP Main propellers aft. (ULSTEIN)
- Two (2) High Lift Rudders (BECKER)

SPEED LOG

- One (1) set, Doppler speed log (dual axis), Sperry, SRD 421 S
- One (1) set, Doppler speed log (single axis), Sperry, SRD 331

WEATHER FACSIMILE RECORDER

- One (1) set, Furuno, Fax 214

NAVTEX RECEIVER

- One (1) set, Sperry, NAV-5

RADIO STATION (SPERRY MARINE INC.)

In accordance with requirements for GMDSS - Radio station

MAIN DIMENSIONS

Length overall	:	271.8M	-	891'8 3/4"
Length between perpendicular	:	258.0M	-	846'5 1/2"
Breadth moulded	:	46.0M	-	150'11"
Depth moulded	:	22.6M	-	74'1 3/4"
Designed draft (moulded)	:	14.8M	-	48'6 3/4"
Draft on summer freeboard (moulded)	:	15.3M	-	50'2 1/4"
Height from keel to top of highest mast/antenna	:	50.9M	-	167'0"
Lightship displacement	:	27,094.5Tonnes		
Deadweight at summer draft	:	126,646.6Tonnes		
Service speed	:	14.8Knots		
Cruising range	:	12,000S.M.		

TONNAGE

	International	Suez
Gross Tonnage	76,216	77,492
Net Tonnage	34,631	68,413

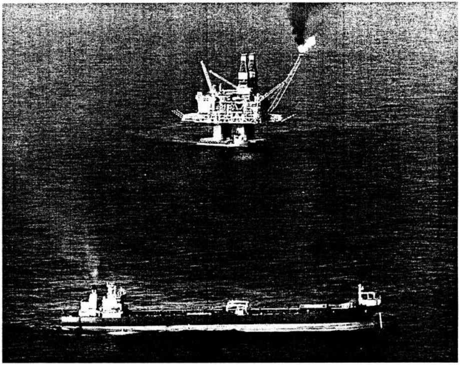
CLASS

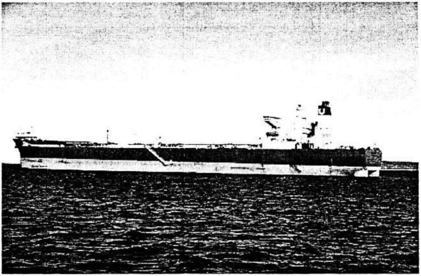
American Bureau Shipping
+A1 (E) Oil Carrier SH DLA; ICE CLASS IC; +AMS; +ACCO

MANIFOLD

Distance from bow to centre of manifold	:	133.91 M - (439'4")
Distance from stern to centre of manifold	:	137.89 M
Distance from cargo manifold to side of vessel	:	4.60 M
Centre height of cargo manifold above deck	:	2.10 M
Number and diameter of manifold connections	:	Three (3) - ANSI 16"
Cargo reducers	:	16" x 16" - 6 pieces 16" x 12" - 3 pieces 16" x 10" - 3 pieces 16" x 8" - 3 pieces

Pictures of M/T Mattea





Appendix B

Probability Distributions

1. Weibull Distribution

A Weibull density function is given as,

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

where,

$\alpha > 0$: scale parameter

$\beta > 0$: shape parameter

and

$$\text{the mean value} = \alpha\Gamma\left(\frac{1}{\beta}+1\right)$$

$$\text{the variance} = \alpha^{2}\left\{\Gamma\left(\frac{2}{\beta}+1\right)-\left(\Gamma\left(\frac{1}{\beta}+1\right)^{2}\right)\right\}$$

Domain: $t > 0$

Mode:

$$\beta\left[\frac{(\alpha-1)}{\alpha}\right]^{\frac{1}{\alpha}} \quad \text{if } \alpha \geq 1 \text{ and}$$

$$0 \quad \text{if } \alpha < 1$$

Where Γ, the gamma function is,

$$\Gamma(x) = \int_{0}^{\infty} u^{x-1} e^{-u}\, du$$

2. Normal Distribution

$$f(t) = \frac{1}{2\pi\sigma^2}\exp\left\{-\frac{(t-\mu)^2}{2\sigma^2}\right\} \qquad \text{for } -\infty < t < \infty$$

with μ : mean (all values)

σ^2 : variance ($\sigma > 0$)

Domain: all t

Mode : μ

Variance : σ

3. Extreme Value Distribution

$$f(t) = \sigma^{-1}\exp\left\{\frac{t-\mu}{\sigma}\right\}\exp\left\{-\exp\left[\frac{t-\mu}{\sigma}\right]\right\} \qquad \text{for } -\infty < t < \infty$$

where μ : location parameter

σ : scale parameter ; $\sigma > 0$

Domain: all t

Mode: μ

Variance: $\frac{\sigma^2\pi^2}{6}$

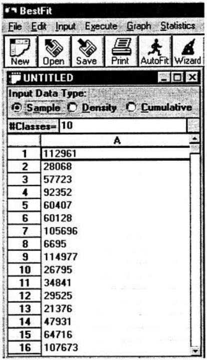
Appendix C

Finding The Goodness of fit Distribution

Finding The Best Distributions

1. Using BestFit Version 2.0d

   Bestfit is a program that fits the data to a selected statistical distribution and displays the results in high-resolution graphs. The procedures followed are very simple. Copy the result from Minitab into a column in the BestFit program as shown in the following figure.

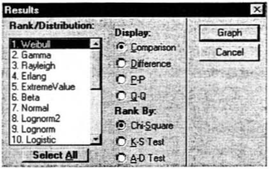


Input Data Type:
● Sample ○ Density ○ Cumulative

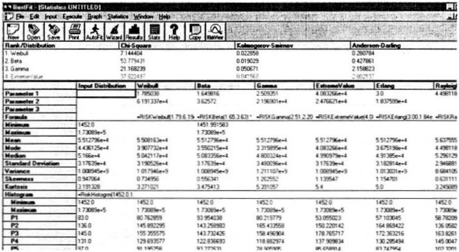
#Classes= 10

	A
1	112961
2	28068
3	57723
4	92352
5	60407
6	60128
7	105696
8	6695
9	114977
10	26795
11	34841
12	29525
13	21376
14	47931
15	64716
16	107673

By setting the goodness of fits test to all possible tests: Chi-Square, Kolmogorov - Smirnov and Anderson-Darling, and click the 'autofit' button, the program will gives the ranks automatically as follows,



For more, the detail parameter and fitting result, Bestfit presents in table such as,



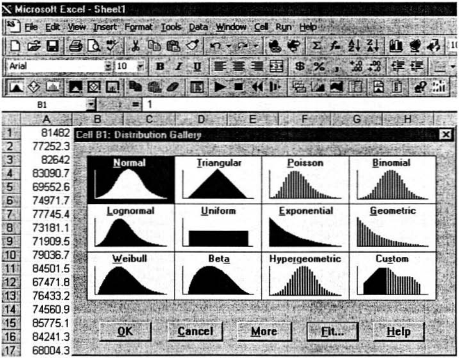
Rank/Distribution	Chi-Square	Kolmogorov-Smirnov	Anderson-Darling
1. Weibull	7.144404	0.022858	0.280784
2. Beta	53.779431	0.019029	0.427861
3. Gamma	21.168239	0.050671	2.158823
4. ExtremeValue	37.622497	0.047563	2.902137

	Input Distribution	Weibull	Beta	Gamma	ExtremeValue	Erlang	Rayleig
Parameter 1		1.785038	1.649816	2.509351	4.083266e+4	3.0	4.498118
Parameter 2		6.191337e+4	3.62572	2.196901e+4	2.476621e+4	1.837599e+4	
Parameter 3							
Formula		=RISKWeibull(1.79,6.19	=RISKBeta(1.65,3.63)*	=RISKGamma(2.51,2.20	=RISKExtremeValue(4.0	=RISKErlang(3.00,1.84e	=RISKRa
Minimum	1452.0		1451.991583				
Maximum	1.73089e+5		1.73089e+5				
Mean	5.512796e+4	5.508163e+4	5.512796e+4	5.512796e+4	5.512796e+4	5.512796e+4	5.637555
Mode	4.436125e+4	3.907732e+4	3.550215e+4	3.315895e+4	4.083266e+4	3.675198e+4	4.498118
Median	5.166e+4	5.042117e+4	5.083356e+4	4.800324e+4	4.990979e+4	4.91385e+4	5.296129
Standard Deviation	3.17639e+4	3.190526e+4	3.17639e+4	3.480096e+4	3.17639e+4	3.182814e+4	2.946881
Variance	1.008945e+9	1.017946e+9	1.008945e+9	1.211107e+9	1.008945e+9	1.013031e+9	8.684105
Skewness	0.947064	0.734956	0.556341	1.262552	1.139547	1.154701	0.631111
Kurtosis	3.191328	3.271021	3.475413	5.391057	5.4	5.0	3.245089
Histogram	=RiskHistogrm(1452.0,1						
Minimum	1452.0	1452.0	1452.0	1452.0	1452.0	1452.0	1452.0
Maximum	1.73089e+5	1.73089e+5	1.73089e+5	1.73089e+5	1.73089e+5	1.73089e+5	1.73089e
P1	83.0	80.762859	93.954038	80.219779	53.055023	57.103045	58.78209
P2	136.0	145.892295	143.258983	165.433558	150.220142	164.869422	136.0582
P3	145.0	155.355575	143.732426	158.496904	178.765717	172.363216	163.8261
P4	131.0	129.693577	122.836693	118.882974	137.909834	130.285494	145.0047
P5	97.0	91.195258	93.272531	78.905905	85.658914	83.747954	102.3201

From the table, we know all parameters and the ranks of goodness of fit of the data. The limitation of the software we have (student version), is that the number of data should not be more than 4500 numbers. In addition, the full version is able to fit around 33,000 random numbers.

2. Crystal Ball Software Version 4.0g

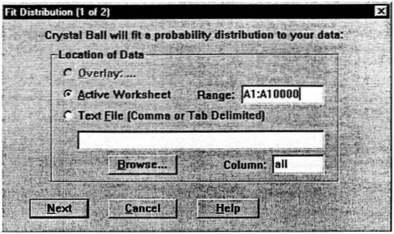
This software is an add-in or macro-program for spreadsheets such as Excel, Q-Pro or Lotus 1-2-3. The software is for forecasting, risk analysis, and optimization tools such as Monte Carlo simulation. In our opinion, the software is not flexible enough to represents the problem since we cannot add a command to do some loops to find a better simulation result. However, this software is capable of finding the best distribution of some random data to the limit of data that Excel can accommodate. The procedure is the same as fitting data using BestFit, we copy the simulation result from Mintab such as,



B1 = 1

	A
1	81482
2	77252.3
3	82642
4	83090.7
5	69552.6
6	74971.7
7	77745.4
8	73181.1
9	71909.5
10	79036.7
11	84501.5
12	67471.8
13	76433.2
14	74560.9
15	85775.1
16	84241.3
17	68004.3

By clicking the Fit button, we then have a window:



Fit Distribution (1 of 2)

Crystal Ball will fit a probability distribution to your data:

Location of Data

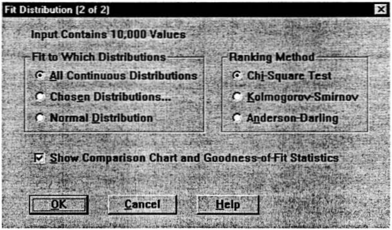
○ Overlay: ....

● Active Worksheet   Range: A1:A10000

○ Text File (Comma or Tab Delimited)

Column: all

Then we have to define the range of data in the Excel sheet. Here, we select A1 to A10000. The program gives the following screen after clicking next button,



Fit Distribution (2 of 2)

Input Contains 10,000 Values

Fit to Which Distributions

● All Continuous Distributions

○ Chosen Distributions...

○ Normal Distribution

Ranking Method

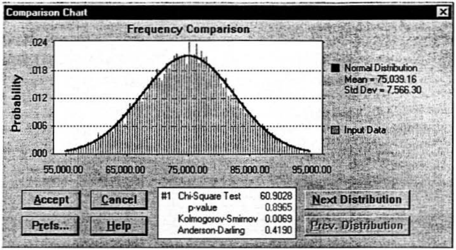
● Chi-Square Test

○ Kolmogorov-Smirnov

○ Anderson-Darling

☑ Show Comparison Chart and Goodness-of-Fit Statistics

Choose one of the options of distributions and ranking methods to find the best distribution,



Normal Distribution
Mean = 75,039.16
Std Dev = 7,566.30

```
#1  Chi-Square Test       60.9028
      p-value              0.8965
    Kolmogorov-Smirnov     0.0069
    Anderson-Darling       0.4190
```

The comparison of fitting data cannot be given in one table. Therefore, we cannot directly compare the resulting parameters.

We used both software packages for finding the distribution of components by taking advantages of the software. For instance, if the random numbers generated was less than 5000, we used both Bestfit and Crystal Ball to find the distribution since the capability of finding distributions are different. However, for more than 5000 data points, the Crystal Ball software is used.

Appendix D

Some Minitab Macros

💾

For Reliability Simulation

🖫 Series Model

```
GMACRO
MCS
erase c1-c150
Let k2 = 1
Let k50 = 10000
Let k56 = 20
Do k102=1:K56
        Random k50 c1;
        Weibull 1.8 62500.
        Random k50 c2;
        Weibull 1.8 73800.
        Random k50 c3;
        Weibull 1.3 52800.
        Random k50 c4;
        Weibull 2.2 52500.
        Random k50 c5;
        Weibull 2.7 32400.
        Random k50 c6;
        Weibull 2.2 73000.
        Random k50 c7;
        Weibull 2.1 50100.
        Random k50 c8;
        Weibull 2.0 58800.
        Random k50 c9;
        Weibull 2.7 80800.
        Random k50 c10;
        Weibull 3.4 78900.
        Random k50 c11;
        Weibull 1.4 75300.
        Random k50 c12;
        Weibull 2.7 68800.
        Random k50 c13;
        Weibull 1.4 63700.
        Random k50 c14;
        Weibull 1.4 66600.
        Random k50 c15;
        Weibull 2.1 78700.
        Random k50 c16;
        Weibull 2.8 82700.
        Random k50 c17;
        Weibull 2.6 54600.
        Random k50 C18;
        Weibull 3.432 31604.
        Random k50 c19;
        Weibull 1.544 69755.
        Random k50 C20;
        Weibull 2.196 74791.
        Random k50 C21;
        Weibull 1.425 83757.
        Random k50 C22;
        Weibull 1.221 210000.
        Random k50 C23;
        Weibull 0.71 60362.
        Random k50 C24;
        Weibull 1.521 31753.
        Let
c25=((1/c1)+(1/c2)+(1/c3)+(1/c4)+(1/c
5)+(1/c6)+(1/c7)+(1/c8)+(1/c9)+(1/c10
)+(1/c11)+(1/c12))
        let
c26=((1/c13)+(1/c14)+(1/c15)+(1/c16)
+(1/c17)+(7/c18)+(7/c19)+(7/c20)+(7/
c21)+(7/c22)+(1/c23)+(7/c24))
        let c27=1/(c25+c26)/2
        if k2=1
        name c28 'Trial 1'
        let c28=c27
        endif
        if k2 = 2
        name c29 'Trial 2'
        let c29 = c27
        endif
        if k2 = 3
        name c30 'Trial 3'
        let c30 = c27
        endif
        if k2 = 4
        name c31 'Trial 4'
        let c31 = c27
        endif
        if k2 = 5
        name c32 'Trial 5'
        let c32 = c27
        endif
```

```
    if k2 = 6
    name c33 'Trial 6'
    let c33 = c27
    endif
    if k2 = 7
    name c34 'Trial 7'
    let c34 = c27
    endif
    if k2 = 8
    name c35 'Trial 8'
    let c35 = c27
    endif
    if k2 = 9
    name c36 'Trial 9'
    let c36 = c27
    endif
    if k2 = 10
    name c37 'Trial 10'
    let c37 = c27
    endif
    if k2 = 11
    name c38 'Trial 11'
    let c38 = c27
    endif
    if k2 = 12
    name c39 'Trial 12'
    let c39 = c27
    endif
    if k2 = 13
    name c40 'Trial 13'
    let c40 = c27
    endif
    if k2 = 14
    name c41 'Trial 14'
    let c41 = c27
    endif
    if k2 = 15
    name c42 'Trial 15'
    let c42 = c27
    endif
    if k2 = 16
    name c43 'Trial 16'
    let c43 = c27
    endif
    if k2 = 17
    name c44 'Trial 17'
    let c44 = c27
    endif
    if k2 = 18
    name c45 'Trial 18'
    let c45 = c27
    endif
    if k2 = 19
    name c46 'Trial 19'
    let c46 = c27
    endif
    if k2 = 20
    name c47 'Trial 20'
    let c47 = c27
    endif
    Let k2 = k2 + 1
Enddo
ENDMACRO
```

🖫 For Parallel Model, see in 3 ½" floppy disk attached.

For Sensitivity Analysis of System Reliability Simulation

🖫For Component: Propeller

```
GMACRO
MCS
erase c1-c150
Let k1 = 1
Let k3 = 1
Let k50 = 1000
Let k53 = 62500
Let k54 = 101
Let k55 = k53
Let k56 = 10
Do k100=1:k54
Do k101=1:1
Let k2 = 1
erase c28
Do k102=1:K56
        Random k50 c1;
        Weibull 1.801 k53.
        Random k50 c2;
        Weibull 1.8 73800.
        Random k50 c3;
        Weibull 1.3 52800.
        Random k50 c4;
        Weibull 2.2 52500.
        Random k50 c5;
        Weibull 2.7 32400.
        Random k50 c6;
        Weibull 2.2 73000.
        Random k50 c7;
        Weibull 2.1 50100.
        Random k50 c8;
        Weibull 2.0 58800.
        Random k50 c9;
        Weibull 2.7 80800.
        Random k50 c10;
        Weibull 3.4 78900.
        Random k50 c11;
        Weibull 1.4 75300.
        Random k50 c12;
        Weibull 2.7 68800.
        Random k50 c13;
        Weibull 1.4 63700.
        Random k50 c14;
        Weibull 1.4 66600.
        Random k50 c15;
        Weibull 2.1 78700.
        Random k50 c16;
        Weibull 2.8 82700.
        Random k50 c17;
        Weibull 2.6 54600.
        Random k50 C18;
        Weibull 3.432 31604.
        Random k50 c19;
        Weibull 1.544 69755.
        Random k50 C20;
        Weibull 2.196 74791.
        Random k50 C21;
        Weibull 1.425 83757.
        Random k50 C22;
        Weibull 1.221 210000.
        Random k50 C23;
        Weibull 0.71 60362.
        Random k50 C24;
        Weibull 1.521 31753.
        Let
c25=((1/c1)+(1/c2)+(1/c3)+(1/c4)+(1/c
5)+(1/c6)+(1/c7)+(1/c8)+(1/c9)+(1/c10
)+(1/c11)+(1/c12))
        let
c26=((1/c13)+(1/c14)+(1/c15)+(1/c16)
+(1/c17)+(7/c18)+(7/c19)+(7/c20)+(7/
c21)+(7/c22)+(1/c23)+(7/c24))
        let c27=1/(c25+c26)
        Let c28(k2) = sum(c27)/k50
        Let c131(k2) = sum(c1)/k50
        Let k2 = k2 + 1
Enddo
        Let c30(k3)=sum(c28)/k56
        Let c31(k3)=3*c30(k3)/2
        Let c32(k3)=sum(c131)/k56
        Let c33(k3)=k53
        Let k3 = k3+1
Enddo
        Let k53 = (k53+0.000001)-
(k55/(k54-1))
        Let c29(k1) = (k1-1)
```

```
        Let k1=k1+1
Enddo
ENDMACRO
```

💾 For other components, see in 3 ½"
floppy disk attached.

For Maintainability Simulation

All Model

```
GMACRO
MCS
erase c1-c150
Let k2 = 1
Let k50 = 100
Let k56 = 20
Do k102=1:K56
        Random k50 c1;
        Weibull 1.8 62500.
        Random k50 c2;
        Weibull 1.8 73800.
        Random k50 c3;
        Weibull 1.3 52800.
        Random k50 c4;
        Weibull 2.2 52500.
        Random k50 c5;
        Weibull 2.7 32400.
        Random k50 c6;
        Weibull 2.2 73000.
        Random k50 c7;
        Weibull 2.1 50100.
        Random k50 c8;
        Weibull 2.0 58800.
        Random k50 c9;
        Weibull 2.7 80800.
        Random k50 c10;
        Weibull 3.4 78900.
        Random k50 c11;
        Weibull 1.4 75300.
        Random k50 c12;
        Weibull 2.7 68800.
        Random k50 c13;
        Weibull 1.4 63700.
        Random k50 c14;
        Weibull 1.4 66600.
        Random k50 c15;
        Weibull 2.1 78700.
        Random k50 c16;
        Weibull 2.8 82700.
        Random k50 c17;
        Weibull 2.6 54600.
        Random k50 C18;
        Weibull 3.432 31604.
        Random k50 c19;
        Weibull 1.544 69755.
        Random k50 C20;
        Weibull 2.196 74791.
        Random k50 C21;
        Weibull 1.425 83757.
        Random k50 C22;
        Weibull 1.221 210000.
        Random k50 C23;
        Weibull 0.71 60362.
        Random k50 C24;
        Weibull 1.521 31753.
        Random k50 C25;
        Normal 75 25.
        Random k50 C26;
        Normal 20 7.
        Random k50 C27;
        Normal 75 30.
        Random k50 C28;
        Normal 10 3.
        Random k50 C29;
        Normal 10 3.
        Random k50 C30;
        Normal 50 12.
        Random k50 C31;
        Normal 25 7.
        Random k50 C32;
        Normal 50 12.
        Random k50 C33;
        Normal 20 6.
        Random k50 C34;
        Normal 20 6.
        Random k50 C35;
        Normal 20 6.
        Random k50 C36;
        Normal 10 2.
        Random k50 C37;
        Normal 40 10.
        Random k50 C38;
        Normal 40 10.
        Random k50 C39;
        Normal 40 10.
        Random k50 C40;
```

```
        Normal 20 5.
        Random k50 C41;
        Normal 15 4.
        Random k50 C42;
        Normal 100 25.
        Random k50 C43;
        Normal 100 25.
        Random k50 C44;
        Normal 150 30.
        Random k50 C45;
        Normal 150 30.
        Random k50 C46;
        Normal 100 25.
        Random k50 C47;
        Normal 120 30.
        Random k50 C48;
        Normal 50 12.
        Let
c49=(c25/c1)+(c26/c2)+(c27/c3)+(c28/
c4)+(c29/c5)+(c30/c6)
        Let
c50=(c31/c7)+(c32/c8)+(c33/c9)+(c34/
c10)+(c35/c11)+(c36/c12)
        let
c51=(c37/c13)+(c38/c14)+(c39/c15)+(
c40/c16)+(c41/c17)+(c42*7/c18)
        Let
c52=(c43*7/c19)+(c44*7/c20)+(c45*7/
c21)+(c46*7/c22)+(c47/c23)+(c48*7/c
24)
        Let
c53=((1/c1)+(1/c2)+(1/c3)+(1/c4)+(1/c
5)+(1/c6)+(1/c7)+(1/c8)+(1/c9)+(1/c10
)+(1/c11)+(1/c12))
        let
c54=((1/c13)+(1/c14)+(1/c15)+(1/c16)
+(1/c17)+(7/c18)+(7/c19)+(7/c20)+(7/
c21)+(7/c22)+(1/c23)+(7/c24))
        let
c55=(c49+c50+c51+c52)/(c53+c54)
        if k2=1
        name c56 'Trial 1'
        let c56 = c55
        endif
if k2 = 2
name c57 'Trial 2'
let c57 = c55
endif
if k2 = 3
name c58 'Trial 3'
let c58 = c55
endif
if k2 = 4
name c59 'Trial 4'
let c59 = c55
endif
if k2 = 5
name c60 'Trial 5'
let c60 = c55
endif
if k2 = 6
name c61 'Trial 6'
let c61 = c55
endif
if k2 = 7
name c62 'Trial 7'
let c62 = c55
endif
if k2 = 8
name c63 'Trial 8'
let c63 = c55
endif
if k2 = 9
name c64 'Trial 9'
let c64 = c55
endif
if k2 = 10
name c65 'Trial 10'
let c65 = c55
endif
if k2 = 11
name c66 'Trial 11'
let c66 = c55
endif
if k2 = 12
name c67 'Trial 12'
let c67 = c55
endif
```

```
        if k2 = 13
        name c68 'Trial 13'
        let c68 = c55
        endif
        if k2 = 14
        name c69 'Trial 14'
        let c69 = c55
        endif
        if k2 = 15
        name c70 'Trial 15'
        let c70 = c55
        endif
        if k2 = 16
        name c71 'Trial 16'
        let c71 = c55
        endif
        if k2 = 17
        name c72 'Trial 17'
        let c72 = c55
        endif
        if k2 = 18
        name c73 'Trial 18'
        let c73 = c55
        endif
        if k2 = 19
        name c74 'Trial 19'
        let c74 = c55
        endif
        if k2 = 20
        name c75 'Trial 20'
        let c75 = c55
        endif
        Let k2 = k2 + 1
Enddo
ENDMACRO
```

For Availability Simulation

Series Model

```
GMACRO
MCS
erase c1-c150
Let k2 = 1
Let k50 = 10000
Let k56 = 20
Do k102=1:K56
        Random k50 c1;
        Weibull 1.8 62500.
        Random k50 c2;
        Weibull 1.8 73800.
        Random k50 c3;
        Weibull 1.3 52800.
        Random k50 c4;
        Weibull 2.2 52500.
        Random k50 c5;
        Weibull 2.7 32400.
        Random k50 c6;
        Weibull 2.2 73000.
        Random k50 c7;
        Weibull 2.1 50100.
        Random k50 c8;
        Weibull 2.0 58800.
        Random k50 c9;
        Weibull 2.7 80800.
        Random k50 c10;
        Weibull 3.4 78900.
        Random k50 c11;
        Weibull 1.4 75300.
        Random k50 c12;
        Weibull 2.7 68800.
        Random k50 c13;
        Weibull 1.4 63700.
        Random k50 c14;
        Weibull 1.4 66600.
        Random k50 c15;
        Weibull 2.1 78700.
        Random k50 c16;
        Weibull 2.8 82700.
        Random k50 c17;
        Weibull 2.6 54600.
        Random k50 C18;
        Weibull 3.432 31604.
        Random k50 c19;
        Weibull 1.544 69755.
        Random k50 C20;
        Weibull 2.196 74791.
        Random k50 C21;
        Weibull 1.425 83757.
        Random k50 C22;
        Weibull 1.221 210000.
        Random k50 C23;
        Weibull 0.71 60362.
        Random k50 C24;
        Weibull 1.521 31753.
        Random k50 C25;
        Normal 15 5.
        Random k50 C26;
        Normal 5 2.
        Random k50 C27;
        Normal 15 5.
        Random k50 C28;
        Normal 5 2.
        Random k50 C29;
        Normal 5 2.
        Random k50 C30;
        Normal 15 5.
        Random k50 C31;
        Normal 5 2.
        Random k50 C32;
        Normal 7 2.
        Random k50 C33;
        Normal 5 1.5.
        Random k50 C34;
        Normal 5 1.5.
        Random k50 C35;
        Normal 5 1.5.
        Random k50 C36;
        Normal 3 1.
        Random k50 C37;
        Normal 7 2.
        Random k50 C38;
        Normal 7 2.
        Random k50 C39;
        Normal 7 2.
        Random k50 C40;
```

```
        Normal 5 2.
        Random k50 C41;
        Normal 4 1.
        Random k50 C42;
        Normal 12 4.
        Random k50 C43;
        Normal 12 4.
        Random k50 C44;
        Normal 15 5.
        Random k50 C45;
        Normal 15 5.
        Random k50 C46;
        Normal 12 4.
        Random k50 C47;
        Normal 16 5.
        Random k50 C48;
        Normal 10 3.
        Let
c49=(c25/c1)+(c26/c2)+(c27/c3)+(c28/
c4)+(c29/c5)+(c30/c6)
        Let
c50=(c31/c7)+(c32/c8)+(c33/c9)+(c34/
c10)+(c35/c11)+(c36/c12)
        let
c51=(c37/c13)+(c38/c14)+(c39/c15)+(
c40/c16)+(c41/c17)+(c42*7/c18)
        Let
c52=(c43*7/c19)+(c44*7/c20)+(c45*7/
c21)+(c46*7/c22)+(c47/c23)+(c48*7/c
24)
        Let
c53=((1/c1)+(1/c2)+(1/c3)+(1/c4)+(1/c
5)+(1/c6)+(1/c7)+(1/c8)+(1/c9)+(1/c10
)+(1/c11)+(1/c12))
        let
c54=((1/c13)+(1/c14)+(1/c15)+(1/c16)
+(1/c17)+(7/c18)+(7/c19)+(7/c20)+(7/
c21)+(7/c22)+(1/c23)+(7/c24))
        let
c55=(c49+c50+c51+c52)/(c53+c54)
        Let
c56=((1/c1)+(1/c2)+(1/c3)+(1/c4)+(1/c
5)+(1/c6)+(1/c7)+(1/c8)+(1/c9)+(1/c10
)+(1/c11)+(1/c12))
        let
c57=((1/c13)+(1/c14)+(1/c15)+(1/c16)
+(1/c17)+(7/c18)+(7/c19)+(7/c20)+(7/
c21)+(7/c22)+(1/c23)+(7/c24))
        let c58=1/(c56+c57)/2
        Let c59=c55/(c55+c58)
        if k2=1
        name c60 'Trial 1'
        let c60 = c59
        endif
        if k2 = 2
        name c61 'Trial 2'
        let c61 = c55
        endif
        if k2 = 3
        name c62 'Trial 3'
        let c62 = c59
        endif
        if k2 = 4
        name c63 'Trial 4'
        let c63 = c59
        endif
        if k2 = 5
        name c64 'Trial 5'
        let c64 = c59
        endif
        if k2 = 6
        name c65 'Trial 6'
        let c65 = c59
        endif
        if k2 = 7
        name c66 'Trial 7'
        let c66 = c59
        endif
        if k2 = 8
        name c67 'Trial 8'
        let c67 = c59
        endif
        if k2 = 9
        name c68 'Trial 9'
        let c68 = c59
        endif
        if k2 = 10
        name c69 'Trial 10'
```

```
    let c69 = c59
    endif
    if k2 = 11
    name c70 'Trial 11'
    let c70 = c59
    endif
    if k2 = 12
    name c71 'Trial 12'
    let c71 = c59
    endif
    if k2 = 13
    name c72 'Trial 13'
    let c72 = c59
    endif
    if k2 = 14
    name c73 'Trial 14'
    let c73 = c59
    endif
    if k2 = 15
    name c74 'Trial 15'
    let c74 = c59
    endif
    if k2 = 16
    name c75 'Trial 16'
    let c75 = c59
    endif
    if k2 = 17
    name c76 'Trial 17'
    let c76 = c59
    endif
    if k2 = 18
    name c77 'Trial 18'
    let c77 = c59
    endif
    if k2 = 19
    name c78 'Trial 19'
    let c78 = c59
    endif
    if k2 = 20
    name c79 'Trial 20'
    let c79 = c59
    endif
    Let k2 = k2 + 1
Enddo
ENDMACRO
```

🖫 For Parallel Model, see in 3 ½" floppy disk attached.

List of Macros attached in 3 ½" floppy disk:

No	File Name	Purpose
1	a:\macro\reliability\reliability-series.mac	System Reliability simulation – series model
2	a:\macro\reliability\reliability-parallel.mac	System Reliability simulation – parallel model
3	a:\macro\sensitivity\sensitivity-comp1.mac	Sensitivity Analysis simulation – component #1 (propeller)
4	a:\macro\sensitivity\sensitivity-comp2.mac	Sensitivity Analysis simulation – component #2 (propeller cap)
5	a:\macro\sensitivity\sensitivity-comp3.mac	Sensitivity Analysis simulation – component #3 (propeller hub)
6	a:\macro\sensitivity\sensitivity-comp4.mac	Sensitivity Analysis simulation – component #4 (fwd ST seal)
7	a:\macro\sensitivity\sensitivity-comp5.mac	Sensitivity Analysis simulation – component #5 (Aft ST Seal)
8	a:\macro\sensitivity\sensitivity-comp6.mac	Sensitivity Analysis simulation – component #6 (Stern Tube)
9	a:\macro\sensitivity\sensitivity-comp7.mac	Sensitivity Analysis simulation – component #7 (aft ST Bush)
10	a:\macro\sensitivity\sensitivity-comp8.mac	Sensitivity Analysis simulation – component #8 (fwd ST Bush)
11	a:\macro\sensitivity\sensitivity-comp9.mac	Sensitivity Analysis simulation – component #9 (aft. Int. Shaft)
12	a:\macro\sensitivity\sensitivity-comp10.mac	Sensitivity Analysis simulation – component #10 (aft. Int. Shaft)
13	a:\macro\sensitivity\sensitivity-comp11.mac	Sensitivity Analysis simulation – component #11 (Int. Shaft)
14	a:\macro\sensitivity\sensitivity-comp12.mac	Sensitivity Analysis simulation – component #12 (Earthing Device)
15	a:\macro\sensitivity\sensitivity-comp13.mac	Sensitivity Analysis simulation – component #13 (prop sd hyd coup)
16	a:\macro\sensitivity\sensitivity-comp14.mac	Sensitivity Analysis simulation – component #14 (Int. sd hyd coup)
17	a:\macro\sensitivity\sensitivity-comp15.mac	Sensitivity Analysis simulation – component #15 (eng. sd hyd coup)
18	a:\macro\sensitivity\sensitivity-comp16.mac	Sensitivity Analysis simulation – component #16 (dismounting ring)
19	a:\macro\sensitivity\sensitivity-comp17.mac	Sensitivity Analysis simulation – component #17 (shaft locking dev)
20	a:\macro\sensitivity\sensitivity-comp18.mac	Sensitivity Analysis simulation – component #18 (cylinder pistons)

21	a:\macro\sensitivity\sensitivity-comp19.mac	Sensitivity Analysis simulation – component #19 (cylinder heads)
22	a:\macro\sensitivity\sensitivity-comp20.mac	Sensitivity Analysis simulation – component #20 (connecting rod bearings)
23	a:\macro\sensitivity\sensitivity-comp21.mac	Sensitivity Analysis simulation – component #21 (cylinder jacket)
24	a:\macro\sensitivity\sensitivity-comp21.mac	Sensitivity Analysis simulation – component #22 (cyl.lin&pis. Ring)
25	a:\macro\sensitivity\sensitivity-comp21.mac	Sensitivity Analysis simulation – component #23 (turbocharger)
27	a:\macro\sensitivity\sensitivity-comp21.mac	Sensitivity Analysis simulation – component #24 (fuel cams)
28	a:\macro\sensitivity\ sensitivity -subcommand.mac	To run all component sensitivity analysis macro in one command
28	a:\macro\maintainability\maintainability.mac	System maintainability simulation – all models
29	a:\macro\availability\availability -series.mac	System availability simulation – series model
30	a:\macro\availability\availability -parallel.mac	System availability simulation – parallel model
31	a:\macro\component-plotting\plotting.mac	Overview plotting of all component