

**NAVAL POSTGRADUATE SCHOOL**  
**Monterey, California**



**THESIS**

**RELIABILITY MODELING AND ESTIMATION  
USING U.S. NAVY 3M MAINTENANCE DATA**

by

Jason J. Michal

September, 1995

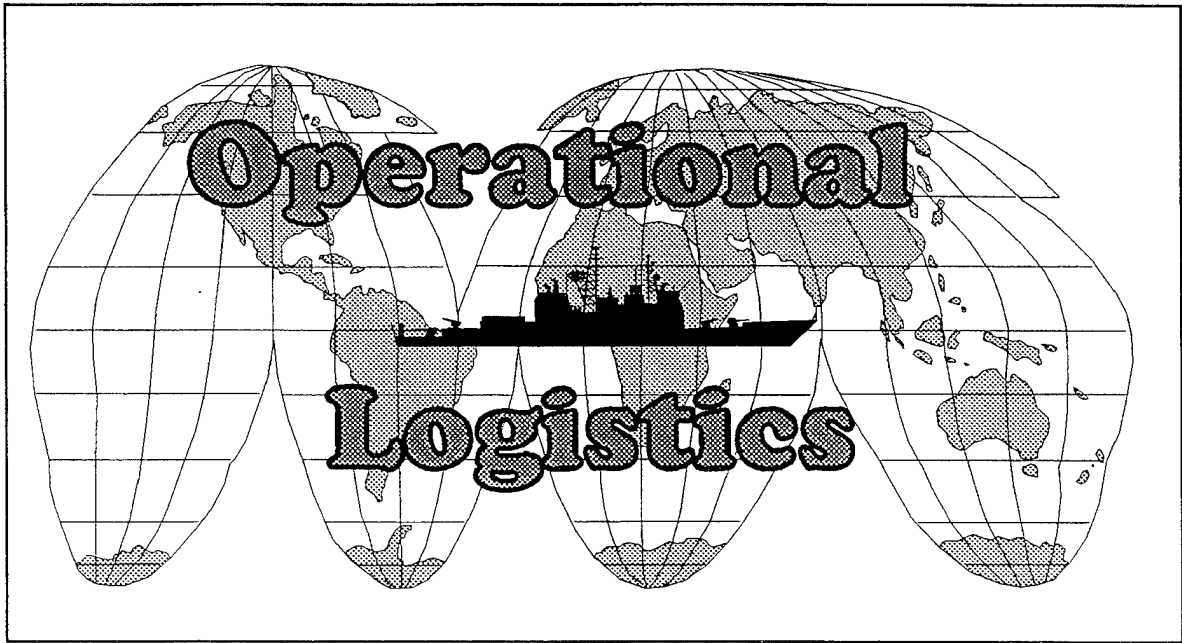
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RELIABILITY MODELING AND ESTIMATION USING  
U.S. NAVY 3M MAINTENANCE DATA

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Submitted in partial fulfillment  
of the requirements for the degree of

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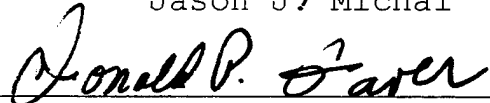
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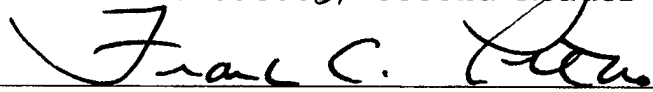
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## ABSTRACT

This thesis provides a statistical and economic assessment tool for the analysis of failure characteristics of equipment whose failure data are reported in the U.S. Navy's Maintenance and Material Management (3M) system. The software accompanying this thesis is written in a programming language compatible with the Microsoft Excel (spreadsheet) operating environment. With the software, the reliability engineer will have the ability to manipulate and analyze 3M data directly using customized menus and point and click mouse operations. Specifically, the software: transforms the complex 3M database into matrices of failure/inter-failure times and their associated costs; estimates the parameters of a discrete time nonhomogeneous Poisson process model having a geometric rate function; and employs the model to derive an optimal maximum replacement interval based on costs and expected number of failures. The software can be used to do sensitivity analysis to help the analyst examine the consequences of different replacement intervals or spare part provisioning and preventive maintenance policies.



## THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.



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## EXECUTIVE SUMMARY

Changing the U.S. Navy to meet fiscal constraints means evaluating many operational programs for their cost effectiveness. Maintenance is one key program which is being evaluated to ensure maximum operational readiness while working within a shrinking budget. A Maintenance Effectiveness Review, (MER), is an ongoing program to evaluate the applicability and effectiveness of all aspects of maintenance. Inputs to this annual review include detailed analysis of equipment performance in terms of failure characteristics and life expectancy.

This thesis provides a statistical and economic assessment tool for the analysis of failure characteristics of equipment whose failure data is reported in the U.S. Navy's Maintenance and Material Management (3M) system. The software accompanying this thesis is written in a programming language compatible with the Microsoft Excel (spreadsheet) operating environment. With the software, the reliability engineer will have the ability to manipulate and analyze 3M data directly using customized menus and point and click mouse operations. Specifically, the software: transforms the complex 3M database into matrices of failure/inter-failure times and their associated costs; estimates the parameters of a discrete time nonhomogeneous

Poisson process model having a geometric rate function; and employs the model to derive an optimal minimum long-run replacement interval based on costs and expected number of failures. The software can be used to do sensitivity analysis to help the analyst examine the consequences of different replacement intervals or spare part provisioning and preventive maintenance policies.

The parametric model used to estimate the failure rate of data from the 3M system is a discrete time nonhomogeneous Poisson process with a geometric failure rate function. The data used to estimate the parameters of the model are the number of maintenance actions in disjoint time intervals whose length is chosen by the analyst (number of months). The model parameters are estimated using maximum likelihood estimation.

The estimated parameters of the stochastic model allow an evaluation of the current time-based replacement policy in effect for the system being considered. Since failures induce expected costs that can be predicted and minimized, a "minimal repair" cost model is described. This cost model determines the most appropriate (cost-effective) replacement interval based on the model's fitted expected number failures and associated costs.

The software used to implement the methodology is illustrated using specific examples of 3M data. The data consist of failures over time of distilling plant regulating valves found on Trident class submarines. Resulting graphs and charts from the software display the parametric model's estimates of the expected number of failures in intervals of time, as well as the minimum long-run replacement interval.

The program is completely portable (on a 3 1/2 inch diskette) and installation procedures are included. However, it is recommended that before the software is loaded and incorporated into a reliability program, this thesis is thoroughly reviewed and kept as a reference.

The software developed in this thesis demonstrates a powerful use of stochastic modelling: the ability to predict expected number of failures and to evaluate maintenance policy decisions based on observed system performance. This provides the analyst with a software tool to enable him/her to perform a structured and standardized review of U.S. Navy 3M maintenance data. With this tool, the analysts recommendations to the MER can be more thorough because of the labor-saving nature of the software. Hopefully, the software will be used as a tool for supporting the difficult decisions necessary to maintain the U.S. Navy in top materiel readiness.

## I. INTRODUCTION

### A. BACKGROUND

As the United States Navy nears its goal of 300 ships, many operational policies are being reevaluated. The Bottom Up Review (BUR) and Mobility Requirement Study (MRS) are examples of recent evaluations of the Navy's operational efficiency. On a smaller scale, the addition of an annual Maintenance Effectiveness Review (MER) ensures that the maintenance needs of the Submarine Force are being met while also meeting the fiscal restraints of the operational budget. Naval Sea Systems Command (NAVSEA) Division PMS390, Submarine Monitoring, Maintenance, and Support Program Office (SMMSO) is in charge of coordinating this review.

In preparation for the MER, the engineers at SMMSO perform an in-depth review of the applicability and effectiveness of all maintenance actions performed by the submarine force. Redundant and ineffective maintenance is eliminated, while optimal materiel and operational readiness is maintained. The initiation of two specific programs, Reliability-Centered Maintenance (RCM) and Reliability-Based Spares (RBS), also aid in the review of inefficient maintenance and spare-part stocking formulas.

Difficulty arises, however, when evaluating a mechanical system for reliability. Many life-limiting

failure modes such as corrosion, erosion, and fatigue simultaneously effect components of a system and have effects that are difficult to quantify. This problem is compounded by the static, cyclic, and dynamic loading often present during different points in the life cycle of the system. These factors all contribute to the uncertainties associated with tradeoff studies involving reliability, availability, cost and maintainability.

#### **B. CURRENT ANALYSIS**

The engineers at SMMSO, using ideas of the RCM and RBS programs, evaluate the effect of reliability on system specifications, design, operation, spare parts stocking, and maintenance. Engineering review teams periodically travel to conduct on-site tests and monitoring. The results of these tests are then analyzed by a SMMSO engineer who is an expert on the system under evaluation.

An important source of information used by the SMMSO engineers is the Navy's Maintenance and Material Management (3M) system. This data base of self-reported corrective maintenance actions chronicles dates of failure and repair, as well as associated costs of repair and a description of the corrective maintenance actions taken. From this data base of failure and replacement information, the SMMSO

engineer can accurately reproduce historical failure data and make maintenance decisions based on predictive analysis.

An effective analysis by the SMMSO engineer must include an estimate of an expected rate of occurrence of identified failures. To establish this estimate, the 3M data base is used frequently as the historical reference for the systems under study. However, inconsistencies in identifying failures or expected rates of occurrence can arise because of several unique characteristics of mechanical equipment. These include:

- Individual components, such as valves, often perform more than one function. Weight and configuration constraints specifically demand the incorporation of multifunctional components on ships and submarines.

- Actual failure rates are not usually well described by a constant failure rate distribution (exponential or geometric) because of the effects of wear, fatigue and operating stresses. Data collection is complicated when constant failure rate cannot be assumed and individual times to failure or counts within disjoint time intervals must be recorded in addition to operating hours and number of failures.

- Mechanical equipment is more sensitive to loading and operating modes than is electronic equipment.

- The definition of mechanical failure may depend on the application. Specifications for "excessive noise" or "leakage" must be established for individual applications, and the lack of such information in a failure rate data base limits its usefulness, Ref.[1].

### C. PROBLEM STATEMENT

Maintenance on ships or submarines can be classified as preventive or corrective. Preventive maintenance is

performed periodically, at scheduled intervals, similar to a tune-up or oil change is performed periodically on an automobile. On the other hand, corrective maintenance is performed when equipment fails (or operates out of designed operating parameters), again analogous to fixing a flat tire on a car. It is this corrective maintenance which is logged in the 3M system.

Historically, shipboard mechanical equipment has demonstrated age-dependent failure characteristics (corrective maintenance actions occur more frequently as the system ages). Shipboard engineers ordinarily handle corrective maintenance, but as the failures become more frequent, they also become more expensive and complex (requiring outside technical assistance or entire equipment changeout). In a recent study, Duddenhoefffer [1994] used 3M maintenance data (for a pump whose failure data displayed increasing failure rate) to derive an optimal long-run cost minimizing replacement interval for a selected engineering system.

However, evaluating mechanical systems from maintenance information contained in the 3M data base is a time-intensive task for the SMMSO engineer. The conversion from tables of Julian-date maintenance data to tables (matrices) of failure and inter-failure times must be done manually and is very time-consuming and sensitive to numerical error.

Additionally, no standardized procedure exists for translating the 3M information to consistent failure rate and reliability data. Without standardized procedures, recommended improvements to maintenance, availability, or costs become difficult to justify.

This thesis documents software that was developed to translate the 3M information and to provide initial reliability calculations for the SMMSO engineer. Specifically, the software transforms the 3M data to matrices of failure and inter-failure times, as well as estimating the parameters for a mathematical model useful for predictive analysis. With the proposed mathematical model, the engineer can also evaluate the costs of current maintenance policies and make trade-off analyses in all areas of the model.

The overall objective of the software developed in this thesis is to provide procedures useful for the following elements of a reliability program:

- provide emphasis on the incorporation of reliability estimation with standardized evaluation procedures;
- provide a rough or early estimate of potential spare parts requirements;
- quantify critical failure modes for initiation of stress or design analysis;
- provide a relative indication of reliability for performing trade-off studies, selecting an optimum maintenance policy, or evaluating a proposed design change;

- determine the approximate or apparent degree of degradation with time for a particular component or failure mode;
- design accelerated testing and evaluation procedures for verification of reliability performance.

The next two chapters in this thesis provide the statistical background for the models used in the software. Chapter IV specifically describes the software application, with emphasis on the user-interfaces. The remaining chapters provide guidance on the software applicability and focus on some limitations and recommendations for its use. Finally, the computer code and its installation instructions are included in the appendices.

## II. MODEL DEVELOPMENT

### A. INTRODUCTION

A plausible parametric model for the temporal occurrence of count data is the Nonhomogeneous Poisson Process (NHPP). This model may also be a good representation for the occurrence of failures in many systems in the real world because it is a consequence of the "minimal repair" assumption. "Minimal repair" implies that only a small fraction of the system's parts are usually replaced [Ref. 2].

Cox and Lewis [1966] introduce

$$\mu(t) = \exp\{\alpha + \beta t\} \quad (2.1)$$

as a time-dependent failure rate for the NHPP model, [Ref. 3]. Their model is a continuous time model and estimation of its parameters assumes that observations are actual times at which the point-process events occur, a form of data which is often only approximately available. This thesis uses an analogous discrete-time model described by Gaver and Jacobs [1995] to address the situation in which time is divided into disjoint, (nominally) equal, steps or intervals, e.g. days, weeks, months, quarters of years, or years, and the data represent the number of events observed in those periods. In the next section, the basic model is presented and maximum likelihood estimation procedures are

derived. This material is taken from Gaver and Jacobs [1995], Ref.[4].

## B. BASIC MODEL

Let  $N_i$  be the number of events (e.g. failures) that occur during the  $i$ th individual time period following installation of a new unit (e.g. pump or valve). We assume  $\{N_i\}$  are independent with Poisson probability distributions (mass functions)

$$p_i(\underline{\theta}) = P(N_i=n_i) = e^{-\mu_i} \frac{\mu_i^{n_i}}{n_i!} \quad n_i = 0, 1, 2, \dots \quad (2.2)$$

Parameterizing in a way analogous to Cox and Lewis, let

$$\mu_i = C h(i; \theta) \quad (2.3)$$

A special case is the geometric increase/decrease model

$$\mu_i = C q^{i-1} \quad i = 1, 2, 3, \dots, T \quad (2.4)$$

which is a discrete-time analogue of (2.1).

## C. MAXIMUM LIKELIHOOD ESTIMATION

Before deriving the maximum likelihood estimate (MLE), it is necessary to define the following:

- $i$  = index for the observation interval number,  $i = 1, 2, \dots, T_j$
- $j$  = index for the system number,  $j = 1, 2, \dots, J$
- $\ell$  = log-likelihood function, viewed as a function of the (unknown) model parameters  $C$  and  $q$  ( $\theta$ ), given data  $(n_{ij}, i \geq 1, j \geq 1)$
- $n_{ij}$  = number of failures in the  $i$ th observation interval of the  $j$ th system
- $T_j$  = the last observation interval of the  $j$ th system

The log-likelihood function associated with the model of (2.2) and (2.3) is

$$\ell(C, h(i; \theta) \ i=1, 2, \dots; \text{data}) = \sum_{j=1}^J \sum_{i=1}^{T_j} [-Ch(i; \theta) + n_{ij}(\ln C + \ln h(i; \theta))] \quad (2.5)$$

The estimating equations resulting from differentiation of  $\ell$  are

$$\frac{\partial \ell}{\partial C} = \sum_{j=1}^J \sum_{i=1}^{T_j} [-h(i; \theta) + \frac{n_{ij}}{C}] = 0 \quad (2.6, a)$$

$$\frac{\partial \ell}{\partial \theta} = \sum_{j=1}^J \sum_{i=1}^{T_j} [-C + \frac{n_{ij}}{h(i; \theta)}] \frac{\partial h(i; \theta)}{\partial \theta} = 0 \quad (2.6, b)$$

Additionally, it is useful to have the second derivatives:

$$\frac{\partial^2 \ell}{\partial C \partial \theta} = - \sum_{j=1}^J \sum_{i=1}^{T_j} \frac{\partial h(i; \theta)}{\partial \theta} \quad (2.6, c)$$

$$\frac{\partial^2 \ell}{\partial C^2} = - \sum_{j=1}^J \sum_{i=1}^{T_j} \frac{n_{ij}}{C^2} \quad (2.6, d)$$

$$\frac{\partial^2 \ell}{\partial \theta^2} = \sum_{j=1}^J \sum_{i=1}^{T_j} [-\frac{n_{ij}}{h(i; \theta)^2}] [\frac{\partial h(i; \theta)}{\partial \theta}]^2 + [-C + \frac{n_{ij}}{h(i; \theta)}] \frac{\partial^2 h(i; \theta)}{\partial \theta^2} \quad (2.6, e)$$

Thus,

$$E[\frac{\partial^2 \ell}{\partial \theta^2}] = \sum_{j=1}^J \sum_{i=1}^{T_j} [-\frac{n_{ij}}{h(i; \theta)^2}] [\frac{\partial h(i; \theta)}{\partial \theta}]^2 \quad (2.6, f)$$

From (2.6, a):

$$\hat{C} = \frac{\sum_{j=1}^J \sum_{i=1}^{T_j} n_{ij}}{\sum_{j=1}^J \sum_{i=1}^{T_j} h(i; \theta)} \quad (2.7)$$

and the observed Fisher information matrix is

$$i(C, \theta) = - \begin{bmatrix} \frac{\partial^2 \ell}{\partial C^2} & \frac{\partial^2 \ell}{\partial C \partial \theta} \\ \frac{\partial^2 \ell}{\partial C \partial \theta} & E \left[ \frac{\partial^2 \ell}{\partial \theta^2} \right] \end{bmatrix} \quad (2.8)$$

The variance/covariance matrix for the estimates of the parameter values is proportional to

$$\begin{bmatrix} \text{Var}[C] & \text{Cov}[C, \theta] \\ \text{Cov}[C, \theta] & \text{Var}[\theta] \end{bmatrix} = i(C, \theta)^{-1} \quad (2.9)$$

### 1. The Geometric Model

In this section, the maximum likelihood estimates for the geometric increase/decrease model (2.3) are discussed. For this model

$$h(i; \theta) = q^{i-1} \quad (2.10)$$

Put

$$h_+(\theta) = \sum_{i=1}^{T_j} q^{i-1} = \frac{1-q^{T_j}}{1-q} \quad (2.11)$$

Substituting (2.11) into (2.7) results in

$$\hat{C} = \frac{\sum_{i=1}^{T_j} n_{ij}}{\sum_{j=1}^J \frac{1-q^{T_j}}{1-q}} \quad (2.12)$$

and

$$\frac{\partial h}{\partial \theta} = \frac{\partial h}{\partial q} = (i-1)q^{i-2} \quad (2.13)$$

Now, after substitution of (2.12) and (2.13) into (2.6,b) and algebraic manipulation, equation (2.6,b) for  $q$  becomes

$$\frac{\sum_{j=1}^J \sum_{i=1}^{T_j} (i-1) n_{ij}}{\sum_{j=1}^J \sum_{i=1}^{T_j} n_{ij}} = \frac{\tilde{n}_{1^*}}{n_*} = \frac{q \sum_{j=1}^J (1-q^{T_j}) - \sum_{j=1}^J T_j q^{T_j} (1-q)}{\sum_{j=1}^J (1-q^{T_j}) (1-q)} \quad (2.14)$$

where

$$\tilde{n}_{1^*} = \sum_{j=1}^J \sum_{i=1}^{T_j} (i-1) n_{ij}$$

and

$$n_* = \sum_{j=1}^J \sum_{i=1}^{T_j} n_{ij} .$$

The equation for  $q$ , namely (2.14), can be solved by one-dimensional search on a computer. This must be done in practice, and the software is included.

Note that if  $q < 1$  and the  $\{T_j\}$  become large, then (2.14) becomes approximately

$$\frac{\tilde{n}_{1^*}}{n_*} \sim \frac{q}{1-q} \quad (2.15)$$

Solving (2.15) for  $q$  results in a first approximation for  $q < 1$  of

$$\hat{q}(T) \approx \frac{\tilde{n}_{1^*}}{\tilde{n}_{1^*} + n_*} \quad (2.16)$$

The application to age-increasing failure requires consideration of  $q > 1$ . If  $q > 1$  and the  $\{T_j\}$  become large, then (2.14) becomes

$$\frac{\tilde{n}_{1+}}{n_+} \sim \frac{\sum_{j=1}^J T_j q^{T_j}}{\sum_{j=1}^J q^{T_j}} = \frac{q}{q-1} \sim \sum_{j=1}^J T_j = \frac{q}{q-1} \quad (2.17)$$

Solving (2.17) for  $q$  results in

$$\hat{q}(T) = \frac{T_+ - \frac{\tilde{n}_{1+}}{n_+}}{T_+ - \frac{\tilde{n}_{1+}}{n_+} - 1} \quad (2.18)$$

where

$$T_+ = \sum_{j=1}^J T_j .$$

Numerical iteration techniques, such as Newton-Raphson can be used to improve upon the approximations for  $q$  in (2.15) and (2.18). However, in the computer software developed for this thesis, a binary (bisection) search algorithm is used, Ref.[5]. The binary search was bounded by  $[0, 10 \times \text{initial } q]$  and terminated when  $q$  was approximated to the accuracy of three decimal places. The estimate of  $C$  is then obtained by using (2.12).

#### D. ADDITIONAL CALCULATIONS

After the model is formulated and its parameters estimated, it can be used to predict the expected number of

failures in successive user-defined time intervals, i.e. as an item ages. Further, approximate asymptotic normal confidence intervals (nominally 95%) can be placed around the estimated model parameters and the expected number of failures. Before constructing confidence limits and predicting failures, however,  $q$  is reparameterized to ensure non-negativity of the geometric rate of change. Put:

$$q = e^{\theta} \quad \text{or} \quad \ln q = \theta$$

so that

$$h(i; \theta) = e^{(i-1)\theta}$$

The maximum likelihood estimate of  $\theta$  is

$$\hat{\theta} = \ln \hat{q}$$

where  $\hat{q}$  is the solution to (2.14). This transformation is implied throughout this thesis, and references to  $\theta$  are equivalent to the natural logarithm of the estimated parameter  $q$  (and vice-versa). Specifically, in Chapter IV and in some software outputs, equation 2.4 is used for simplicity.

#### 1. Expected Number of Failures

The estimate of the expected number of failures in the time interval  $(S_1, S_2]$  is (after substitution):

$$E[N(S_2)-N(S_1)] = E[N(S_2)]-E[N(S_1)] = \hat{C} \frac{e^{\hat{\theta}S_1}-e^{\hat{\theta}S_2}}{1-e^{\hat{\theta}}} = f(\hat{C}, \hat{\theta}) \quad (2.19)$$

An estimate of the variance of the expected number of failures is (after setting  $f(C, \theta) =$  the right hand side of (2.18)):

$$\text{Var}[f(C, \theta)] \sim \left(\frac{\partial f}{\partial C}\right)^2 \text{Var}[C] + 2\left(\frac{\partial f}{\partial C}\right)\left(\frac{\partial f}{\partial \theta}\right) \text{Cov}(C, \theta) + \left(\frac{\partial f}{\partial \theta}\right)^2 \text{Var}[\theta] \quad (2.20)$$

where the variance and covariance are estimated by

$$\begin{bmatrix} \text{Var}[\hat{C}] & \text{Cov}[\hat{C}, \hat{\theta}] \\ \text{Cov}[\hat{C}, \hat{\theta}] & \text{Var}[\hat{\theta}] \end{bmatrix} = i(\hat{C}, \hat{\theta})^{-1}$$

and the partial derivatives of  $f$  are evaluated at the estimates of  $C$  and  $\theta$ .

## 2. Confidence Intervals

The approximate asymptotic normal confidence intervals (95% here) for  $C, \theta, q$ , and the expected failures in  $(0, T]$  follow:

For  $C$ :

$$[C-1.96\text{Var}[C], C+1.96\text{Var}[C]] \quad (2.21)$$

For  $\theta$ :

$$[\theta-(1.96\text{Var}[\theta]), \theta+(1.96\text{Var}[\theta])] = [\theta_0, \theta_1] \quad (2.22)$$

For  $q$ :

$$[e^{\theta_0}, e^{\theta_1}] \quad (2.23)$$

For the expected number of failures:

$$\left[ C \frac{1-e^{\theta T}}{1-e^{\theta}} - 1.96 \sqrt{\text{Var}[g(C, \theta)]} , C \frac{1-e^{\theta T}}{1-e^{\theta}} + 1.96 \sqrt{\text{Var}[g(C, \theta)]} \right] \quad (2.24)$$

Where  $g(C, \theta) = f(C, \theta)$  in (2.18) with  $T_1 = 0$ . Note that the factor 1.96 is the 0.975 point for a unit normal; if different confidence levels are required, this number must be changed.

#### **E. ASSUMPTIONS AND LIMITATIONS**

When fitting a mathematical model to represent the performance of a system, the analyst must consider the limitations of the model and how those may impact the decisions which it will be affecting. No model will perfectly predict performance, but the analyst can use an approximate model in conjunction with common sense and sound engineering principles to make practical recommendations that helpfully guide future policy decisions.

Specifically in this thesis, the SMMSO analyst must remember that this discrete-time model fits strictly increasing or decreasing rates of failure. If it is suspected that the system under study shows both initially decreasing and ultimately increasing failure rates (e.g. the "bathtub" curve, or instances of "infant mortality" and later "aging"), the data set must then either be censored or partitioned to handle both rates of failure individually,

using the present model. Additionally, when this model fits a decreasing rate of failure ( $q < 1$  {or  $\theta < 0$ }) to the selected 3M data, the model will not recommend a minimum long-run cost policy (the system is improving with age!). It is the experience from available data, though, that this never occurs forever.

### 1. Validity of the 3M Data

The 3M data collection, although theoretically thorough, is to some degree flawed. The problem lies in the completion and review of the 3M maintenance form (done on the ship). The 3M form is complicated (equipment identification code, date of failure, symptoms of failure, cause, required repair parts, repair hours, etc.), and with (usually junior) enlisted personnel assigned to complete it, the information can be inaccurate or incomplete. The shipboard personnel in the 3M chain of command (division chief, division officer, and department head) are responsible for reviewing the form, but it has been my experience as a division officer, 3M manager, and repair and maintenance coordinator that those people in the chain of command do not thoroughly review the form (either from lack of knowledge or motivation or both) and incomplete forms occasionally leave the ship to be "interpreted" by the shore-based maintenance coordinator. Fortunately, only a

few of the hundreds of 3M forms which are reported to the shore-based teams are incomplete, and those which are incomplete or incorrect are usually corrected by experienced shore-based maintenance coordinators.

Also, the generic nature of the 3M form and lack of standardization for specific failure information is often reflected in non-specific entries for failure symptoms and causes; this, in turn, leads to confusion when reconstructing the actual system performance. Additionally, work performed by the shipyard (non-ship's force personnel) is not always recorded. All of these factors contribute to inaccuracies in the 3M data. The subsequent analysis based on this somewhat deficient data can, nevertheless, be practically useful.

## **2. Assumptions**

Several assumptions were made regarding the treatment of system maintenance data. These assumptions are:

1. Every component failure causes equipment failure.
2. Failures are immediately evident.
3. Every repair corrects the cause of the problem, i.e., there are no incomplete repairs, and system failures do not damage other parts which could lead to subsequent failure.
4. Downtime can include, but does not necessarily represent, delays from waiting for spare parts.
5. Equipment is only repaired at failure, and not in anticipation of failure.

6. Consecutive interval counts of failures recorded on individual systems are assumed statistically independent, but are or may be age dependent.

7. A repair returns the equipment to full operation, but not to "as good as new" condition. Equipment failures may be age dependent.

8. A replacement constitutes the installation of a new system or a complete overhaul of the current system. The result is an "as good as new" system performing the assigned function.

### III. REPLACEMENT POLICY

Failures induce expected costs (and also operational consequences) that can be predicted and minimized, at least approximately. The cost model used in this thesis is the "minimal repair" policy based on a planned replacement interval, Ref[6]. The system under study is completely replaced at predetermined intervals (regardless of the condition of the system) and "minimally repaired" when failures occur between the replacement times. Valdez-Flores and Feldman [1989] summarize "minimal repair" and its effect on long-run system costs:

There are many instances where complex systems with several components are regarded as single units for maintenance purposes. However, the performance of complex systems depends on the individual components. Thus, when a component of a complex system fails, failure is often reflected in the entire system. At system failure, a decision has to be made to determine whether it is economical to replace the system, or to repair (replace) the failed component and reset the system to operation. If a repair or replacement of the failed component restores function to the entire system but the failure rate of the system remains as it was just before failure, the repair is called minimal repair. Since the failure rate of most complex systems increases with age, it would become increasingly expensive to maintain operation by minimal repairs. The question is, then, when is it optimal to replace the entire system instead of performing minimal repair? Ref[7].

The value of this planned replacement lies in the ability to schedule parts and support facilities, which minimizes the nonavailability time (critically important for

operational readiness). The challenge is to determine the most appropriate replacement interval (the cost-effective duration) without sacrificing reliability and availability. Note that in this thesis, age-replacement is done in anticipation of increasingly-many minor failures, but also in view of the likelihood of a non-repairable failure.

#### **A. CURRENT PRACTICES**

An age or time-based replacement policy applies to many Naval systems, from simple oil filters to complex gas turbine propulsion assemblies. Replacement policy intervals, however, are usually determined by design engineers, without consideration of observed performance, operating characteristics or mission requirements.

As mentioned in the introduction, the Navy has begun to pursue Reliability Centered Maintenance (RCM), which requires that the replacement intervals be adjusted based on equipment performance and equipment failure rate. However, without specific guidelines for determining equipment performance and failure rate, recommendations by an analyst to modify existing replacement intervals become difficult to justify.

##### **1. Criteria for Time-Based Replacement**

To aid the design and reliability engineer in determining if the maintained system is a candidate for

time-based replacement, MIL-STD-2173 (AS) provides the following guidance for timed-based applicability criteria:

1. The item must be capable of having an acceptable level of failure resistance after being repaired or restored to operation within specific tolerances.

2. The item must exhibit wearout characteristics, which are identified by an increase in the conditional probability of failure with increasing usage (age). This property can lead to establishment of a *wearout age* or a *life-limit*.

3. A large percent of the items must survive to the *wearout age* or *life-limit*.

4. A safe *life-limit* for an item must be established at an age below which relatively few failures are expected to occur. [Ref. 8]

Item (1) is addressed earlier in this thesis (assumptions in section II.E). The remaining items ((2), (3), and (4)) can be analyzed using the software developed as part of this thesis.

#### B. DERIVING THE COST MINIMIZING FUNCTION

The long run expected cost per unit time (using replacement age  $t$ ) for the basic discrete time model is:

$$C(t) = \frac{c_f E[N(t)] + c_r}{t} \quad (3.1)$$

where  $E[N(t)]$  = Expected number of failures (minimal repairs) in the period  $(0, t]$   
 $c_f$  = cost of a failure (minimal repair)  
 $c_r$  = cost of replacement

Also, we assume each observation interval is one time unit.

However, this model must be modified to include the probability of a catastrophic failure (and an unplanned replacement) prior to a scheduled replacement time  $t$ . This means that actual replacement time is a random variable.

Let  $X$  be a random variable representing the age of the system when it is replaced and let  $t$  be a candidate planned replacement age. Further define a *cycle* to be the interval between actual replacements (planned or unplanned). Then the *cycle length*, denoted by  $L$ , can be summarized by the following:

$$L = \begin{cases} X & \text{if } 0 \leq X < t \\ t & \text{if } t \leq X \end{cases} \quad (3.2)$$

Further, define  $p$  = probability that a failure is repairable;  
 $q$  = probability that a failure results in an unplanned changeout;  
 $p+q=1$ .

The probability that a system survives to its scheduled replacement interval is (Ref[9])

$$P(X \geq t) = e^{-q\Lambda(t)} \quad (3.3)$$

and the probability that it does not survive to its scheduled replacement interval is

$$P(X < t) = 1 - e^{-q\Lambda(t)} \quad (3.4)$$

where

$$\Lambda(t) = \sum_{i=1}^t \mu_i = \sum_{i=1}^t C e^{\theta(i-1)} = \frac{C(1-e^{-\theta t})}{1-e^{-\theta}} \quad (3.5)$$

Again, we assume each observation interval is one time unit.

The expected life of the system, denoted by  $E[L]$  is

$$E[L(t)] = \sum_{i=1}^t k P(X=k) + tP(X \geq t) \quad (3.6)$$

The expected number of failures in the life of the system before replacement is ([Ref 10])

$$E[N(L(t))] = \frac{P}{q} (1 - e^{-q\lambda(t)}) \quad (3.7)$$

Finally, the long run average cost per unit time becomes

$$z(t) = \frac{c_f E[N(L(t))] + c_r}{E[L(t)]} \quad (3.8)$$

The objective is now to select  $t$  so as to minimize  $z(t)$  in (3.8), or, more generally, to use (3.8) to study the cost implication of a particular choice of  $t$ .

## IV. SOFTWARE DEVELOPMENT

### A. INTRODUCTION

This software application allows manipulation and analysis of 3M maintenance data in the Microsoft Excel operating environment. It builds tables of failure times, inter-failure times, costs, and availability based on a user-defined selection of data from the 3M database. The software also estimates the parameters of a mathematical model useful for predicting reliability and estimating minimum long-run maintenance costs; that is, it studies the cost function,  $z(t)$  of (3.8). The ability to perform sensitivity (what-if or trade-off) analysis of costs, mathematical estimates, mission reliability, and many other aspects of the model is also included.

### B. OVERVIEW

Table 4.1 shows a typical section of the 3M database. In this example, the system (component) is a regulating valve from a salt-water distilling plant (denoted SD-2). This valve (installed on every Ohio class submarine) is considered critical for the safe operation of the distilling plant, and its 3M history includes twelve years of reported maintenance data for twenty valves installed on many different submarines.

Table 4.1. Example 3M Data (SD-2 Valve)

YR	DATE	YR	DATE	TOT	DESCRIPTION
DISC	DISC	COMP	COMP	COST	OF MAINTENANCE
92	1	92	1	0	THIS IS THE RECORD OF THE INITIAL INSTALLATION OF TRIPER
92	109	92	111	0	EXCESSIVE CORROSION ON SD-2 AND NEARBY STEAM PIPING.
92	229	92	243	33.93	STEAM DUMP VALVE PACKING LEAKAGE OUT OF SPECIFICATIO
92	319	92	323	0	V. SOL 2 IN/ SD-2 VPI GROUNDED DUE TO PACKING LEAKAGE.
93	35	93	43	31.48	SD-2 VALVE SOLENIOD IS SHORTED. S/F RPLD SOLENOID.
93	110	93	122	0	SD-2 HAD PACKING LEAKS BEYOND SPECS. S/F REPACKED SA
93	172	93	180	360.22	SD-2 LIMIT SWITCH FAILED; INSTALLED WRONG SWITCH, SINGL
93	254	93	255	5.91	SD-2 INDICATION MICRO-SWITCH FAILED, REPAIRED
93	312	93	330	686.5	S/F REPLACED COIL AND RECTIFIER DUE TO SD-2 BLOWN FUSE
93	339	93	345	5.66	SD-2 INLET AND OUTLET FLEX GASKETS LEAK. REPLACED GAS
93	357	93	362	931.3	SD-2 HAD EXCESSIVE PACKING LEAK. ATTEMPTS TO TIGHTEN

The column headings are:

- Yr Disc** - The year when the maintenance was reported
- Date Disc** - The day when the maintenance was reported (Julian date). This is the date of failure.
- Yr Comp** - The year when maintenance was completed
- Date Comp** - The day when maintenance was completed (Julian date). This is the date of repair.
- Tot Cost** - The cost of the maintenance. This cost is only material cost, or the cost of the supplies needed. These numbers are expressed in dollars.

Without the software application developed in this thesis, the SMMSO analyst would have to calculate (by hand) the failure times for every line item for every valve. Mathematical modeling and cost calculation is just as labor-intensive and complex. However, with the software application loaded into Excel, the analyst can simply select (by point-and-click mouse operations) a section or multiple

sections of the database and allow the program to make the computations. A description of the initial calculations performed in the software follow.

### 1. Initial Calculations

First, define the following (as in Chapter II):

$i$  = index for the observation interval number,  $i = 1, 2, \dots T_j$   
 $j$  = index for the system number,  $j = 1, 2, \dots J$   
 $T_j$  = the number of the last observation interval of the  $j$ th system  
 $N_j$  = total number of failures in each of the  $j$  systems

The matrix of arrival times is formed by calculating the day and year difference between the  $i$ th and  $i+1$ st maintenance action (for each system  $j$ ). The multiplier 365 is used because the 3M data is expressed in days, while the program's outputs are expressed in months (one month is defined as 30.4 days).

$$arrival_i = (day\ disc_{i+1} - day\ comp_i) + ((yr\ disc_{i+1} - yr\ comp_i) \times 365) \quad (4.1)$$

The matrix of inter-arrival times is then the difference between the  $i$ th and  $i+1$ st arrival (from (4.1)). This number (and all other outputs expressed in months) are converted from days by dividing by the factor 30.4.

To determine availability, downtime for each maintenance action  $i$  (and total downtime) is found by computing

$$\text{downtime}_i = (\text{date comp}_i - \text{date disc}_i) + ((\text{yr comp}_i - \text{yr disc}_i) \times 365) \quad (4.2)$$

$$\text{Total downtime} = \sum_{j=1}^J \sum_{i=1}^{T_j} \text{downtime}_i \quad (4.3)$$

The availability (expressed as a fraction of an interval) is

$$\text{Availability (\%)} = \frac{\text{Total operating time} - \text{total downtime}}{\text{Total operating time}} \quad (4.4)$$

Overlapping downtimes (maintenance occurring across observation intervals) are separated into their respective intervals for downtime and availability calculations; that is, if a repair began in observation interval  $i$  and was completed in interval  $i+1$ , that time is separated into the  $i$  and  $i+1$ st interval for the downtime calculation (for the representation of downtime per observation interval in the output). In the case of more than one system, each system availability is calculated and displayed separately.

The cost equations used are

$$\text{Total cost} = \sum_{j=1}^J \sum_{i=1}^{T_j} \text{cost}_i \quad (4.5)$$

$$\text{Avg cost (per failure)} = \frac{\text{Total cost}}{\sum_{j=1}^J N_j} \quad (4.6)$$

$$\text{Avg cost (per interval)} = \frac{\text{Total cost}}{\text{Total no. intervals}} \quad (4.7)$$

where  $cost_i$  = column 5 from the 3M database, cost for failure  $i$  (Table 4.1).

After the initial calculations are complete, the program then estimates the parameters in the mathematical model derived in Chapter II. With this model, replacement policy cost and basic mission reliability analysis can be done.

The remainder of this chapter focuses on the inputs to the software. Menu items (and selections directly from menus) will be shown in brackets such as <Create Data Set>, while specific inputs or outputs will be displayed in italics. Additionally, program flow and input/output can be reviewed in Figure 4.1, with explanations of inputs following later in the chapter.

An underlying assumption through the rest of this chapter (and in the software) is that the SMMSO analyst (and the reader of this thesis) is familiar with the Microsoft Excel operating environment. Additionally, in some resulting graphs and charts in the following sections, the parameters of the mathematical model are expressed in terms of  $C$  and  $q$ , rather than  $\theta$ .

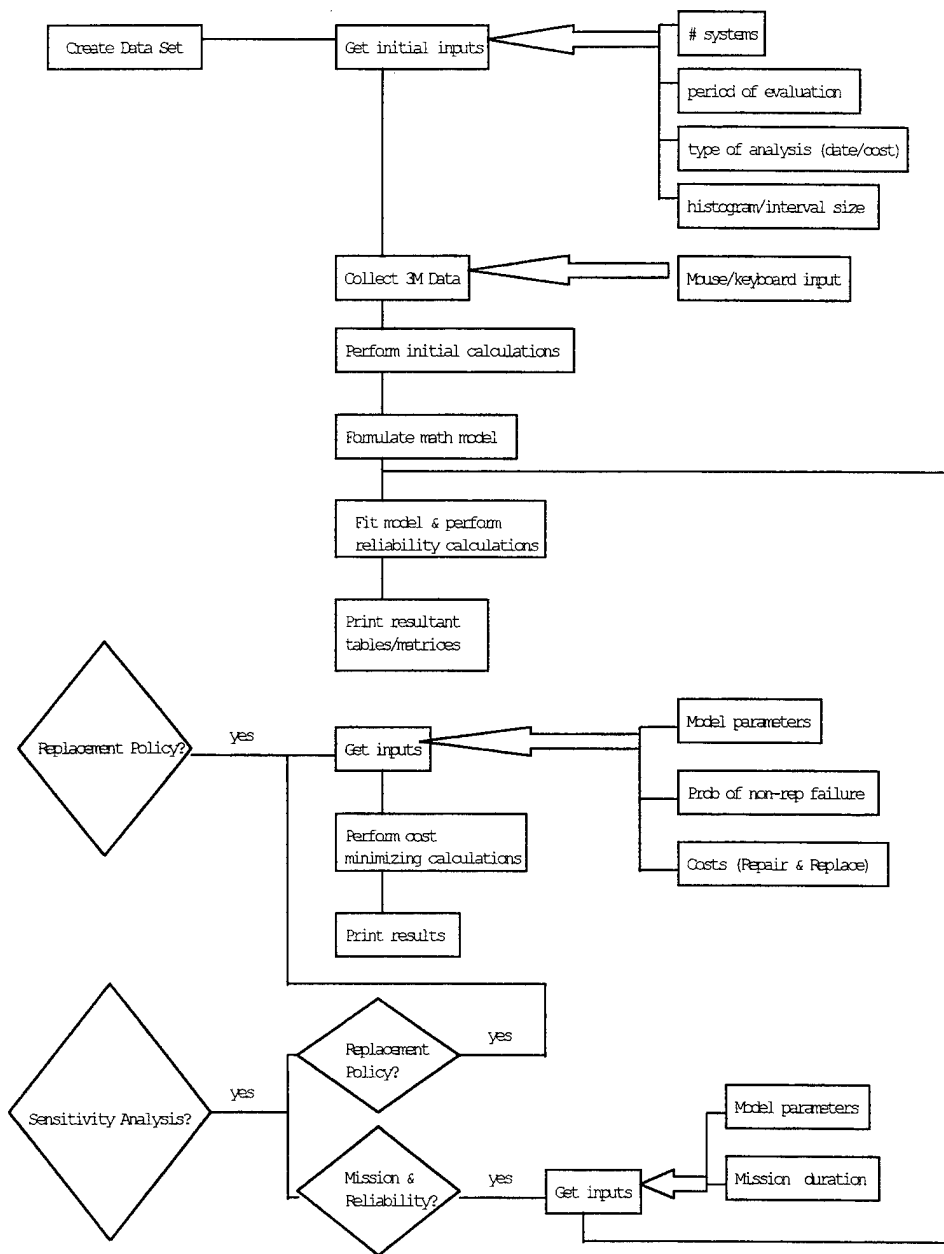


Figure 4.1. Software Flowchart

## C. SOFTWARE FEATURES

### 1. Create Data Set

This is first procedure used in the software application. It translates the 3M data into failure time, inter-failure time, availability, cost, and reliability matrices. It also estimates parameters of the mathematical model (described in detail in Chapter II). It is important that <Create Data Set> is run prior to any other subsection in the software because the tables and matrices created are necessary for the other sections to produce accurate results.

The resulting matrices and graphs are displayed on Excel worksheets selected by the user. An explanation of each worksheet follows:

*Arrival times:* displays the time (in months) of each failure (arrival). The graph produced shows failure number versus time. Departures from linearity in this graph could indicate a trend of increasing or decreasing arrival rates, but analyzing the data in conjunction with the inter-failure (arrival) worksheet provides a more complete picture.

*Inter-arrival times:* displays the time (in months) between each failure. The graph shows failure

number versus inter-failure time. The average, standard deviation, variance, and skewness of the times between failures are also shown. These values (variance, standard deviation and skewness) are computed, and they may or may not provide the best description of the data, if the failure rate of the system is changing.

*Availability/Downtime:* displays the "downtime" per interval. Downtime is defined as the operation of the system in a degraded condition and is calculated by the difference in the reported failure date and the repair (completion) date. The system is considered "available" when it is not "down".

*Costs:* displays costs per interval. This is not the same as the long-run costs calculated in the <Replacement Policy> section; (formulas are explained earlier in this chapter). The cost column in the 3M database is used for this calculation, and the costs associated with that column are simply the cost of all of new parts or supplies required to make the repair (charges such as labor, surcharges, delivery charges, etc. are not included).

*Interval failure:* displays the actual number of failures per observation interval versus the model's

predicted expected number of failures per interval. The model fits the 3M data to a discrete time Non Homogeneous Poisson Process (NHPP) with failure rate

$$\mu(i) = e^{\theta(i-1)} = Cq^{i-1}$$

where  $i$  = time interval  
 $C, q, \theta$  = model parameters

When  $q > 1$  ( $\theta < 0$ ), the system has an increasing failure rate and when  $q < 1$  ( $\theta > 0$ ), the system has a decreasing failure rate. It is important to note that when  $q < 1$ , the <Replacement Policy> should not be run because it will not find a minimum value (the system is improving with age). The resulting graph of the actual failures per interval versus the model's estimated predicted number of failures shows how well the model "describes" or "fits" the actual data. Confidence limits (95%) for the total number of failures and model parameters are also shown.

The second output section of the resultant worksheet displays the reliability of the system. The reliability graph can be interpreted as the probability of no failures from time zero to the end of each time interval. The equation used for this calculation is

$$\text{Prob}(\text{no failures } (0,t)) = \exp \{- \text{Expected no. failures } (0,t)\} \quad (4.8)$$

a. *Inputs to <Create Data Set>*

*Dates Only.* This option is selected if the user wishes to exclude cost analysis (column 5 in Fig 4.1 is ignored). The ability to formulate the cost model will be lost if this is chosen. This option might be chosen if the analyst only wants to review equipment reliability and its associated sensitivity analysis.

*Dates and Costs.* This option is selected if the analyst wishes to include cost analysis.

*Single/Multiple systems.* Allows analysis of one or many (of the same kind of) system(s). When selecting multiple systems, this entry must be an integer greater than one.

*Number of Months & Histogram/Interval Size.* This is how the lifetime of the data is partitioned. For example, if the data is to be analyzed over two years in three months intervals, the analyst should consider entering 24 months for the number of months and three months for the interval size. The minimum interval size is one month, and all entries must be expressed in multiples of months.

The selection of interval size is very important. If too few intervals are chosen (large interval size), the data will be "bunched" together and accuracy will be lost. Conversely, if one month is selected as interval size (the smallest interval possible), the data may spread out too much and graphical and statistical analysis becomes just as difficult as it was when the data was "bunched" together.

Additionally, the accuracy of the replacement policy analysis depends on the interval size. For example, if interval size is three months, the month resulting in minimum long-run average cost per unit time will only be accurate to within three months (the program will only consider replacement intervals which are multiples of three months).

*Input location of data.* This allows the analyst to select the 3M data to be analyzed from the spreadsheet. The location can be input either by the cursor (mouse) highlighting the section or typing the cell location in the input box. The program requires four columns to be selected for date analysis, while five are needed for date/cost analysis. Also, columns cannot be hidden (excluded from the open workbook, but residing within the active workbook) within the selection. If this condition exists (columns are

hidden), the user must activate the *Column⇌Unhide* feature of Excel prior to selecting data. When selecting the data, it is important not to exclude censored data sets (systems which do not survive to the end of the total observation period because of catastrophic failure). In these cases, the data contributes to the model only until the time when it was removed from service (it is not considered failed or "down" during the remainder of the total observation period). Additionally, the time in that particular observation interval *after* its catastrophic failure is also excluded from the model's parameter estimates.

*Display Results.* Here, active worksheets are identified where the results are to be displayed. The worksheet names must reside in the active workbook. These selections are not mandatory; only those which the analyst wishes to display need be selected. However, the last selection (interval failure matrix) must be selected in order to perform replacement policy or sensitivity analysis.

## **2. Replacement Policy**

After the program estimates the parameters of the nonhomogeneous Poisson process model in <Create Data Set>, the cost-minimizing replacement policy program can be run. The results show the optimal minimum cost replacement

interval (in months) for timed-based replacement analysis. Recall that the intervals considered in the cost replacement calculation are the same as those used in the data analysis; that is, if the data analysis interval is three months, then the optimal minimum cost replacement interval will be a multiple of three months. It is recommended that this result not be the only criteria for making policy changes concerning system maintenance. Real world factors, such as labor costs and scheduled inspection costs, which are not addressed in the replacement policy model, should also be considered.

*a. Inputs to <Replacement Policy>*

*Probability of a non-repairable failure.* This is a number between zero and one and it represents the chance of a system failure resulting in immediate overhaul or replacement. Entering zero indicates that the system never experiences catastrophic failure and entering one indicates every failure is catastrophic. This number can be estimated by counting the number of catastrophic failures and dividing by the total number of failures (maintenance actions). This counting must be done manually, as the software has no ability to interpret the verbal description of the repair (failure).

*Cost of an new unit/system.* This number is found by reviewing the ship's Coordinated Shipboard Allowance List (COSAL), supply records, or other current price documentation; it is input manually.

*Cost of repair.* The average repair cost (sample average of all repair costs over all observation periods) for the data set selected will automatically appear (defaults to the value calculated in the <Create Data Set> cost section), but this can be changed if desired when performing sensitivity analysis.

*Location of results.* This is the worksheet name where the table and graph are to be placed.

### **3. Sensitivity Analysis**

During the course of the program, the analyst might wonder about how changing the model's parameters might affect long-run costs or reliability. Common examples include:

- does the replacement policy change when the cost of a new unit is increased from \$10,000 to \$12,000?
- if the existing preventive maintenance schedule was modified to improve reliability during the later life of a system (effectively decreasing the model parameter  $q$ ), how will this affect overall reliability?
- what is the system reliability (as measured by the expected number of failures) for the upcoming six month deployment?

When this section of the program is run, the model can be modified to answer these questions (integer and non-negative restrictions apply to some parameters). Graphs and tables similar to those in earlier sections will display the results.

**a. Inputs to <Sensitivity Analysis>**

*Mission Reliability.* The parameters  $C$  and  $q$  can be changed but  $C$  must remain positive. The parameter  $q$  must remain positive as well, but recall that a value of  $q < 1$  indicates a system that is improving with age. Also, the expected number of failures and reliability between intervals (for mission or deployment cycle analysis) will be calculated. Intervals chosen must be positive integers which are (month) multiples of the observation interval length.

*Cost/Replacement.* This dialog (input) box is exactly the same as the one displayed during <Replacement Policy>, except the parameters  $C$  and  $q$  are included.

**D. EXAMPLES**

In this section, the 3M data from the distilling plant valve (Table 4.1) are analyzed by the software described in this thesis. Resulting figures (tables and charts) shown are taken directly from the Microsoft Excel worksheets which

would be reviewed by the SMMSO analyst. The data in these examples were chosen for its exaggerated (obvious) age-deterioration characteristics. Although the 3M summary information is accurate, it is not representative of the SD-2 valve currently installed on the Trident submarines (its reliability is much better).

The first example shows results of the analysis on the data in Table 4.1. The second example displays results from two (SD-2) valves (the 3M data for these valves can be found in Appendix C). Recall that the analyst need not display every output table which is shown in the following examples.

An appropriate interval size for these condensed data sets is quarters (3 months), and the total observation period is 24 months. In practice, the selection of interval size may take some trial-and-error review of the software outputs.

#### **1. Single System**

Figure 4.2 shows the resulting arrival-time matrix and graph of the data from Table 4.1. The units for the second column are in months.

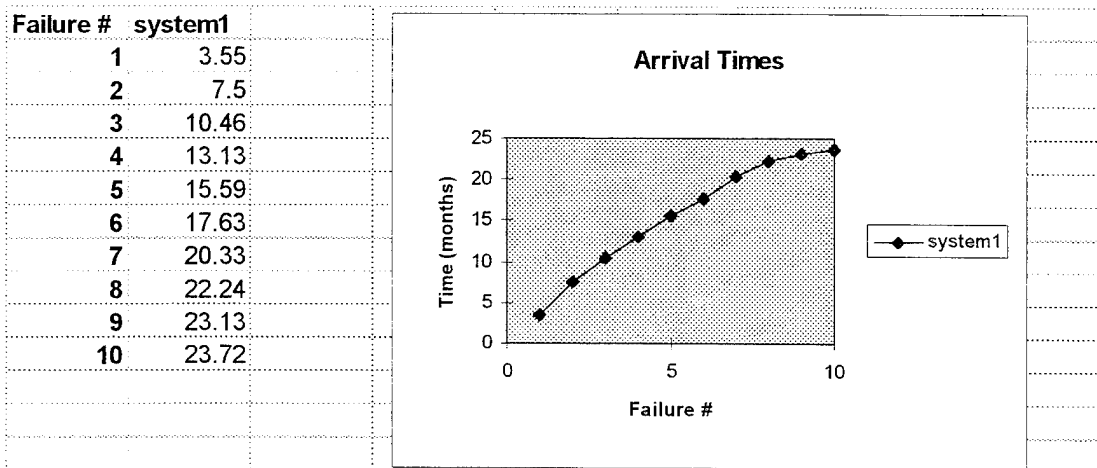


Figure 4.2. Arrival-Times of SD-2 Failures (Single System)

As mentioned earlier, a departure from linearity in the graph could indicate a trend in failure rates. However, the monotonically increasing nature of the graph tends to mask local variations and make interpretation difficult (if the trend is gradual).

With Figure 4.3, the trend is much more evident. The decreasing inter-arrival (inter-failure) times (and graph) indicate that the failure rate is apparently increasing (equipment deteriorating with age). The mean time between failure (MTBF) is the average of the inter-arrival times. Variance, standard deviation, and skewness are also shown. Units are again expressed in months.

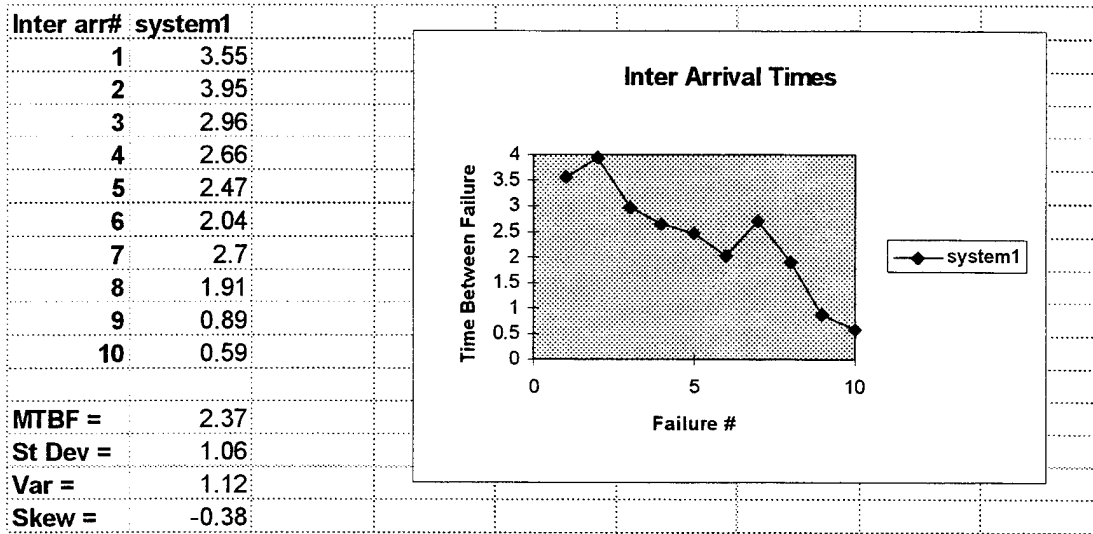


Figure 4.3. Inter-Arrival Times for SD-2

Figure 4.4 shows the downtime per (3 month) interval. The graph suggests that the valve may require more maintenance as it ages. The increased downtime could also indicate that more serious failures (consuming more repair time and costs) occur during the later stages of valve life. Review of Figures 4.2 and 4.3 (as well as 4.5 and 4.6) may help the analyst draw conclusions from this graph. It may also be necessary to read over the 3M data again, for one or two repairs (which may have been delayed due to logistics problems) may have caused large delays in repair.

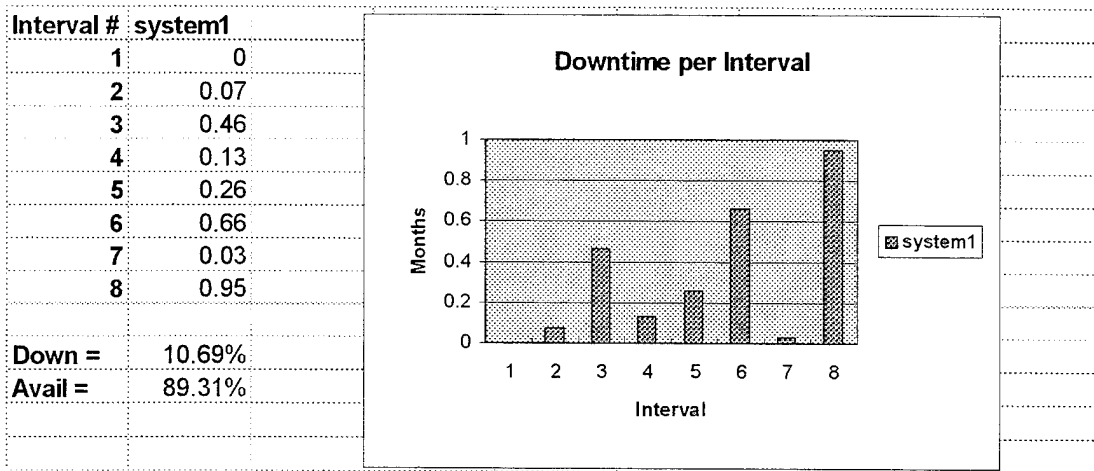


Figure 4.4. Downtime per Interval of SD-2

Figure 4.5 displays the costs (per three month interval). The results are a little misleading. Due to the small data set (very few reported maintenance actions), the cost graph is dominated by a few expensive failures. In a larger data set, this graph would be less skewed. The interval and individual failure averages are displayed (the individual average is used during the replacement policy analysis). The units for the second column are dollars spent per interval.

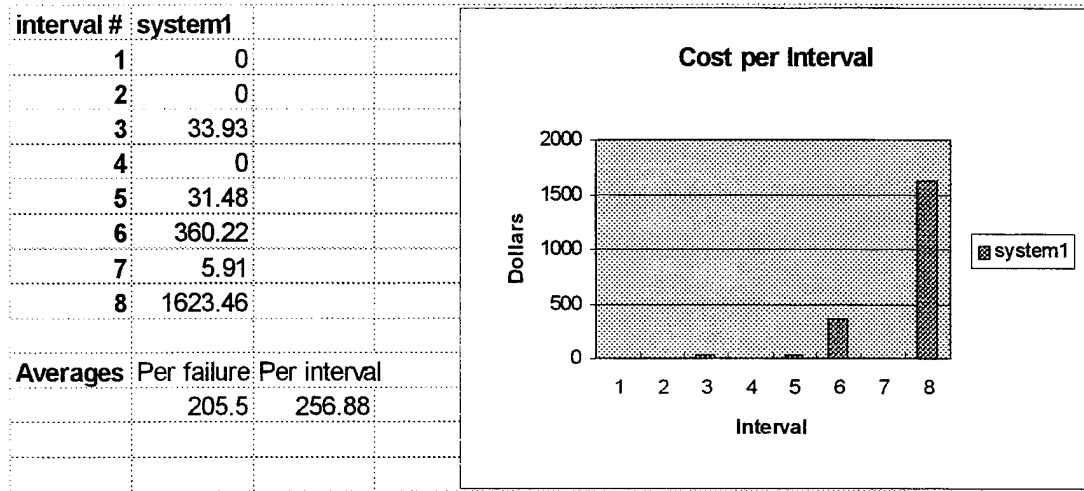


Figure 4.5. Cost per Interval for SD-2

The results of the estimates of the model's parameters are shown in Figure 4.6. The actual number of failures per interval are plotted along with the model's estimated expected number of failures. The chart graphically represents how well the model "fits" the 3M data. The parameters of the model are given, along with their upper and lower (LCL and UCL) 95% confidence limits. The expected number of failures in the entire 24 month period (calculated from the mathematical model) is also shown (with its confidence limits). In this example, the confidence interval is large because of the relatively small sample size.

The lower portion of Figure 4.6 represents the reliability. This is the probability that the valve will

not fail (calculated from time zero to the end of each interval).

When the parameter  $q$  is greater than one (1.27 in this example), the system is deteriorating with age . The aging is also evident in the slope of the reliability curve.

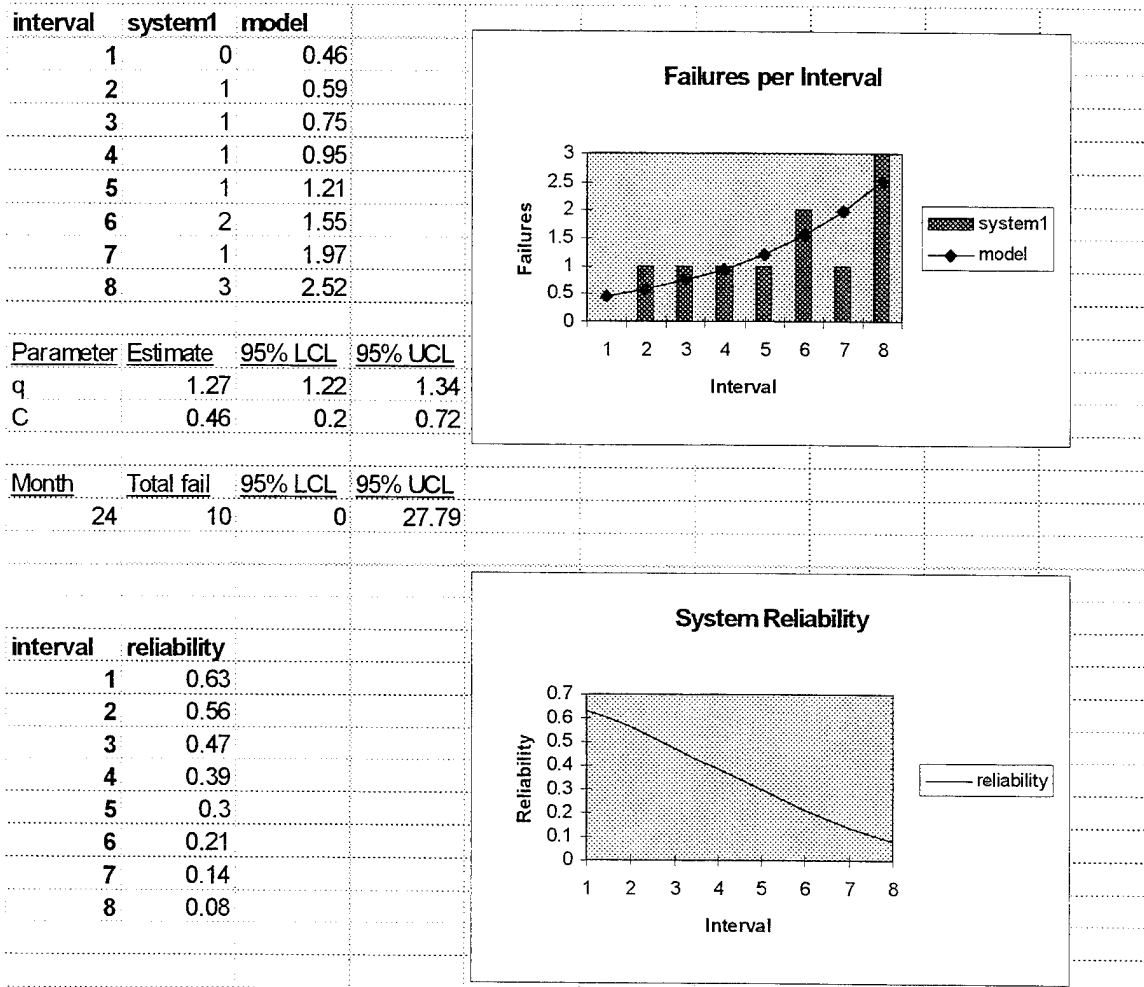


Figure 4.6. Failures per Interval and Reliability of SD-2

Figure 4.7 shows the results of the replacement policy analysis. The minimum cost per interval (in this example) falls in interval thirteen (month 39 on the chart output). This value can also be visually verified by locating the lowest point in the graph.

The cost for a new valve (from Navy supply documentation) is \$16,800. The average cost of repair was calculated earlier as \$205.50. The probability of a non-repairable failure is .02 (approximately 2 out of every 100 failures in the 3M data for this valve are non-repairable and require an unplanned changeout).

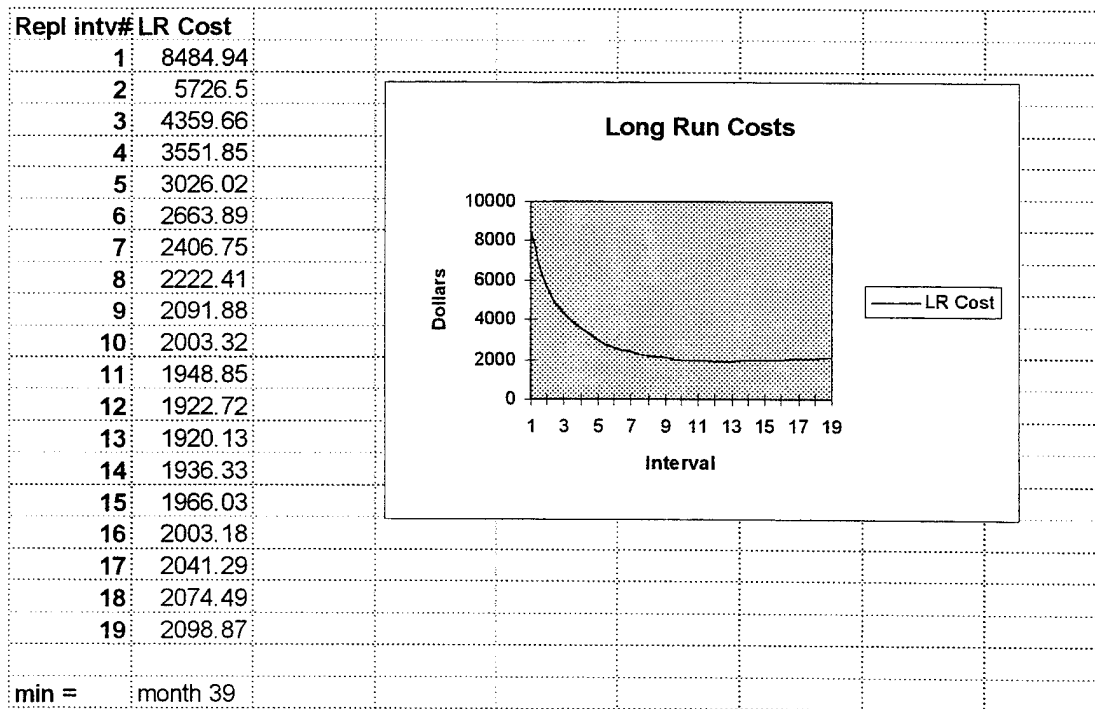


Figure 4.7. Long-Run Costs

Sensitivity analysis was then performed on this data.

The question was:

- If this submarine deployed for six months (two intervals), and the valve had already been in service for 18 months, how many failures are expected, and what is the probability of no failures (mission reliability)?

The answer to this question is in Figure 4.8. The interval adjustment on the second graph means the starting interval number on the graph coincides with the one in the reliability table immediately to the left of the graph.

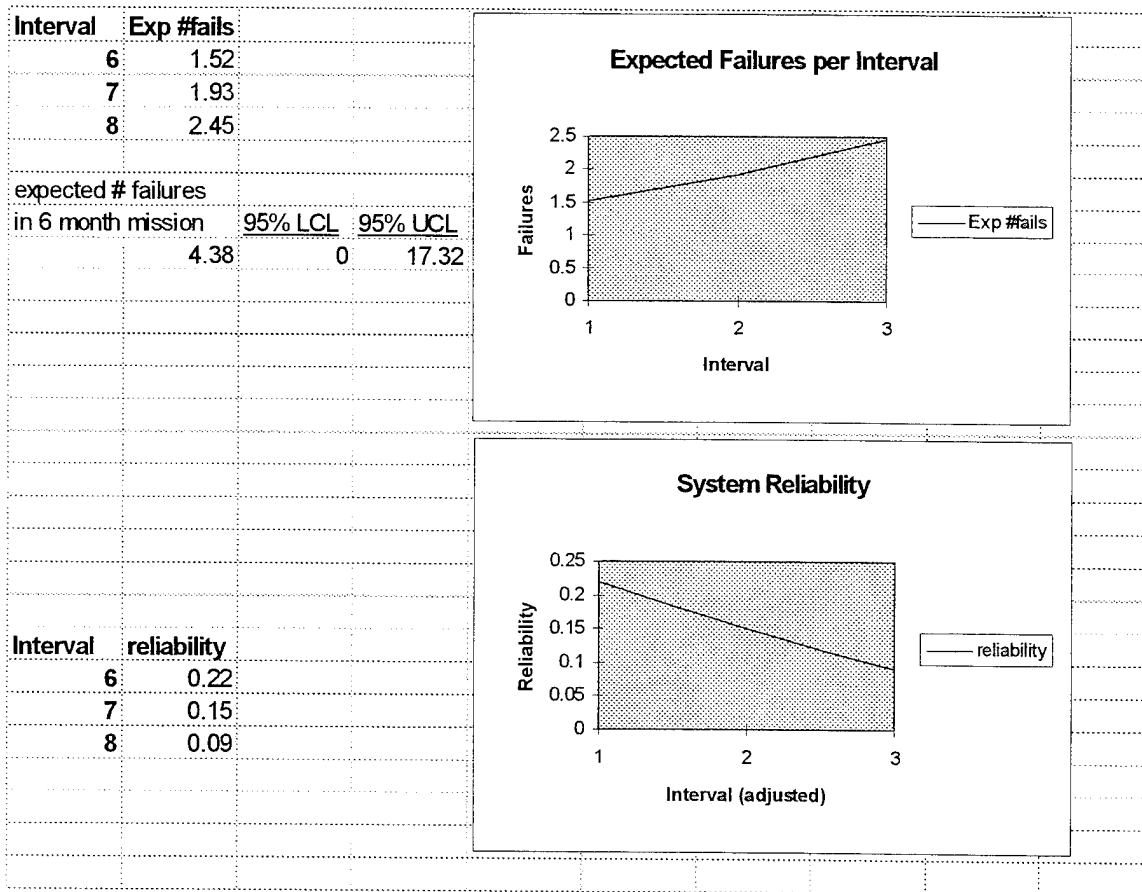


Figure 4.8. Sensitivity Analysis (Mission Reliability)

## 2. Multiple Systems

In this example, two more SD-2 valves were chosen from the 3M data base. As in the first example, these data are not representative of the SD-2 valve currently installed.

Figures 4.9-4.13 display results similar to those obtained with the single system example. The replacement policy analysis is not displayed because the estimated model parameters using data from the two valves are very close to those using the previous valve. Thus, the replacement policy is the same. Additionally, the system averages, variances, etc., displayed in the next few figures are calculated using the combined data for both systems, not individually.

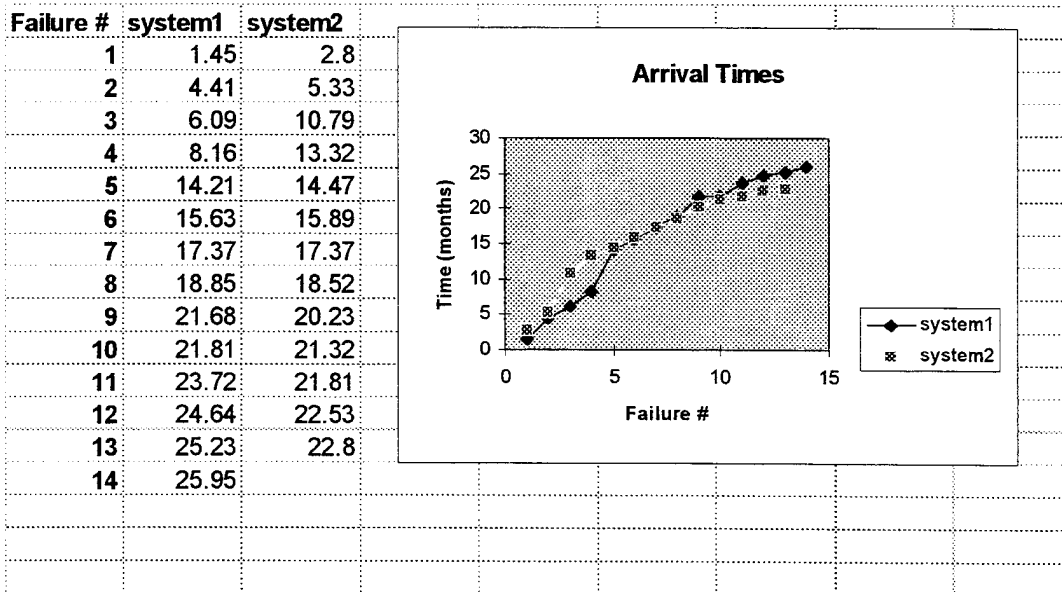


Figure 4.9. Arrival-Times of SD-2 Failures

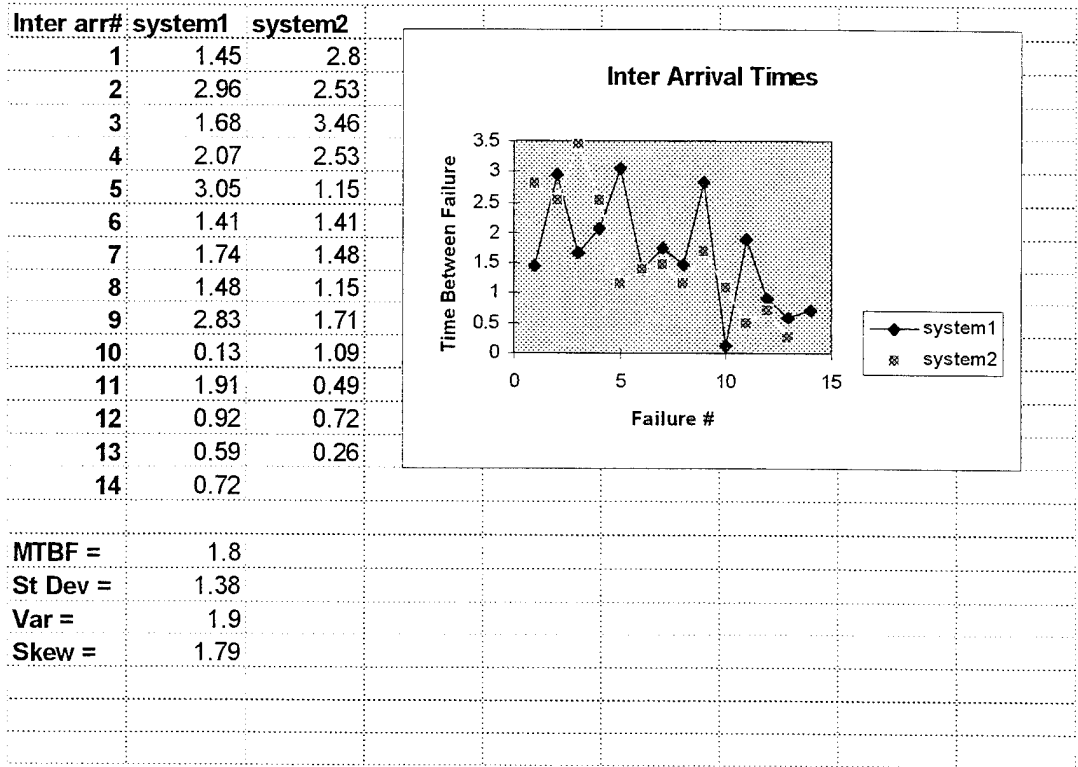


Figure 4.10. Inter-Arrival Times for SD-2

Notice that in Figure 4.11, the downtime per interval percentage is greater than that of the single system example. With the first valve (in Fig. 4.11), the last two intervals show that it was out of service (degraded) for the entire interval. This was the major factor contributing to the increase in the non-availability.

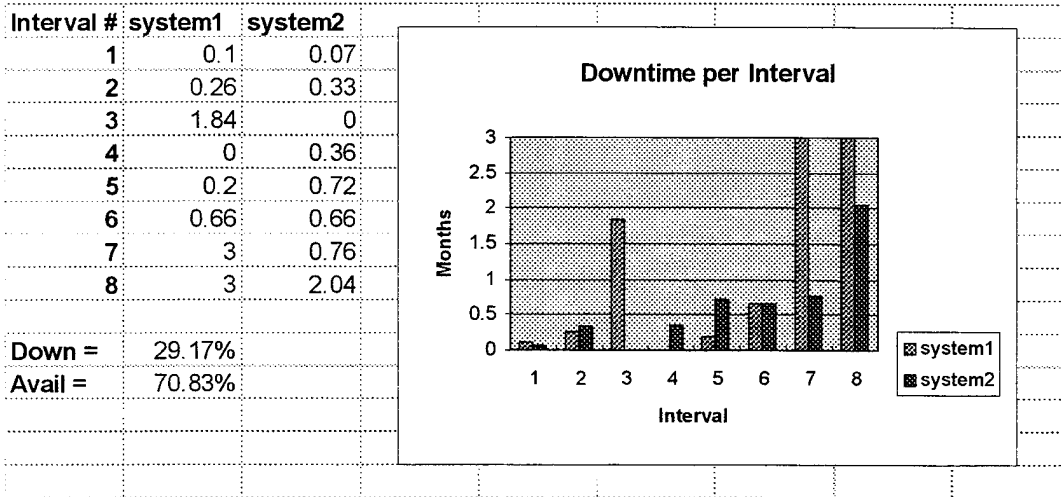


Figure 4.11. Downtime per Interval for SD-2

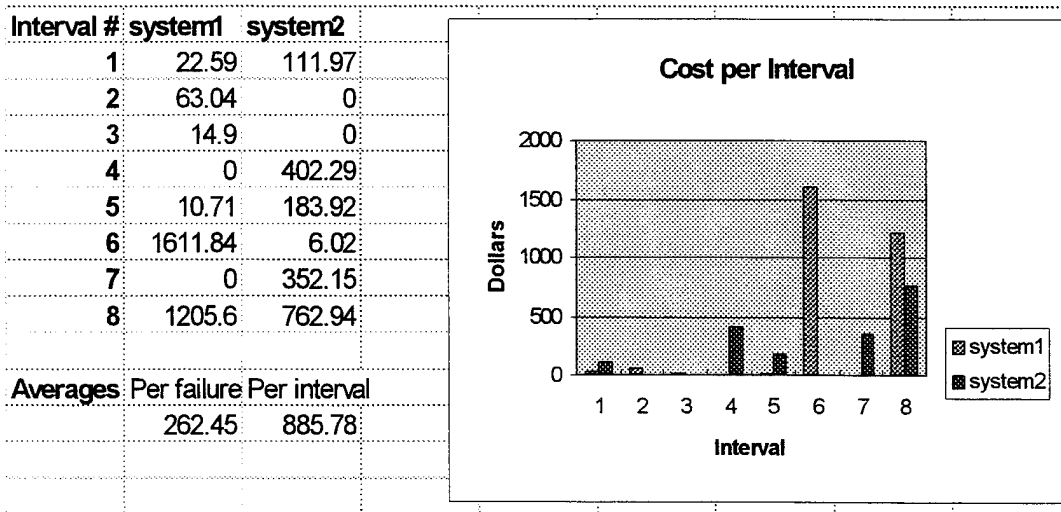


Figure 4.12. Cost per Interval for SD-2

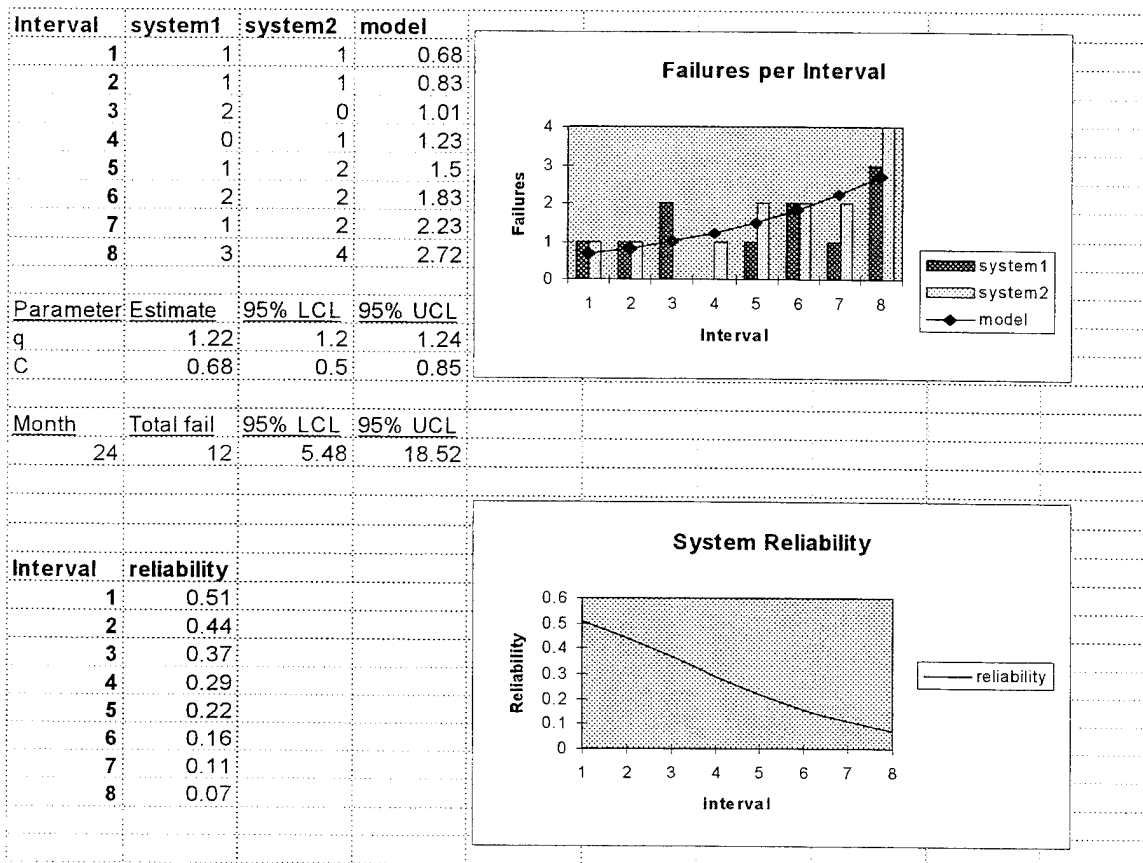


Figure 4.13. Failures per Interval and Reliability of SD-2

From these examples, the capabilities and usefulness of this software application are shown. Some of the limitations (in terms of model capabilities), however, will be investigated in the next section and alternative models will be introduced to possibly provide a better representation of the behavior of the data.

## V. FUTURE WORK

The accuracy and usefulness of the software developed in this thesis is limited by the completeness of the 3M data and the descriptive ability of the specific model proposed. Other probabilistic models are possible, and a different model could possibly provide a better representation of the failure data of the system under study. Ideally, as this software is used and revised, future editions will compare the abilities of different probabilistic models to summarize the data and the results obtained will be based on the most appropriate model. The next two sections introduce alternative models to that used in this thesis and incorporated in the software.

### A. THE PARETO MODEL

If the exponential fall-off hazard introduced in Chapter II is too abrupt, then an alternative is

$$h(i;\theta) = \frac{1}{1 + \beta(i-1)} \quad (5.1)$$

This form can arise as a special case of a probability mixture of (2.10) when  $q$  has a particular Beta density over  $(0,1)$ .

The sum of (5.1) can only be approximated, although it can be carried out numerically by

$$\sum_{i=1}^{T_j} h(i; \theta) = \sum_{i=1}^{T_j} \frac{1}{1+\beta(i-1)} \approx \frac{1}{\beta} \int_0^{T_j} \frac{\beta dx}{1+\beta x} = \frac{1}{\beta} \ln(1+\beta T_j) \quad ; \quad (5.2)$$

which can then be used in (2.6,a). The derivative is

$$\frac{\partial h}{\partial \theta} = \frac{\partial}{\partial \beta} (1+\beta(i-1))^{-1} = - \frac{i-1}{[1+\beta(i-1)]^2} \quad ; \quad (5.3)$$

Equation (5.3) can then be inserted into (2.6,b) giving again a single non-linear equation, this time for  $\beta$ . But now

$$\tilde{n}_{1+} = \tilde{n}_{1+}(T; \beta) = \sum_{j=1}^J \sum_{i=1}^{T_j} \frac{(i-1) n_{ij}}{1+\beta(i-1)} \quad .$$

#### B. THE BOLAND-PROCHAN MINIMAL REPAIR COST MODEL

The minimal repair model introduced in Chapter III can be modified to include a repair cost which is not fixed, but depends on the age of the system. Thus  $c_i$  is considered a continuous nondecreasing function which increases as the system ages, as is usually the case in mechanical systems. An expression corresponding to (3.1) is

$$c(t) = \frac{\int_0^t c_f(u) h(u) du + c_r}{t} \quad (5.4)$$

An optimal replacement interval can be found by taking the derivative of (5.2), setting it equal to zero, and solving for  $t$ ; (this model assumes no catastrophic failures).

These are just two alternatives to the models used in this thesis. As stated earlier, many others exist, and future enhancements to the software developed in this thesis should experiment with different probabilistic models and different statistical techniques.

Although this thesis introduces useful software and further promising research, it is difficult to combine the fields of computer science (programming and logic) with statistical theory and its applications. Additionally, real-world experience in mechanical systems and their characteristics is an important tool for the reliability analyst. However, with the resources at the Naval Postgraduate School, further applications of computer science, probability models, and statistics to this field are being pursued.

## VI. CONCLUSIONS & RECOMMENDATIONS

As stated in the Introduction, the goal of this thesis has been to develop software to support reliability analysis using U.S. Navy 3M maintenance data. Equipped with this software, the analyst is capable of structured and standardized review of 3M data. In turn, the analyst's recommendations to the annual Maintenance Effectiveness Review (MER) can be more thorough and because of the manual labor-saving nature of the software can include a wider range and greater number of systems.

The accuracy of the results obtained by the software developed in this thesis is again affected greatly by the quality and quantity of the 3M data. As more data become available, the model should be updated. Likewise, the 3M data collection and reporting system needs to be monitored to ensure that only accurate and complete information is being reported.

The SMMSO analyst must also remember that this software is only a tool for his continuing work to improve the current U.S. Navy maintenance structure. Care should be taken not to rely too heavily on the statistical models proposed in this thesis. Statistical "tunnel vision" can

result and relying only on limited reliability methodologies could produce erroneous results.

This thesis has demonstrated the benefits of applying further quantitative analysis and stochastic modeling to benefit an already existing reliability methodology. With this software, future decisions concerning maintenance policy modifications can be further supported. It is hoped that the policy makers will recognize this as a useful tool to support the difficult decisions necessary to maintain the U.S. Navy in peak materiel readiness.

## APPENDIX A. VISUAL BASIC CODE

The following code is written in Visual Basic for Applications as an add-in to Microsoft Excel (file \*.XLA). Comments are preceded by an apostrophe (').

```
'=====
'      LT Jason Michal
'      Summer, 1995
'      Reliability Add-in to Excel
'=====

' This section provides the definitions (declarations) of all of the
variables (public) used in the code. They include arrays (), integers,
single precision and boolean variables. Every effort has been made to
use descriptive identifiers for each of the variables and subroutines
used in the program.
' Public variable definitions

Dim data()
Dim inter()
Dim tempy()
Dim fail()
Dim arrivals()
Dim price()
Dim inter_arrive()
Dim downtime()
Dim downstart()
Dim interval_downtime()
Dim interval_cost()
Dim expect()
Dim expectans()
Dim proby()
Dim costs()

Dim jsys As Integer
Dim numrows As Integer
Dim numcols As Integer
Dim cmax As Integer
Dim months As Integer
Dim interval_size As Integer
Dim num_intervals As Integer
Dim loopsize As Integer
Dim minimum As Integer
Dim t1 As Integer
Dim t2 As Integer
Dim cont1 As Integer
Dim flag As Integer

Dim place As String
Dim msg As String
Dim ftb As String
Dim iftb As String
Dim crb As String
```

```

Dim avb As String
Dim imb As String

Dim big As Single
Dim totprice As Single
Dim avgprice As Single
Dim q_hat As Single
Dim c As Single
Dim clow As Single
Dim cup As Single
Dim qup As Single
Dim qlow As Single
Dim expect_no As Single
Dim varc As Single
Dim vartheta As Single
Dim cov As Single
Dim expt_no As Single
Dim expt_no_low As Single
Dim expt_no_up As Single

Dim dateval As Boolean
Dim sensitive As Boolean
Dim er As Boolean
Dim in3m As Boolean

```

```

'=====
' This subroutine controls the flow of the program. Each of the
routines (in capital letters) is called on as shown in the flowchart in
Chapter IV. CONTROLLER controls flow; GETDATA allows the 3M data to be
initialized; MAKEDATA transforms the data from Julian-date format to
months; INTERVALS performs the respective interval calculations; GET3M
enables the mouse to select more data; and PRINTING prints the
results.

```

```

Sub CONTROLLER()
GETDATA
MAKEDATA
INTERVALS
GET3M
PRINTING
End Sub

```

```

'=====
' This subroutine adds the reliability menu to Excel menubar. It also
adds all of the respective submenus and submenuing procedure calls.
Subroutines SINGLE and MULTIPLE_CLICK set the focus (cursor) to specific
user entries.

```

```

Sub MAKEMENU()

Set bar = MenuBars(xlWorksheet)
bar.Reset
bar.Menu.Add Caption:="&Reliability"
Set reliabilitymenu = bar.Menus("&Reliability")
reliabilitymenu.MenuItems.Add Caption:="&Create Data Set", _

```

```

        OnAction:="controller"
reliabilitymenu.MenuItems.Add Caption:="&Replacement Policy", _
        OnAction:="cost"
reliabilitymenu.MenuItems.Add Caption:="-"
reliabilitymenu.MenuItems.addmenu "&Sensitivity Analysis"
reliabilitymenu.MenuItems("&Sensitivity Analysis").MenuItems.Add _
        Caption:="&Mission Reliability", OnAction:="msense" _
reliabilitymenu.MenuItems("&Sensitivity Analysis").MenuItems.Add _
        Caption:="&Cost/Replacement", OnAction:="sensecost" _
reliabilitymenu.MenuItems.Add Caption:="-"
reliabilitymenu.MenuItems.Add Caption:="&Help", OnAction:="showhelp"

End Sub
'=====
' This routine presents a dialog box which allows the user to
initialize the 3M data. The number of systems, interval size and other
important information for the model is entered here.

Sub GETDATA()

On Error GoTo handler
hereb:
jsys = 1
er = False
ThisWorkbook.dialogsheets("getinfo").OptionButtons("single").Value =
xlOn
ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Enabled = False
ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Text = ""
dboxok = ThisWorkbook.dialogsheets("getinfo").Show
If Not dboxok Then Exit Sub

If ThisWorkbook.dialogsheets("getinfo").OptionButtons("multiple").Value
= xlOn Then
    If ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Text =
"" Then
        MsgBox "Must contain more than one system", vbExclamation
        GoTo hereb
    End If
    jsys = ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Text
    If jsys <= 0 Then
        MsgBox "Must contain more than one system", vbExclamation
        GoTo hereb
    End If
End If

dateval =
ThisWorkbook.dialogsheets("getinfo").OptionButtons("date").Value

Select Case
ThisWorkbook.dialogsheets("getinfo").OptionButtons("date").Value
    Case xlOn: dateval = True
    Case xlOff: dateval = False
End Select

months = ThisWorkbook.dialogsheets("getinfo").EditBoxes("mo").Text

```

```

interval_size =
ThisWorkbook.dialogsheets("getinfo").EditBoxes("int").Text

If interval_size = 0 Then GoTo handler

If months Mod interval_size <> 0 Then
    MsgBox ("Ensure the months are divisible by the interval"), _
        vbExclamation
    GoTo hereb
End If

num_intervals = months / interval_size

If interval_size < 1 Then
    MsgBox ("Interval size must be greater than one"), vbExclamation
    GoTo hereb
End If

ERRNO (jsys)
If er = True Then GoTo hereb
ERRINT (jsys)
If er = True Then GoTo hereb
ERRNEG (jsys)
If er = True Then GoTo hereb
ERRNEG (months)
If er = True Then GoTo hereb
ERRNO (months)
If er = True Then GoTo hereb
ERRINT (months)
If er = True Then GoTo hereb
ERRNEG (interval_size)
If er = True Then GoTo hereb
ERRNO (interval_size)
If er = True Then GoTo hereb
er = False
Exit Sub

handler:
MsgBox ("Can't proceed - please ensure:") & Chr(13) & _
    ("(1) All data is numeric ") & Chr(13) & _
    ("(2) All data is integer-valued") & Chr(13) & _
    ("(3) All data is non zero or non-negative"), vbExclamation
GoTo hereb

End Sub
'-----
Sub MULTIPLE_CLICK()

    ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Enabled =
True
    ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Text = "2"
    ThisWorkbook.dialogsheets("getinfo").Focus = "numsys"

End Sub
'-----

```

```

Sub SINGLE_CLICK()

    ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Text = ""
    ThisWorkbook.dialogsheets("getinfo").EditBoxes("numsys").Enabled =
False

End Sub

'=====
' This routine gets (allows the user to input) the first section of 3M
data. It calls procedures to set the locations of the resultant
displays. A description of the procedure acronyms are:
FTB - failure times
IFTB- inter-failure times
AV - availability
CR - cost
IM - interval matrix summary

Sub GET3M()

heret:
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("ftbull").Enabled =
False
ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("ft").Value = xlOff
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("iftbull").Enabled =
False
ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("ift").Value = xlOff
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("avbull").Enabled =
False
ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("av").Value = xlOff
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("crbull").Enabled =
False
ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("cr").Value = xlOff
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("imbull").Enabled =
False
ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("im").Value = xlOff
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("ftbull").Text = ""
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("iftbull").Text = ""
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("avbull").Text = ""
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("crbull").Text = ""
ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("imbull").Text = ""
dboxok = ThisWorkbook.dialogsheets("3mdisplay").Show
If Not dboxok Then Exit Sub
ftb = ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("ftbull").Text
iftb = ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("iftbull").Text
avb = ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("avbull").Text
crb = ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("crbull").Text
imb = ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("imbull").Text

End Sub

'-----
Sub FTB_CLICK()

    ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("ftbull").Enabled =
True

```

```

        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("ftbull").Text =
"Sheet1"
        ThisWorkbook.dialogsheets("3mdisplay").Focus = "ftbull"
        cont1 = cont1 + 1

End Sub
'-----
Sub IFTB_CLICK()

        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("iftbull").Enabled
= True
        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("iftbull").Text =
"Sheet1"
        ThisWorkbook.dialogsheets("3mdisplay").Focus = "iftbull"
        cont1 = cont1 + 1

End Sub
'-----
Sub AV_CLICK()

        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("avbull").Enabled =
True
        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("avbull").Text =
"Sheet1"
        ThisWorkbook.dialogsheets("3mdisplay").Focus = "avbull"
        cont1 = cont1 + 1

End Sub
'-----
Sub CR_CLICK()

        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("crbull").Enabled =
True
        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("crbull").Text =
"Sheet1"
        ThisWorkbook.dialogsheets("3mdisplay").Focus = "crbull"
        cont1 = cont1 + 1

End Sub
'-----
Sub IM_CLICK()

        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("imbull").Enabled =
True
        ThisWorkbook.dialogsheets("3mdisplay").EditBoxes("imbull").Text =
"Sheet1"
        ThisWorkbook.dialogsheets("3mdisplay").Focus = "imbull"
        cont1 = cont1 + 1

End Sub
'=====
' This subroutine performs initial calculations described in Chapter IV.
Each output parameter defined in the previous subroutine is assigned to
an array which holds the calculated values. The routine GETRANGE is
called to get the mouse (or keyboard) inputs for the 3M data.

```

```

Sub MAKEDATA()

On Error GoTo handle
ReDim arrivals(1 To 100, 1 To jsys)
ReDim price(1 To 100, 1 To jsys)
ReDim downtime(1 To 100, 1 To jsys)
ReDim downstart(1 To 100, 1 To jsys)
ReDim interval_downtime(1 To 100, 1 To jsys)
ReDim interval_cost(1 To 100, 1 To jsys)

j = 1
cmax = 0
countr = 0
totprice = 0

For j = 1 To jsys
again:
    msg = "Enter (highlight) the location of system #" & j
    GETRANGE
    If er = True Then Exit Sub
    i = 1
    failtime = 0
    ofset = 0
    datediff = 0
    yrdiff = 0
    For i = 1 To c - 1
        countr = countr + 1
        yrdiff = Selection.Cells(i + 1, 1) - Selection.Cells(i, 3)
        datediff = Selection.Cells(i + 1, 2) - Selection.Cells(i, 4) _
            + (365 * yrdiff)
        ofset = ((Selection.Cells(i + 1, 3) - _
            Selection.Cells(i + 1, 1)) * (365)) _
            + Selection.Cells(i + 1, 4) - _
            Selection.Cells(i + 1, 2)
        failtime = failtime + datediff
        price(i, j) = Selection.Cells(i + 1, 5).Value
        If Not IsNumeric(price(i, j)) Then GoTo handle
        downstart(i, j) = failtime
        downtime(i, j) = ofset
        totprice = totprice + price(i, j)
        avgprice = totprice / countr
        arrivals(i, j) = failtime / 30.4
        failtime = failtime + ofset
    Next i
Next j

Exit Sub

handle:
    MsgBox ("Data selection/entry error:") & Chr(13) & _
        ("Ensure columns selected are date/dollar valued"), vbExclamation
    GoTo again

End Sub

```

```

'-----
Sub GETRANGE()

herey:
    Dim userrange As Object
    default = Selection.Address
    On Error GoTo canceled
    Set userrange = Application.InputBox(prompt:=msg, Type:=8)
    userrange.Select
    c = userrange.Rows.Count
    col = userrange.Columns.Count

    If col <> 4 And dateval = True Then
        MsgBox ("This selection must have four columns"), vbExclamation
        GoTo herey
    End If

    If col <> 5 And dateval = False Then
        MsgBox ("This selection must have five columns"), vbExclamation
        GoTo herey
    End If

    If c < 2 Then
        MsgBox ("This selection must have more than one row"),
vbExclamation
        GoTo herey
    End If

    If cmax < c Then cmax = c
Exit Sub
canceled:
er = True
End Sub
'=====
' This prints 3M results of the worksheets selected in the
initialization dialog box. Each procedure called in the If..Then
construct loops through the array associated with that output parameter.

Sub PRINTING()

Set oldactive = ActiveSheet

If ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("ft").Value = xlOn
Then
    ARRIVAL_RESULTS
End If

If ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("ift").Value = xlOn
Then
    INTER_ARRIVAL_RESULTS
End If

If ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("av").Value = xlOn
Then
    AVAILABILITY_RESULTS

```

```

End If

If ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("im").Value = xlOn
Then
    INTERVAL_RESULTS
End If

If ThisWorkbook.dialogsheets("3mdisplay").CheckBoxes("cr").Value = xlOn
Then
    COST_RESULTS
End If

oldactive.Activate

End Sub

'=====
' This subroutine separates data into the appropriate intervals for the
model calculations.

Sub INTERVALS()

ReDim tempy(1 To 100, 1 To jsys)
ReDim inter(1 To 100, 1 To jsys)
ReDim tempy2(1 To 100, 1 To jsys)
ReDim tempy3(1 To 100, 1 To jsys)

counter = 0

For j = 1 To jsys
    interval_downtime(1, j) = 0
    interval_cost(1, j) = 0
    For k = 1 To num_intervals
        For i = 1 To cmax
            If arrivals(i, j) = "" Then GoTo skip
            If arrivals(i, j) <= k * interval_size Then
                counter = counter + 1
                If downstart(i, j) + downtime(i, j) < k * interval_size *
30.4 _
                    Then
                        interval_downtime(k, j) = interval_downtime(k, j) _
+ downtime(i, j)
                    End If
                If downstart(i, j) + downtime(i, j) >= k * interval_size
* 30.4 _
                    Then
                        interval_downtime(k, j) = interval_downtime(k, j) +
-
                        (k * interval_size * 30.4) - downstart(i, j)
                    End If
                interval_cost(k, j) = interval_cost(k, j) _
+ price(i, j)
            End If
            inter(k, j) = counter
        Next i
    Next k
Next j

skip:

```

```

        Next i
        counter = 0
    Next k
Next j

For j = 1 To jsys
    For i = 1 To num_intervals
        tempy(i, j) = inter(i, j)
        tempy2(i, j) = interval_downtime(i, j)
        tempy3(i, j) = interval_cost(i, j)
        If i > 1 Then
            inter(i, j) = inter(i, j) - tempy(i - 1, j)
            interval_downtime(i, j) = interval_downtime(i, j) -
                tempy2(i - 1, j)
            interval_cost(i, j) = interval_cost(i, j) - tempy3(i - 1, j)
        End If
    Next i
Next j

End Sub

'=====
' This section defines the procedures called in the printing result
subroutine earlier.

Sub ARRIVAL_RESULTS()

On Error GoTo a1
Worksheets(ftb).Activate
ActiveSheet.Cells(1, 1).Value = "Failure #"
ActiveSheet.Cells(1, 1).Font.Bold = True
counter = 2

For j = 1 To jsys
    ActiveSheet.Cells(1, counter).Value = "system" & j
    ActiveSheet.Cells(1, counter).Font.Bold = True
    counter = counter + 1
Next j

For i = 1 To cmax - 1
    ActiveSheet.Cells(i + 1, 1).Value = i
    ActiveSheet.Cells(i + 1, 1).Font.Bold = True
Next i

For j = 1 To jsys
    For i = 1 To cmax - 1
        ActiveSheet.Cells(i + 1, j + 1).Value = _
            Application.Round(arrivals(i, j), 2)
        If ActiveSheet.Cells(i + 1, j + 1).Value = 0 Then _
            ActiveSheet.Cells(i + 1, j + 1).Value = ""
    Next i
Next j

ActiveSheet.ChartObjects.Add(160, 10, 250, 175).Select
Application.CutCopyMode = False

```

```

ActiveChart.ChartWizard Source:=Range(Cells(1, 2), _
    Cells(cmax + 1, jsys + 1)), Gallery:=xlXYScatter, Format:=2, _
    PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
    :=1, HasLegend:=1, Title:="Arrival Times", CategoryTitle:= _
    "Failure #", ValueTitle:="Time (months)"
Exit Sub

a1:
MsgBox ("Failures won't be displayed because ") & ftb & Chr(13) & _
    (" is not a valid worksheet name"), vbExclamation

End Sub
'-----
Sub MAKE_INTER_ARRIVE()

ReDim inter_arrive(1 To cmax, 1 To jsys)

For j = 1 To jsys
    For i = 1 To cmax
        If i = 1 Then inter_arrive(i, j) = arrivals(i, j)
        If i > 1 Then inter_arrive(i, j) = _
            arrivals(i, j) - arrivals(i - 1, j)
        If arrivals(i, j) = 0 Then inter_arrive(i, j) = -999
    Next i
Next j

End Sub
'-----
Sub INTER_ARRIVAL_RESULTS()

On Error GoTo a2
Worksheets(iftb).Activate
MAKE_INTER_ARRIVE
ActiveSheet.Cells(1, 1).Value = "inter #"
ActiveSheet.Cells(1, 1).Font.Bold = True
counter = 2

For j = 1 To jsys
    ActiveSheet.Cells(1, counter).Value = "system" & j
    ActiveSheet.Cells(1, counter).Font.Bold = True
    counter = counter + 1
Next j

For i = 1 To cmax - 1
    ActiveSheet.Cells(i + 1, 1).Value = i
    ActiveSheet.Cells(i + 1, 1).Font.Bold = True
Next i

For j = 1 To jsys
    For i = 1 To cmax - 1
        ActiveSheet.Cells(i + 1, j + 1).Value = _
            Application.Round(inter_arrive(i, j), 2)
        If ActiveSheet.Cells(i + 1, j + 1).Value = -999 Then _
            ActiveSheet.Cells(i + 1, j + 1).Value = ""
    Next i

```

Next j

```
vals = Range(Cells(2, 2), Cells(cmax + 1, jsys + 1))
valavg = Application.Average(vals)
valsd = Application.StDev(vals)
valvar = Application.Var(vals)
valskew = Application.Skew(vals)
```

```
ActiveSheet.Cells(cmax + 2, 1).Value = "MTBF ="
ActiveSheet.Cells(cmax + 2, 1).Font.Bold = True
ActiveSheet.Cells(cmax + 2, 2).Value = _
    Application.Round(valavg, 2)
ActiveSheet.Cells(cmax + 3, 1).Value = "St Dev ="
ActiveSheet.Cells(cmax + 3, 1).Font.Bold = True
ActiveSheet.Cells(cmax + 3, 2).Value = _
    Application.Round(valsd, 2)
ActiveSheet.Cells(cmax + 4, 1).Value = "Var ="
ActiveSheet.Cells(cmax + 4, 1).Font.Bold = True
ActiveSheet.Cells(cmax + 4, 2).Value = _
    Application.Round(valvar, 2)
ActiveSheet.Cells(cmax + 5, 1).Value = "Skew ="
ActiveSheet.Cells(cmax + 5, 1).Font.Bold = True
ActiveSheet.Cells(cmax + 5, 2).Value = _
    Application.Round(valskew, 2)
```

```
ActiveSheet.ChartObjects.Add(160, 10, 250, 175).Select
Application.CutCopyMode = False
ActiveChart.ChartWizard Source:=Range(Cells(1, 2), _
    Cells(cmax + 1, jsys + 1)), Gallery:=xlXYScatter, Format:=2, _
    PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
    :=1, HasLegend:=1, Title:="Inter Arrival Times", CategoryTitle:= _
    "Failure #", ValueTitle:="Time Between Failure"
```

Exit Sub

```
a2:
MsgBox ("Inter-failures won't be displayed because ") & iftb & Chr(13) &
    (" is not a valid worksheet name"), vbExclamation
```

End Sub

```
Sub AVAILABILITY_RESULTS()
```

```
On Error GoTo a3
Worksheets(avb).Activate
ActiveSheet.Cells(1, 1).Value = "interval #"
ActiveSheet.Cells(1, 1).Font.Bold = True
counter = 2
totdown = 0
```

```
For j = 1 To jsys
    ActiveSheet.Cells(1, counter).Value = "system" & j
    ActiveSheet.Cells(1, counter).Font.Bold = True
    counter = counter + 1
```

```

Next j

For i = 1 To num_intervals
    ActiveSheet.Cells(i + 1, 1).Value = i
    ActiveSheet.Cells(i + 1, 1).Font.Bold = True
Next i

For j = 1 To jsys
    For i = 1 To num_intervals
        If interval_downtime(i, j) > interval_size * 30.4 Then _
            interval_downtime(i, j) = interval_size * 30.4
            ActiveSheet.Cells(i + 1, j + 1).Value = _
                Application.Round(interval_downtime(i, j) / 30.4, 2)
            totdown = totdown + interval_downtime(i, j)
        Next i
    Next j

tottime = interval_size * num_intervals * 30.4 * jsys
totup = tottime - totdown

ActiveSheet.Cells(num_intervals + 3, 1).Value = "Down ="
ActiveSheet.Cells(num_intervals + 3, 1).Font.Bold = True
ActiveSheet.Cells(num_intervals + 3, 2).Value = totdown / tottime
ActiveSheet.Cells(num_intervals + 4, 1).Value = "Avail ="
ActiveSheet.Cells(num_intervals + 4, 1).Font.Bold = True
ActiveSheet.Cells(num_intervals + 4, 2).Value = totup / tottime
Range(Cells(num_intervals + 3, 2), Cells(num_intervals + 4, 2)).Select
    Selection.NumberFormat = "0.00%"

ActiveSheet.ChartObjects.Add(160, 10, 250, 175).Select
Application.CutCopyMode = False
ActiveChart.ChartWizard Source:=Range(Cells(1, 2), _
    Cells(num_intervals + 1, jsys + 1)), Gallery:=xlColumn, _
    Format:=6, PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
    :=1, HasLegend:=1, Title:="Downtime per Interval", CategoryTitle:= _
    "Interval", ValueTitle:="Months"

Exit Sub

a3:
MsgBox ("Availability won't be displayed because ") & avb & Chr(13) & _
    (" is not a valid worksheet name"), vbExclamation

End Sub
'-----
Sub COST_RESULTS()

On Error GoTo a4
Worksheets(crb).Activate
ActiveSheet.Cells(1, 1).Value = "interval #"
ActiveSheet.Cells(1, 1).Font.Bold = True
counter = 2

For j = 1 To jsys
    ActiveSheet.Cells(1, counter).Value = "system" & j

```

```

        ActiveSheet.Cells(1, counter).Font.Bold = True
        counter = counter + 1
    Next j

    For i = 1 To num_intervals
        ActiveSheet.Cells(i + 1, 1).Value = i
        ActiveSheet.Cells(i + 1, 1).Font.Bold = True
    Next i

    For j = 1 To jsys
        For i = 1 To num_intervals
            ActiveSheet.Cells(i + 1, j + 1).Value = interval_cost(i, j)
        Next i
    Next j

    ActiveSheet.Cells(num_intervals + 3, 1).Value = "Averages:"
    ActiveSheet.Cells(num_intervals + 3, 1).Font.Bold = True
    ActiveSheet.Cells(num_intervals + 3, 2).Value = "Per failure"
    ActiveSheet.Cells(num_intervals + 3, 3).Value = "Per interval"
    ActiveSheet.Cells(num_intervals + 4, 2).Value = _
        Application.Round(avgprice, 2)
    ActiveSheet.Cells(num_intervals + 4, 3).Value = _
        Application.Round(totprice / num_intervals, 2)

    ActiveSheet.ChartObjects.Add(180, 5, 250, 175).Select
    Application.CutCopyMode = False
    ActiveChart.ChartWizard Source:=Range(Cells(1, 2), _
        Cells(num_intervals + 1, jsys + 1)), Gallery:=xlColumn, _
        Format:=6, PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
        :=1, HasLegend:=1, Title:="Cost per Interval", CategoryTitle:= _
        "Interval", ValueTitle:="Dollars"

    Exit Sub

a4:
MsgBox ("Costs won't be displayed because ") & crb & Chr(13) & _
    (" is not a valid worksheet name"), vbExclamation

End Sub
'-----
Sub INTERVAL_RESULTS()

On Error GoTo a5
Worksheets(imb).Activate
ActiveSheet.Cells(1, 1).Value = "interval"
ActiveSheet.Cells(1, 1).Font.Bold = True
ActiveSheet.Cells(num_intervals + 12, 1).Value = "interval"
ActiveSheet.Cells(num_intervals + 12, 1).Font.Bold = True
counter = 2

For j = 1 To jsys
    ActiveSheet.Cells(1, counter).Value = "system" & j
    ActiveSheet.Cells(1, counter).Font.Bold = True
    counter = counter + 1
Next j

```

```

ActiveSheet.Cells(num_intervals + 12, 2).Value = "reliability"
ActiveSheet.Cells(num_intervals + 12, 2).Font.Bold = True

For i = 1 To num_intervals
    ActiveSheet.Cells(i + 1, 1).Value = i
    ActiveSheet.Cells(i + 1, 1).Font.Bold = True
    ActiveSheet.Cells(i + num_intervals + 12, 1).Value = i
    ActiveSheet.Cells(i + num_intervals + 12, 1).Font.Bold = True
Next i

For j = 1 To jsys
    For i = 1 To num_intervals
        ActiveSheet.Cells(i + 1, j + 1).Value = inter(i, j)
    Next i
Next j

ESTIMATE

ActiveSheet.Cells(1, jsys + 2).Value = "model"
ActiveSheet.Cells(1, jsys + 2).Font.Bold = True

For i = 1 To num_intervals
    ActiveSheet.Cells(i + 1, jsys + 2).Value = _
        Application.Round(expect(i), 2)
    ActiveSheet.Cells(i + num_intervals + 12, 2).Value = _
        Application.Round(proby(i), 2)
Next i

ActiveSheet.Cells(num_intervals + 3, 1).Value = "Parameter"
ActiveSheet.Cells(num_intervals + 3, 1).Font.Underline = xlSingle
ActiveSheet.Cells(num_intervals + 3, 2).Value = "Estimate"
ActiveSheet.Cells(num_intervals + 3, 2).Font.Underline = xlSingle
ActiveSheet.Cells(num_intervals + 3, 3).Value = "95% LCL"
ActiveSheet.Cells(num_intervals + 3, 3).Font.Underline = xlSingle
ActiveSheet.Cells(num_intervals + 3, 4).Value = "95% UCL"
ActiveSheet.Cells(num_intervals + 3, 4).Font.Underline = xlSingle
ActiveSheet.Cells(num_intervals + 4, 1).Value = "q"
ActiveSheet.Cells(num_intervals + 4, 2).Value = Application.Round(q_hat,
2)
ActiveSheet.Cells(num_intervals + 4, 3).Value = Application.Round(q_low,
2)
ActiveSheet.Cells(num_intervals + 4, 4).Value = Application.Round(q_up,
2)
ActiveSheet.Cells(num_intervals + 5, 1).Value = "C"
ActiveSheet.Cells(num_intervals + 5, 2).Value = Application.Round(c, 2)
ActiveSheet.Cells(num_intervals + 5, 3).Value = Application.Round(c_low,
2)
ActiveSheet.Cells(num_intervals + 5, 4).Value = Application.Round(cup,
2)
ActiveSheet.Cells(num_intervals + 7, 1).Value = "Month"
ActiveSheet.Cells(num_intervals + 7, 1).Font.Underline = xlSingle
ActiveSheet.Cells(num_intervals + 7, 2).Value = "Total fail"
ActiveSheet.Cells(num_intervals + 7, 2).Font.Underline = xlSingle
ActiveSheet.Cells(num_intervals + 7, 3).Value = "95% LCL"
ActiveSheet.Cells(num_intervals + 7, 3).Font.Underline = xlSingle

```

```

ActiveSheet.Cells(num_intervals + 7, 4).Value = "95% UCL"
ActiveSheet.Cells(num_intervals + 7, 4).Font.Underline = xlSingle
ActiveSheet.Cells(num_intervals + 8, 1).Value = months
ActiveSheet.Cells(num_intervals + 8, 2).Value = _
    Application.Round(expt_no, 2)
ActiveSheet.Cells(num_intervals + 8, 3).Value = _
    Application.Round(expt_no_low, 2)
ActiveSheet.Cells(num_intervals + 8, 4).Value = _
    Application.Round(expt_no_up, 2)

ActiveSheet.ChartObjects.Add(195, 10, 250, 160).Select
Application.CutCopyMode = False
ActiveChart.ChartWizard Source:=Range(Cells(1, 2), _
    Cells(num_intervals + 1, jsys + 2)), Gallery:=xlCombination, _
    Format:=1, PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
    :=1, HasLegend:=1, Title:="Failures per Interval", CategoryTitle:= _
    "Interval", ValueTitle:="Failures"

ActiveSheet.ChartObjects.Add(195, 250, 250, 160).Select
Application.CutCopyMode = False
ActiveChart.ChartWizard Source:=Range(Cells(num_intervals + 12, 2), _
    Cells(num_intervals + num_intervals + 12, 2)), Gallery:=xlLine, _
    Format:=10, PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
    :=1, HasLegend:=1, Title:="System Reliability", CategoryTitle:= _
    "Interval", ValueTitle:="Reliability"

Exit Sub

a5:
MsgBox ("Costs won't be displayed because ") & crb & Chr(13) & _
    (" is not a valid worksheet name"), vbExclamation

End Sub
'=====
' This subroutine formulates the model's parameters as detailed in
Chapter II. A binary search is used to approximate the initial
parameters. The subroutine CI is called repeatedly to form the
confidence limits (hardcoded at 95%).

Sub ESTIMATE()

CHECKDATA

If numrows <= 1 Then
    MsgBox "There must be more than one interval (row)", vbExclamation
    Exit Sub
End If
flag = -99
div_by_zero_offset = 0.001
ntweedle = 0
nplus = 0
temp = 0
power1 = 1

For j = 1 To numcols

```

```

    For i = 1 To numRows
        temp = fail(i, j) * (i - 1)
        ntweedle = ntweedle + temp
        nplus = nplus + fail(i, j)
    Next i
Next j

If Application.Round(nplus, 4) = 0 Then nplus = nplus +
div_by_zero_offset
n = ntweedle / nplus
If numRows - n - 1 = 0 Then n = n - div_by_zero_offset
q_hat = (numrows - n) / (numrows - n - 1)
qlow = div_by_zero_offset
qup = q_hat + (q_hat * 10)
power1 = 1

For i = 1 To numRows
    power1 = power1 * q_hat
Next i

For i=1 to numRows
    s1=s1+(1+power1)
    s2=s2+numrows*power1*(1-q_hat)
    s3=s3+(1-power1)*(1-q_hat)
next i
If Application.Round(q_hat, 4) = 1 Then q_hat = q_hat +
div_by_zero_offset
If Application.Round(power1, 4) = 1 Then power1 = power1 +
div_by_zero_offset
rhs = ((q*s1)-s2)/s3

righty = Application.Round(rhs, 3)
lefty = Application.Round(n, 3)
cnt = 0
Do
    If n < rhs Then
        qup = q_hat
        q_hat = ((qup - qlow) / 2) + qlow
        power1 = 1
        For i = 1 To numRows
            power1 = power1 * q_hat
        Next i
    End If
    If n > rhs Then
        qlow = q_hat
        q_hat = qup - ((qup - qlow) / 2)
        power1 = 1
        For i = 1 To numRows
            power1 = power1 * q_hat
        Next i
    End If
    If Application.Round(q_hat, 4) = 1 Then q_hat = q_hat +
div_by_zero_offset
    If Application.Round(power1, 4) = 1 Then power1 = power1 +
div_by_zero_offset

```

```

    rhs = ((q*s1)-s2)/s3
    righty = Application.Round(rhs, 3)
    lefty = Application.Round(n, 3)
    cnt = cnt + 1
Loop While lefty <> righty And cnt < 50

c = (nplus / ((1 - power1) / (1 - q_hat))) / numcols

CI

expect_no = 0

For i = 1 To numrows + 1
    expect(i) = c * (q_hat ^ (i - 1))
    proby(i) = Exp(-expect(i))
    If i <= numrows Then expect_no = expect_no + expect(i)
Next i

t1 = 0
t2 = num_intervals

MISSION

End Sub
'-----
Sub CHECKDATA()

sensitive = False
Range(Cells(2, 2), Cells(num_intervals + 1, jsys + 1)).Select
numrows = Selection.Rows.Count
numcols = Selection.Columns.Count

ReDim fail(1 To numrows, 1 To numcols)
ReDim expect(1 To numrows + 1)
ReDim expectans(1 To numrows + 1)
ReDim tempy(1 To numrows)
ReDim proby(1 To numrows + 1)

For i = 1 To numrows
    For j = 1 To numcols
        fail(i, j) = Selection.Cells(i, j).Value
        If fail(i, j) = "" Then GoTo herez
        If fail(i, j) > big Then
            big = fail(i, j)
            cmax = i
        End If
    Next j
herez:
    Next j
Next i
flag = -999

End Sub
'-----
Sub CI()

```

```

dldc = 0
dldtheta = 0
dldcdt = 0
theta = Application.Ln(q_hat)

For j = 1 To numcols
  For i = 1 To numRows
    dldc = dldc + (fail(i, j) * (1 / c ^ 2))
    dldtheta = dldtheta + (((i - 1) ^ 2) * fail(i, j))
    dldcdt = dldcdt + ((i - 1) * (Exp(theta * (i - 1))))
  Next i
Next j

det = (dldc * dldtheta) - (dldcdt ^ 2)
varc = -(dldtheta / det)
vartheta = -(dldc / det)
cov = dldcdt / det
clow = c + (1.96 * varc)
cup = c - (1.96 * varc)
thetalow = theta + (1.96 * vartheta)
thetaup = theta - (1.96 * vartheta)
qlow = Exp(thetalow)
qup = Exp(thetaup)
End Sub

'=====
' This routine calculates expected failures in the mission durations.
First, the expected failures are calculated for the entire observation
period, and then the user has the option to modify this when performing
sensitivity analysis.

Sub MISSION()

theta = Application.Ln(q_hat)
p1 = theta * t1
p2 = theta * t2
e1 = Exp(p1)
e2 = Exp(p2)
e3 = Exp(theta)
multy = (e1 - e2) / (1 - e3)
expt_no = c * multy
dfdc = multy
dfdtheta = (((t1 * e1) - (t2 * e2)) / (1 - e3)) + _
            (e3 * (e1 - e2) / ((1 - e3) ^ 2))
varg = ((dfdc ^ 2) * varc) + (2 * dfdc * dfdtheta * cov) + _
        ((dfdtheta ^ 2) * vartheta)
expt_no_low = expt_no - (1.96 * (Sqr(Abs(varg))))
expt_no_up = expt_no + (1.96 * (Sqr(Abs(varg))))
If expt_no_low < 0 Then expt_no_low = 0

End Sub

'=====
' This routine performs the minimum cost replacement analysis. It loops
through each interval and calculates the cycle costs, then stores the
value (if it is lower than the previous one)

```

```

Sub SENSECOST()

ERR1
If er = True Then GoTo here
sensitive = True
COST
sensitive = False

here:
End Sub
'-----
Sub COST()

On Error GoTo heresay

ERR1
If er = True Then GoTo here

ReDim costs(1 To 150)
repeat:
oldc = c
oldq = q_hat
If sensitive = True Then
    ThisWorkbook.dialogsheets("getcost").EditBoxes("ccost").Text = _
        Application.Round(c, 2)
    ThisWorkbook.dialogsheets("getcost").EditBoxes("qcost").Text = _
        Application.Round(q_hat, 2)
    ThisWorkbook.dialogsheets("getcost").EditBoxes("qbox").Text = "0"
    ThisWorkbook.dialogsheets("getcost").EditBoxes("newc").Text = ""
    ThisWorkbook.dialogsheets("getcost").EditBoxes("repc").Text = _
        Application.Round(avgprice, 2)
    ThisWorkbook.dialogsheets("getcost").EditBoxes("replc").Text =
"Sheet1"
    dboxok = ThisWorkbook.dialogsheets("getcost").Show
    If Not dboxok Then Exit Sub
    newcost =
ThisWorkbook.dialogsheets("getcost").EditBoxes("newc").Text
    repcost =
ThisWorkbook.dialogsheets("getcost").EditBoxes("repc").Text
    ERRNO (repcost)
    If er = True Then GoTo repeat
    ERRNEG (repcost)
    If er = True Then GoTo repeat
    ERRNO (newcost)
    If er = True Then GoTo repeat
    ERRNEG (newcost)
    If er = True Then GoTo repeat
    c = ThisWorkbook.dialogsheets("getcost").EditBoxes("ccost").Text
    q_hat = ThisWorkbook.dialogsheets("getcost").EditBoxes("qcost").Text
    ERRNO (q_hat)
    If er = True Then GoTo repeat
    ERRNEG (q_hat)
    If er = True Then GoTo repeat
    ERRNO (c)
    If er = True Then GoTo repeat

```

```

ERRNEG (c)
If er = True Then GoTo repeat
er = False
costloc =
ThisWorkbook.dialogsheets("getcost").EditBoxes("replc").Text
q = ThisWorkbook.dialogsheets("getcost").EditBoxes("qbox").Text
ERRNO (q)
If er = True Then GoTo repeat
If q < 0 Or q > 1 Then
    MsgBox ("q must be between 0 and 1"), vbExclamation
    GoTo repeat
End If
End If

If sensitive = False Then
    ThisWorkbook.dialogsheets("costrep").EditBoxes("newc").Text = ""
    ThisWorkbook.dialogsheets("costrep").EditBoxes("repc").Text = _
        Application.Round(avgprice, 2)
    ThisWorkbook.dialogsheets("costrep").EditBoxes("qbox").Text = "0"
    ThisWorkbook.dialogsheets("costrep").EditBoxes("replc").Text =
"Sheet1"
    dboxok = ThisWorkbook.dialogsheets("costrep").Show
    If Not dboxok Then Exit Sub
    newcost =
ThisWorkbook.dialogsheets("costrep").EditBoxes("newc").Text
    repcost =
ThisWorkbook.dialogsheets("costrep").EditBoxes("repc").Text
ERRNO (repcost)
If er = True Then GoTo repeat
ERRNEG (repcost)
If er = True Then GoTo repeat
ERRNO (newcost)
If er = True Then GoTo repeat
ERRNEG (newcost)
If er = True Then GoTo repeat
costloc =
ThisWorkbook.dialogsheets("costrep").EditBoxes("replc").Text
q = ThisWorkbook.dialogsheets("costrep").EditBoxes("qbox").Text
ERRNO (q)
If er = True Then GoTo repeat
If q < 0 Or q > 1 Then
    MsgBox ("q must be between 0 and 1"), vbExclamation
    GoTo repeat
End If
End If

mins = 100000000
p = 1 - q
k = Application.Round(240 / interval_size, 0)

For i = 1 To k
    tot = 1
    If costs(i) > 100000000 Then GoTo skip
    For j = 1 To i
        num1 = q_hat ^ j

```

```

        num2 = 1 - q_hat
        num3 = 1 - num1
        efail = c * num3 / num2
        lq = q * efail
        summ = Exp(-lq)
        tot = tot + summ
    Next j
    num1 = q_hat ^ i
    num2 = 1 - q_hat
    num3 = 1 - num1
    expf = c * num3 / num2
    num4 = -(q * expf)
    num5 = Exp(num4)
    If Application.Round(q, 4) = 0 Then q = q + 0.001
    expfail = (p / q) * (1 - num5)
    costs(i) = (newcost + (repcost * expfail)) / tot
    If costs(i) < mins Then
        mins = costs(i)
        minimum = i
    End If
    If costs(i) > mins Then
        ct = ct + 1
        If ct = Application.Round((minimum / 2), 0) Then GoTo skip
    End If
Next i

skip:
Worksheets(costloc).Activate
loopsize = (minimum * 2) - Application.Round((minimum / 2), 0)
ActiveSheet.Cells(1, 1).Value = "interval #"
ActiveSheet.Cells(1, 1).Font.Bold = True
ActiveSheet.Cells(1, 2).Value = "int cost"
ActiveSheet.Cells(1, 2).Font.Bold = True
cntr = 2

For i = 1 To loopsize
    ActiveSheet.Cells(cntr, 1).Value = i
    ActiveSheet.Cells(cntr, 1).Font.Bold = True
    ActiveSheet.Cells(cntr, 2).Value = Application.Round(costs(i), 2)
    cntr = cntr + 1
Next i

ActiveSheet.Cells(loopsize + 3, 1).Value = "min ="
ActiveSheet.Cells(loopsize + 3, 1).Font.Bold = True
ActiveSheet.Cells(loopsize + 3, 2).Value = _
    "month " & (minimum * interval_size)

ActiveSheet.ChartObjects.Add(180, 20, 250, 175).Select
Application.CutCopyMode = False
ActiveChart.ChartWizard Source:=Range(Cells(1, 2), _
    Cells(1 + loopsize, 2)), Gallery:=xlLine, _
    Format:=10, PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
:=1, HasLegend:=1, Title:="Long Run Costs", CategoryTitle:= _
    "Interval", ValueTitle:="Dollars"

```

```

If sensitive = True Then
    c = oldc
    q_hat = oldq
End If

Exit Sub
heresay:
MsgBox ("Non-numeric entry or invalid worksheet name error"),
vbExclamation
GoTo repeat

here:

End Sub
'=====
' This calculates mission reliability. It loops through each interval
and calculates each interval's reliability.

Sub MSENSE()

On Error GoTo heresay
ERR1
If er = True Then GoTo here

Dim proby()
Dim expn()
repeat:
qold = q_hat
cold = c
ThisWorkbook.dialogsheets("mishun").EditBoxes("ccost").Text = _
    Application.Round(c, 2)
ThisWorkbook.dialogsheets("mishun").EditBoxes("qcost").Text = _
    Application.Round(q_hat, 2)
ThisWorkbook.dialogsheets("mishun").EditBoxes("st").Text = "0"
ThisWorkbook.dialogsheets("mishun").EditBoxes("ct").Text = num_intervals
ThisWorkbook.dialogsheets("mishun").EditBoxes("rr").Text = "Sheet1"
dboxok = ThisWorkbook.dialogsheets("mishun").Show
If Not dboxok Then Exit Sub
t1 = ThisWorkbook.dialogsheets("mishun").EditBoxes("st").Text
t2 = ThisWorkbook.dialogsheets("mishun").EditBoxes("ct").Text
If t2 <= t1 Then
    MsgBox ("Start time can't be larger than completion time"),
vbExclamation
    GoTo repeat
End If
ERRNO (t1)
If er = True Then GoTo repeat
ERRINT (t1)
If er = True Then GoTo repeat
ERRNEG (t1)
If er = True Then GoTo repeat
ERRNEG (t2)
If er = True Then GoTo repeat
ERRNO (t2)
If er = True Then GoTo repeat

```

```

ERRINT (t2)
If er = True Then GoTo repeat
er = False
rloc = ThisWorkbook.dialogsheets("mishun").EditBoxes("rr").Text
q_hat = ThisWorkbook.dialogsheets("mishun").EditBoxes("qcost").Text
c = ThisWorkbook.dialogsheets("mishun").EditBoxes("ccost").Text
ERRNO (q_hat)
If er = True Then GoTo repeat
ERRNEG (q_hat)
If er = True Then GoTo repeat
ERRNO (c)
If er = True Then GoTo repeat
ERRNEG (c)
If er = True Then GoTo repeat
er = False

ReDim proby(t2)
ReDim expn(t2)

For i = t1 To t2
    expn(i) = c * (q_hat ^ (i - 1))
    proby(i) = Exp(-expn(i))
Next i

MISSION

q_hat = gold
c = cold
Worksheets(rloc).Activate
ActiveSheet.Cells(1, 1).Value = "interval"
ActiveSheet.Cells(1, 1).Font.Bold = True
ActiveSheet.Cells(1, 2).Value = "# failures"
ActiveSheet.Cells(1, 2).Font.Bold = True
ActiveSheet.Cells((t2 - t1) + 9, 1).Value = "interval"
ActiveSheet.Cells((t2 - t1) + 9, 1).Font.Bold = True
ActiveSheet.Cells((t2 - t1) + 9, 2).Value = "reliability"
ActiveSheet.Cells((t2 - t1) + 9, 2).Font.Bold = True
ActiveSheet.Cells((t2 - t1) + 4, 1).Value = "expected # failures"
ActiveSheet.Cells((t2 - t1) + 5, 1).Value = "in " & _
    (t2 - t1) * interval_size & " month mission"
Application.Cells((t2 - t1) + 6, 2).Value = Application.Round(expt_no,
2)
ActiveSheet.Cells((t2 - t1) + 5, 3).Value = "95% LCL"
ActiveSheet.Cells((t2 - t1) + 5, 3).Font.Underline = xlSingle
ActiveSheet.Cells((t2 - t1) + 6, 3).Value =
Application.Round(expt_no_low, 2)
ActiveSheet.Cells((t2 - t1) + 5, 4).Value = "95% UCL"
ActiveSheet.Cells((t2 - t1) + 5, 4).Font.Underline = xlSingle
ActiveSheet.Cells((t2 - t1) + 6, 4).Value =
Application.Round(expt_no_up, 2)
temp = t1

For i = 1 To (t2 - t1) + 1
    ActiveSheet.Cells(i + 1, 1).Value = temp
    ActiveSheet.Cells(i + 1, 1).Font.Bold = True

```

```

        ActiveSheet.Cells(i + (t2 - t1) + 9, 1).Value = temp
        ActiveSheet.Cells(i + (t2 - t1) + 9, 1).Font.Bold = True
        ActiveSheet.Cells(i + 1, 2).Value = Application.Round(expn(temp), 2)
        ActiveSheet.Cells(i + (t2 - t1) + 9, 2).Value = _
            Application.Round(proby(temp), 2)
        temp = temp + 1
    Next i

ActiveSheet.ChartObjects.Add(195, 10, 250, 160).Select
Application.CutCopyMode = False
ActiveChart.ChartSource:=Range(Cells(1, 2), _
    Cells((t2 - t1) + 2, 2)), Gallery:=xlLine, _
    Format:=10, PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
    :=1, HasLegend:=1, Title:="Expected Failures per Interval", _
    CategoryTitle:="Interval", ValueTitle:="Failures"

ActiveSheet.ChartObjects.Add(195, 200, 250, 160).Select
Application.CutCopyMode = False
ActiveChart.ChartWizard Source:=Range(Cells((t2 - t1) + 9, 2), _
    Cells(2 * (t2 - t1) + 10, 2)), Gallery:=xlLine, _
    Format:=10, PlotBy:=xlColumns, CategoryLabels:=0, SeriesLabels _
    :=1, HasLegend:=1, Title:="System Reliability", CategoryTitle:= _
    "Interval (adjusted)", ValueTitle:="Reliability"

Exit Sub
heresay:
MsgBox ("Non-numeric entry or invalid worksheet name error"),
vbExclamation
GoTo repeat

here:

End Sub
'=====
' The rest of the procedures are error handling code (for non-integer,
negative values, etc.)

Sub ERR1()

er = False
If c = 0 And q_hat = 0 Or flag <> -99 Then
    MsgBox ("Cannot continue until <Create Data Set> is run"), _
        vbExclamation
    er = True
End If

End Sub
'-----
Sub ERRNO(num)

er = False
If Not IsNumeric(num) Then
    er = True
    MsgBox ("Non-numeric input value detected"), vbExclamation
End If

```

```

End Sub
'-----
Sub ERRINT(numb)

er = False
If numb Mod 1 <> 0 Then
    er = True
    MsgBox ("Non-integer input value detected"), vbExclamation
End If

End Sub
'-----
Sub ERRNEG(numb)

er = False
If numb < 0 Then
    er = True
    MsgBox ("Negative input detected"), vbExclamation
End If

End Sub
'-----
Sub SHOWHELP()
helpfile = ThisWorkbook.Path & "\" & "relyhlp.wri"
appname = "write"
appfile = "write.exe"
On Error GoTo notrunning
AppActivate (appname)
Exit Sub

notrunning:
Shell (appfile & " " & helpfile)
End Sub
'-----

```

## APPENDIX B. INSTALLATION INSTRUCTIONS

The installation diskette has the following four files:

1. *rely.xla* - the add-in application file which is used by Excel
2. *rely.xls* - the program source code
3. *a\_rely.xls* - the start-up file which adds the reliability menu-maker to the Tools menu
4. *relyhlp.wri* - the add-in application help file

To install the add-in program, follow these steps:

1. Copy *a\_rely.xls* to the Excel start-up directory. This is usually C:\excel\xlstart.
2. Copy *rely.xla* and *relyhlp.wri* to the Excel working directory. This is usually C:\excel.
3. The add-in application is now ready to be loaded into memory. This is accomplished by starting Excel and selecting <Add-ins> from the <Tools> menu. Select the Reliability Add-in from the dialog box containing all of the Excel add-in applications. The box to the left of your selection will then appear checked. Select <Ok> to return to the worksheet.
4. Restart Excel (exit Excel and start it again)
5. When you are ready to use the add-in, select <Reliability Menu> from the <Tools> menu of your active worksheet. You will then notice the Reliability menu item has been added to the application toolbar.

\* Subsequent use of the add-in can be accomplished by repeating step 5 above.

APPENDIX C. ADDITIONAL DATA

The data for the multiple system example is shown below. The description of the maintenance action is omitted.

YR	DATE	YR	DATE	TOT
DISC	DISC	COMP	COMP	COST
86	92	86	92	15.78
86	136	86	139	22.59
86	226	86	234	63.04
86	277	86	316	11.17
86	340	86	357	3.73
87	159	87	165	10.71
87	202	87	203	543.85
87	255	88	266	1067.99
87	300	87	309	0
88	21	88	36	0
88	25	88	27	5.6
88	83	88	124	1200
88	111	89	233	2200
88	129	88	134	13.17
88	151	88	204	125.08
90	137	90	137	0
90	222	90	224	111.97
90	299	90	309	0
91	100	91	111	402.29
91	177	91	199	183.92
91	212	91	212	0
91	255	91	266	0
91	300	91	309	6.02
91	335	91	350	333
92	22	92	30	19.15
92	55	92	66	222
92	70	92	88	11.44
92	92	92	92	85.5
92	100	92	133	444



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