A DYNAMIC PROGRAMMING APPROACH TO THE

MULTI-STREAM REPLACEMENT PROBLEM

by

James Thomas Luxhoj

Dissertation submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Industrial Engineering and Operations Research

APPROVED:

_____
Marvin H. Agee, Co-Chairman

_____   _____
    Marilyn S. Jones,   Wolter J. Fabrycky
      Co-Chairman

_____   _____
   Charles J. Malmborg   Bradley O. Skarpness

May 22, 1986

Blacksburg, Virginia

A DYNAMIC PROGRAMMING APPROACH TO THE

MULTI-STREAM REPLACEMENT PROBLEM

by

James T. Luxhoj

(ABSTRACT)

Often, in both the military and industrial sectors, the unavailability of essential components renders a complex system inoperable. Therefore, the primary objective of this research is to develop a methodology for determination of feasible strategies for the repair/replace decision. In the general equipment replacement problem, a finite planning horizon may be partitioned into stages such that an end item deteriorates toward a final stage where it is no longer economically or operationally feasible to continue to repair the item, or the item experiences fatal failure. This multi-stage deterioration process is very amenable to a dynamic programming solution methodology where the output from one stage becomes the input to the next stage.

In the multi-stream replacement problem, the population of end items is grouped into streams depending upon such parameters as item age, the number of operational hours, or the environment in which the item operates. The reliability function is used to describe the survivor probability in this population model. A dynamic repair/replace program is formulated where the state functions are characterized by two parameters - item age and current operational condition.

A computerized model is then developed that facilitates evaluation of repair/replacement strategies with respect to total life cycle costs of a logistics system. The solution methodology accommodates both

stochastic and/or deterministic demand; different hazard models; a budget constraint; repair capacity constraint; various levels of repair; technological improvement; and organizational implementation issues. The operations impact of a generalized methodology for supporting the repair/replace decision and mode of repair is to provide opportunities for a more efficient use of organizational resources such as capital and repair facilities.

ACKNOWLEDGMENTS

iv

Although they were not committee members, I thank Dr. Joel A. Nachlas and Dr. Ralph L. Disney for their technical assistance with this dissertation. To all my fellow classmates, I also extend my appreciation.

I also thank Mrs. Joni Chambers for her assistance with the tables and figures in this dissertation.

As for my family, I am eternally grateful for their support and encouragement through the hard times. I thank my brother,   , and my sister-in-law,   , for helping me to keep my work in perspective. I thank my sister,   ., my brother-in-law,   , and nephew,   ., for their love. I am also eternally grateful to my father,   , who is no longer with us, for his love, encouragement, and example. I thank my grandmother,   ., for her example of determination. There are many other relatives to whom I also extend my gratitude. This dissertation is dedicated to my mother,   , who gave me life - twice. Finally, I thank the Creator for making life possible.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I.   INTRODUCTION

> For want of a nail, the shoe was lost,
> For want of a shoe, the horse was lost,
> For want of a horse, the rider was lost,
> For want of a rider, the battle was lost,
> For want of a battle, the kingdom was lost,
> And all for the want of a horseshoenail.
>
> (Margaret de Angelis, Mother Goose)

Often, in both the military and industrial sectors, the unavailability of essential components renders a complex system inoperable. The "horseshoenail" may be an essential component of a sophisticated weapons system, fighter jet, submarine, or a shipping manifest system in a distribution center. If aircraft are unable to fly, ships unable to sail, merchandise unable to leave a distribution center, then the "battle" may indeed be lost, and this tactical loss may result in a strategic loss for a nation, industrial enterprise, or other "kingdoms". In the face of budget, warehouse space, and repair personnel constraints, the repair/replace decision becomes all the more difficult. Moreover, multiplicity and diversity of components, alternative procurement and maintenance policies, technological forecasting, and organizational issues all contribute to the complexity of the problem.

Therefore, this dissertation is concerned with the development of a generalized methodology for supporting logistics planning. Correct and timely decisions concerning repair/replacement strategies and selection of repair mode can facilitate system availability by ensuring that there are a reduced number of shortages of "horseshoenails" in crucial situations.

Systematic maintenance requirements planning began with the advent of the Industrial Revolution. Franz A. P. Frisch in "Mortality and Spareparts: A Conceptual Analysis", observes that:

> The (repair/replace) problem is presumably as old as machines since the time of bow and arrows and the wooden plough. However, only with the railroad age has the problem entered our consciousness and been found worthy to be analyzed. This happened because railroad engineers searched for a way to maintain tracks, cars, and steam locomotives without peaks and valleys in the workload for the repair shops and the maintenance crews. Data collection on railroad maintenance started about 1880.[1]

Thus, successful economic operation of the technological innovations of the Industrial Revolution necessitated a me-

---

[1] Franz A.P. Frisch, "Mortality and Spareparts: A Conceptual Analysis", Proceedings of the 1983 Federal Acquisition Symposium , p. 467.

thodical approach to the repair/replace decision. Today, the problem of economic replacement involves much more than the decision of whether to repair or replace equipment. The evolving field of logistics is concerned with the procurement, distribution, maintenance, and replacement of both material and personnel. Although the term "logistics" is historically associated with military operations, the contemporary use of the word has broader industrial applications.

Moreover, the field of maintenance management has also developed through the years with the increase in technological sophistication. Today, maintenance management and control involves training programs to improve worker skills, inventory control of spare parts, planned maintenance (PM) programs, and an increasing use of automation. Furthermore, modern maintenance programs also interface with the Research and Development (R&D), production, engineering, design, and procurement functions.

"Terotechnology" involves a systems approach to maintenance management. "Terotechnology" derives from a Greek word, and the latinized version is "terein" which means "to care for", "to watch over", "to maintain".[2] The British Department of Trade and Industry defines "terotechnology" as:

---

[2]   R.F. de la Mare, <u>Manufacturing System Economics</u> , London: Holt, Rinehart, and Winston, 1982, p. 172.

a combination of management, financial, engineering and other practices applied to physical assets in pursuit of economic life-cycle costs. Its practice is concerned with the specification and design for reliability and maintainability of plant, machinery, equipment, buildings, and structures, with their installation, commissioning, maintenance, modification, and replacement, and with feedback of information on design, performance, and costs.[3]

Moreover, "terotechnology" is connected with the concept of a life cycle cost. Blanchard (11) defines life cycle costing as an integrative rather than a fragmentary approach to "cost consciousness". He maintains that a life cycle cost involves a unified treatment of the following individual costs:

(a) acquisition cost (research, design, testing, production, construction)

(b) product distribution cost (transportation and handling)

(c) operation cost (facilities, energy, utilities, taxes)

(d) maintenance cost (customers service, field and supplier factory maintenance)

(e) training cost (operation and maintenance training)

(f) inventory cost (spare and material support, warehousing)

---

[3]   Ibid., p. 174.

(g)   technical data cost

(h)   retirement and disposal cost.

Life cycle costing aids the decision maker with resource allocation and facilitates the repair/replace decision.

Thus, the essence of this dissertation invokes the concept of "terotechnology" and the systems approach to logistics planning. A generalized mathematical model is developed that utilizes decision networks, or planning models for a system. Decision networks involve states, actions, stages, returns, and sometimes, state transition probabilities. The model uses a progressive or stagewise decision network. Each of these terms is explained in the chapter, "A General Modeling Approach".

In this dissertation, a dynamic program is formulated where the state function is characterized by two parameters - item age and current operational status of the equipment. The reliability or survivor function R(t) is used to give the probability that a system will perform its designed function at a specified time t. The solution methodology that is developed incorporates both Markovian and approximate Markovian deterioration. With Markovian deterioration, the system undergoes a sequence of probabilistic transitions in which the transition probabilities are dependent only on the current state of the system. In this situation, a constant hazard model can be used to describe the instantaneous rate

of failure, and the transition function is considered to be time-homogeneous. Due to the "forgetfulness" property of the exponential distribution, how long a unit has been operating does not affect future operational performance. However, if a non-constant hazard model is applicable, then the transition function is dependent on time and is considered to be non-homogeneous. In this situation, the deterioration law of the system is considered to be approximate Markovian, since future operational performance depends on both item age and the current operational status of the equipment. The transition probabilities are time-dependent and act in accordance with a Markov chain.

The Dynamic Repair/Replace Population Model (DRRPM) that is described in this dissertation represents a significant advance towards providing practitioners with a pragmatic decision aid for multi-stream repairable systems. With the multi-stream replacement problem, a concept of nested Markov chains is used to model a population of repairable items.[*] The population is grouped into streams depending upon such parameters as item age, the number of item operational hours, or the environment in which the item operates. Figure 1 graphically depicts the multi-stream concept.

Homogeneity within each stream or group of items is maintained by assuming this grouping of items are at the same

---

[*] Frisch, p. 471.

THE NESTED MARKOV CHAIN, MULTI-STREAM CONCEPT MODELS THE NONSTEADY STATE.
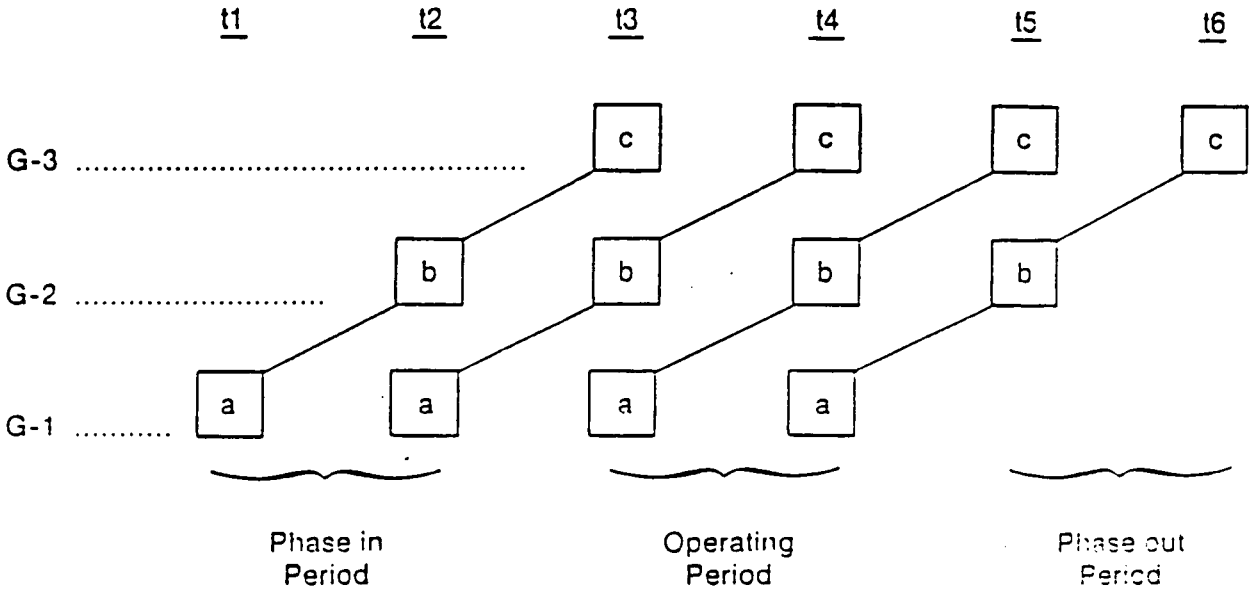
t_n = rime period over which inventory requirements are evaluated (Could be on a weekly basis, on an annual basis, etc.).

G-n = age of units. The largest G-n represents the retirement age of the unit.

abc = a stream or a Markov chain (All of the streams together represent the nested Markov chain concept).

a = number of units procured during time period, t_n

a,b,c $\geq$ 0

Each node has a maintenance tree attached to it

Figure 1. The Multi-Stream Concept.

deterioration level and experience similar failure charac-
teristics.   A stream begins when the first item in that
grouping is procured, and the stream ends when the last item
in that grouping is removed from operation through retirement
or fatal failure.   Each stream is a Markov chain, and the
grouping of streams together form nested Markov chains that
represent a population of repairable items.   This grouping
of end items into streams avoids the necessity of individual
item by item tracking.   A step in the Markov chain is defined
by a unit of time that could represent item age.   The Dynamic
Repair/Replace Population Model (DRRPM) attempts a unified,
holistic treatment of the multi-stream replacement problem
by utilizing the "terotechnology" concept.

The problem of technological forecasting represents a
significant challenge in the development of a paradigm for
the repair/replace decision.   A hypothesis of this author is
that the accelerative thrust of technological expansion and
the accompanying explosion of information create a high de-
gree of cognitive stress on executive decision making.   Thus,
decision aids must increasingly be able to process tremendous
amounts of data and respond to a dybamic environment that
involves rapid technological change.

Linstone . and   Sahal   discuss   this   "Age   of
Substitutability":

It took about 75 years to substitute steam for sail
(10% to 90% of gross tonnage) and 42 years for the

open hearth to replace the Bessemer steel manufac-
turing process.   More recently, it took a mere 18
years for synthetics to replace natural tire fibers
and less than nine years to substitute detergents for
natural soap in the United States ...[5]

Linstone and Sahal maintain that technological substi-
tution tends to follow an S-shaped or "logistic" curve.
Technological substitution starts slowly, since innovations
do not usually win universal acceptance. Once the new tech-
nology gains acceptance, the substitution process advances
more rapidly as the new technology consistently outperforms
the old technology. Finally, the substitution process tapers
off to a fixed saturation level as the new technology becomes
firmly adopted.

In section 2.1.8, "Remarks", various techniques for in-
corporating technological progress are discussed.   An ex-
plicit approach that involves the input of an estimated rate
of gradual technological improvement is espoused in the
chapter, "A General Modeling Approach."   The Dynamic
Repair/Replace Population Model (DRRPM) is also demonstrated
with data for a population of repairable items from the Side
Loadable Warping Tug (SLWT) that is currently in use by the

---

[5]   Harold A. Linstone and Devendra Sahal, <u>Technological
      Substitution: Forecasting Techniques and Applications</u>,
      New York: American Elsevier Publishing Company, Inc.,
      1976, p. xiii.

United States Navy. In the remaining sections of this chapter, a more detailed discussion of the problem and the objectives of this research are presented.

1.1 Statement of the Problem

"When to replace individual units of durable equipment
by similar or improved units is one of the main problems,
upon which the success of industrial enterprise depends."

(Gabriel A.D. Preinreich, "The Economic Life of Industrial

Equipment", Econometrica , Vol.8, 1940, p. 12.)

As Preinreich observed, the optimal replacement of
equipment is crucial to the operational and economic success
of any industrial enterprise. In replacement analysis, there
is a "defender" or the incumbent asset being considered for
replacement, and a "challenger" or the potential replacement
asset. Some basic reasons for replacement include excessive
maintenance, declining efficiency, and obsolescence.

The fundamental problem of replacement analysis is to
find the service life for an asset that will minimize the
average cost per period. As equipment ages, operation and
maintenance costs typically increase, and capital recovery
cost decreases. Thus, the objective is to select n, the
service life, so as to minimize

$$AC(n) = I/n + 1/n \sum_{j=1}^{n} c_j$$

where

AC(n) = Average cost per period over n periods
I   = Initial investment in the asset
c_j = Sum of operation and maintenance costs in
       period j

The concept of economic service life is graphically illustrated in Figure 2. As the figure demonstrates, beyond the service life n, it is no longer economically desirable to retain an asset, since the average cost per period begins to increase. More complex replacement models may include technological improvement, maintenance, taxes, an interest rate, and/or budget, warehouse, or repair personnel constraints. These models could have either a finite or infinite planning horizon and be either deterministic or stochastic with respect to cost parameters. Cost parameters include initial cost (of an end item), salvage value (of an end item), procurements costs (administrative costs incurred each time a procurement of an end item occurs), repair costs (includes labor, transportation and overhead costs that are incurred, on the average, each time an end item is serviced by a repair facility), shortage cost (cost incurred when there are not enough end items in operation to satisfy the demand), and normal operation and maintenance costs.

In the general equipment replacement problem, a finite planning horizon may be partitioned into stages in which the item deteriorates toward a final stage where it is no longer economically or operationally feasible to continue to repair the item or the item experiences fatal failure. The stages represent discrete points in time where decisions are to be made. There are two possible states of equipment conditions at the start of a period, either good or failed. Also, the
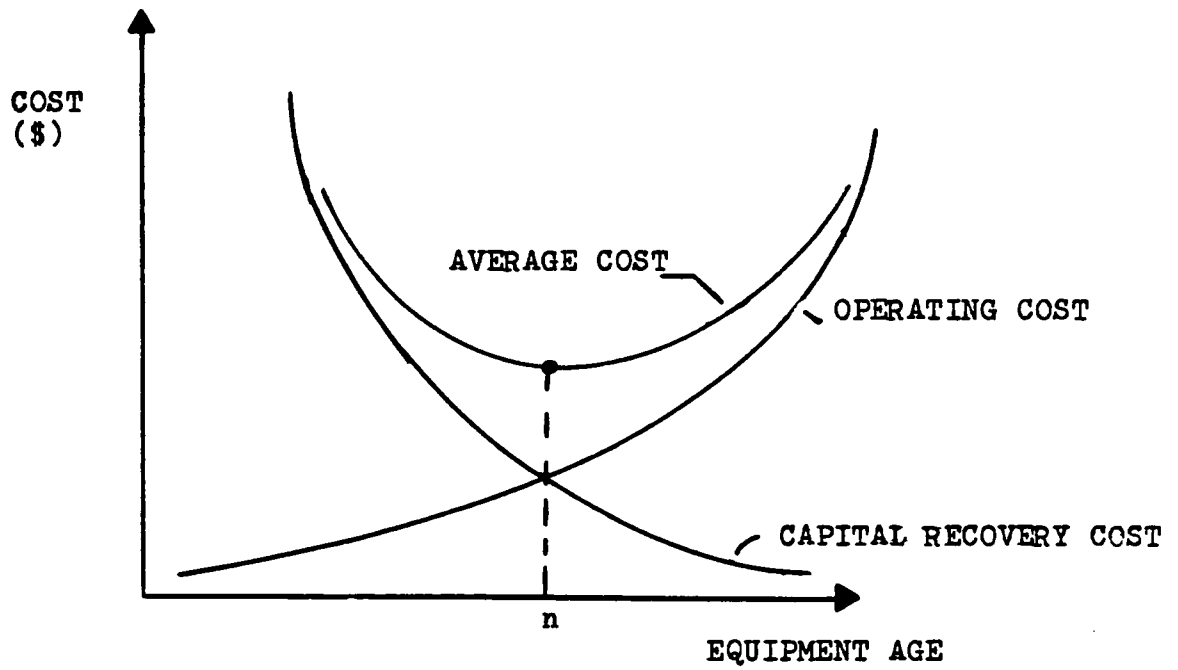
Figure 2. Average Cost Per Period.

equipment condition at the end of the period is either good or failed. Probabilities of occurrence/non-occurrence are attached to these states of equipment conditions. Decision actions involve the repair or replacement of end items. Decision variables are the number of end items to replace and the number of end items to repair. Finally, there are also probabilities that the equipment will go from one state to another state if a certain decision is taken. For example, if the decision is made to repair an end item that has failed, the probability that the item will go from state "failed" to state "good" may be .92. This probability is the item's state transition probability. The system objective may be to minimize total equipment costs subject to budget and repair capacity constraints.

This multi-stage deterioration process is very amenable to a dynamic programming (DP) solution methodology and the principle of optimality. The principle of optimality states that "an optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."[6] In other words, the principle of optimality states that an optimal policy or decision strategy consists of optimal subpolicies. As Frisch

---

[6]   Richard E. Bellman and Stuart E. Dreyfus, _Applied Dynamic Programming_ , Princeton, NJ: Princeton University Press, 1962, p. 15.

observes, "as soon as (1) the quality of a system and (2) the mode of fielding the system (are) determined, all logistic requirements are given."[7] Frisch defines quality as "the deterioration of performance over time, measured against the design performance of the new product."[8] Mode of fielding refers to alternative procurement policies.

In the dynamic programming approach, the output from one stage becomes the input to the next stage. By deciding upon the "best thing to do" in period 1, the decision maker determines the logistics requirements for subsequent periods. This stagewise evaluation of end items depends on the item age and the current operational status of the equipment. In the case of Markovian deterioration, it is only necessary to know the present state of an item in order to forecast future states. For the case of approximate Markovian deterioration, it is necessary to know both item age and current operational status of the equipment in order to forecast future operational performance. The return function factors are the costs associated with either the repair or replace decision. For example, if the decision is made to replace an incumbent asset, then the relevant costs are the purchase price, salvage value, and the operating and maintenance costs for the new equipment during that period. Dynamic programming has

---

[7]   Frisch, p. 467.

[8]   Ibid., p. 468.

the flexibility to incorporate budget or repair capacity constraints by suppressing a repair/replace alternative and continuing along a sub-optimal path. The penalty cost of doing so can be readily computed. Furthermore, dynamic programming offers a ready made sensitivity analysis, since the DP approach allows parametric variations. Also, dynamic programming is adaptive in that this solution methodology can respond to changes in the environment.

Essentially, in the multi-stream replacement problem, the streams are initially disaggregated and later merged to determine optimal system performance. The dynamic programming approach is applied to each individual stream to determine the best repair/replacement strategy for that particular stream or grouping of end items. This decomposition of the multi-stream replacement problem converts a n-dimensional problem into n-single dimensional problems. Moreover, by taking cognizance of the special structure of the problem, it is also possible to use less than the entire data horizon, or the full number of periods, to obtain optimal decision strategies. This concept is referred to as the planning horizon theorem, and is discussed in more detail in the chapter, "A General Modeling Approach".

Multi-stream production/inventory systems possess unique problems concerning the demand process, multi-criteria optimization, shortages, computational requirements, and model implementation. Different echelons or levels may exist that

involve two or more interrelated activities such as mainte-
nance or transportation. The demand may be either
deterministic or stochastic at different levels in the sys-
tem. Moreover, given that certain physical (repair capacity)
and non-physical (budget) constraints exist, system optimal-
ity may be difficult to achieve. Shortages undermine system
availability and, in a military context, weaken national de-
fense. Note that a system refers to an end item and could
be either an aircraft carrier, a tug, a fighter jet, a sub-
marine, an automobile, radar or sonar equipment, etc. A
network of activities or echelons involves repair facilities,
field sites, as well as the vehicles used to transport end
items between activities.

Furthermore, the complex nature of the multi-stream
production/inventory problem requires the assistance of com-
puters with considerable memory capabilities, since solution
methodologies often involve a multi-level multi-variable dy-
namic program. Finally inadequate communication at the
strategic and tactical or field levels hinders model imple-
mentation and results in poor utilization of supporting re-
sources. Thus, failure to make timely replacements and
incorrect choices of repair mode increase the life cycle cost
of a logistics system.

Consequently, the development of a logistics model for a
multi-stream production/inventory system that can be easily
implemented by practitioners represents a significant advance

I.   Introduction   17

in logistics modeling. This new model needs to accommodate both stochastic and/or deterministic demand; a budget constraint; repair capacity constraint; discounting; both constant and non-constant hazard models; technological improvement; and model implementation issues. Early equipment replacement models assumed that equipment would be replaced with like equipment. However, it is unrealistic to assume that technologically improved models will not be developed that may have lower purchase cost, lower operating cost, greater production capacity, operate more efficiently, etc. For example, as a digital computer ages it can no longer satisfy increased demands. Although the purchase cost and installation cost of a new computer are high, there comes a time when the benefits from the decrease in operating costs and from the increase in productivity outweigh the initial costs of the "challenger" equipment. Implementation issues involve providing guidelines for model interfacing at both the strategic and tactical or field levels to ensure effective organizational communication.

The implementation of such a logistics model offers significant benefits. For example, in 1968, 52% of the total investment in spare parts by the Air Force was in repairable items, which at that time amounted to ten billion dollars.[9]

---

[9]   Steven Nahmias, "Managing Repairable Item Inventory Systems: A Review", Multi-Level Production/Inventory Control Systems: Theory and Practice ,edited by L.B.

By 1975, the percentage had risen to about 65%.[19] Therefore, the development and implementation of a Dynamic Repair/Replace Population Model (DRRPM) for system repair/replacement is an attempt to assist decision makers with assuring adequate system availability while addressing life cycle cost reduction and efficient resource utilization.

Schwarz, TIMS Studies in the Management Sciences, North-Holland, Amsterdam, Vol. 16, 1981, p. 253.

[19] Ibid., p. 253.

1.2 Research Objective

The primary objective of this research is to develop a methodology for determination of feasible strategies for the repair/replace decision. A generalized methodology for supporting repair/replacement decisions attempts to ensure system availability and strives to lower procurement costs associated with logistic support. This logistics model is programmed on a mainframe computer and is interactive in nature.

The model is able to facilitate evaluation of repair/replacement strategies with respect to total life cycle costs of a logistics system. The solution methodology accommodates both stochastic and/or deterministic demand; a budget constraint; repair capacity constraint; various levels of repair; discounting; both constant and non-constant hazard models; technological improvement; and organizational implementation issues.

Therefore, the research objectives can be summarized into three major classifications. These categories are:

1. to determine minimal information requirements necessary to support the repair/replace decision by
    a. analyzing the quantity, source, quality, and structure of available data (separation of physical and non-physical constraints)
    b. developing guidelines for constructing the Dynamic Repair/Replace Population Model (DRRPM)

data base (i.e. what cost inputs are required, procedures for determining equipment failure distributions and state transition probabilities, etc.)

2. to establish a generalized modeling strategy to evaluate the impact of alternative replacement intervals and repair strategies within logistics systems by

   a. developing a computerized model supporting the repair/replace decision for mainframe implementation (linkage of the physical system and equipment failure characteristics with cost data that reflects an anticipated percentage improvement in technology)

   b. providing guidelines for interfacing model implementation at both the strategic and tactical or field levels (model output should reflect percentage improvement in repair service, availability, etc. that can be readily translated into monetary units at any level in the organization)

3. to determine guidelines for implementation of the Dynamic Repiar/Replace Population Model (DRRPM) for a variety of systems by

a. providing extensive model documentation
    that explains how to perform sensitivity
    analysis

b. demonstrating the Dynamic Repair/Replace
    Population Model (DRRPM) with a realistic
    case study

The operations impact of a generalized methodology for
supporting the repair/replace decision and mode of repair is
to provide opportunities for a more efficient use of organ-
izational resources such as capital and repair facilities.
The systematic allocation of resources aids in minimizing
life cycle costs while assuring that support requirements for
a system (end item) are met.

1.3 Overview of this Dissertation

The following five chapters are included in this research document: Literature Review, A General Modeling Approach, Population Model Implementation, Population Sensitivity Analyses, and Further Remarks. The Literature Review is subdivided into discussions on durable equipment models and "sudden failure" models. A taxonomy of replacement/maintenance models is developed that is based on eight factors. The contributions of this research to logistics modeling are also elucidated. Chapter III focuses on the modeling approach. The basic features of the dynamic programming solution methodology are discussed along with modeling assumptions. A mathematical model with technology effects is eventually developed and demonstrated via a numerical example that analyzes a two stream multi-item multi-repair problem. A conceptual model of multi-stream repair activity is also presented.

Chapter IV, "Population Model Implementation", presents a description of the software package "A Dynamic Repair/Replace Population Model", or DRRPM, that is developed to support the modeling approach. DRRPM is explained via flowcharts and other grpahical aids. The computer model is demonstrated with data from the U.S. Navy's Side Loadable Warping Tug (SLWT) in Chapter V, "Population Sensitivity Analyses". The results of a case study on the pump system for the SLWT are presented. Ten different scenarios are then

developed that involve both single- and multi-parametric variations of base case inputs. The intent of this chapter is to demonstrate the multi-faceted features of DRRPM and how the computer model can assist decision makers with the determination of feasible repair/replace policies. Finally, the dissertation is summarized, research conclusions are presented in concise form, recommendations for model embellishment are addressed, and areas for future research are highlighted. System documentation (i.e. Program Operator's Manual) is included in Appendix I and explains how to use the software package, "A Dynamic Repair/Replace Population Model", that is used to implement the modeling approach that is presented in this dissertation. The results of the base case study on the SLWT and subsequent sensitivity analyses are included in Appendix II (Appendices A.1 - A.11). The source code for DRRPM is listed in Appendix III (Appendices B.1 - B.5).

II. LITERATURE REVIEW

The literature on the equipment replacement problem is quite diverse and extensive. A general treatment of replacement analysis is presented in White, Agee, and Case (134), Thuesen and Fabrycky (125), de la Mare (28), and Morris (82). Operations research texts by Churchman, Ackoff, and Arnoff (22), Fabrycky, Ghare, and Torgersen (38), and Phillips, Ravindran, and Solberg (89) also discuss equipment replacement. Textbooks by Jardine (56), Jorgenson, McCall, and Radner (61), Smith (118), and Dean (27), attempt unified treatments of replacement modeling. Jardine (57) presents a compilation of Operations Research techniques that could be used in a maintenance management program. Moreover, Salvendy (103) includes a chapter on replacement analysis as well as a chapter on distribution and logistics that briefly introduces the topics of demand variations, source constraints, delay cost, and route considerations.

A number of survey articles appear in the literature. McCall (78) presents a review of various equipment maintenance policies up to 1965. Pierskalla and Voelker (90) present a well researched article on maintenance models after 1965. Finally, Sherif and Smith (111) expound upon Pierskalla and Voelker's work and review optimal maintenance models since the 1976 survey. Together, this trilogy of

survey articles provides a comprehensive overview of economic/maintenance models to date.

As the literature reveals, numerous economic replacement models have been developed through the years. Consequently, there are a variety of ways to classify equipment replacement models. A multi-dimensional grid concept that incorporates the suggestions of Pierskalla and Voelker (90) could be developed with the following axes:

(a) states of the system - includes deterioration level, number of spare parts, number of units in service, number of state variables.

(b) decision action(s) - include(s) repair, replacement, opportunistic replacement, spare part replacement, continuous monitoring, discrete inspections, destructive inspections.

(c) planning horizon - either finite or infinite, discrete or continuous.

(d) system knowledge - involves either complete or partial knowledge about unknown costs, unknown failure distributions, etc.

(e) life pattern - includes replacement of items that deteriorate over time versus items that fail suddenly.

(f) system objective - either cost minimization or profit maximization.

(g) solution method - includes linear programming, dynamic programming, decision theory, generalized Lagrange multipliers, queueing theory, etc.

(h) replacement model - either stochastic or deterministic with respect to model parameters, and may include the factor(s) of obsolescence (technological improvement), salvage value, alternative procurement and maintenance policies, interest rate and/or taxes. More-

over, multi-echelon or multi-level models
involve a hierarchy of repair facilities.

Thus, the various economic replacement models could be placed in the appropriate cell of the grid. This systematic placement of models would then represent a taxonomy of replacement models. Although it is fairly easy to conceive of such a multi-dimensional grid, it is quite another matter to graphically represent the grid since there are a multitude of possible combinations.

In the review of the literature, only one actual attempt at a systematic classification of replacement models is discovered. Reisman and Buffa (96) develop a mathematical model that describes a general case in equipment investment policy. Their model reduces to their present worth all expenses (E) and receipts (R) involved in the purchase and operation of a chain (C) of equipment with varying initial purchase prices (B), life spans, salvage values (S), and income and cost functions. Thus, the CERBS case is the most general situation, since it considers a chain or succession of equipment while each item in the chain has a unique purchase price, salvage value, life span, and individual operating and expense functions. Less complicated cases, for example, ERBS, where alternative items of equipment are not to be succeeded, all derive from the CERBS case. Reisman and Buffa develop a graphical taxonomy for the 31 conceivable subgroups of CERBS. The authors then categorize various historical models ac-

cording to their scheme. Although this taxonomy does present a systematic approach to the classification of replacement models, CERBS only considers a subset of the factors presented above in (a)-(h).

Therefore, a more realistic taxonomy of replacement/maintenance models that is based on the multidimensional grid concept is subsequently developed. In this taxonomy, a broad distinction is made between the <u>life span</u> characteristic of replacement/maintenance models. Replacement problems generally fall into two categories:

(1) replacement of items that deteriorate with time (durable equipment models), and

(2) replacement of items that fail suddenly (for example, light bulbs).

For purposes of this discussion, replacement/maintenance models will be referred to as just replacement models.

Within this broad classification, replacement models may be either stochastic or deterministic with respect to model parameters and could have either a finite or infinite horizon. There could be uncertain or certain system knowledge. Thus, there are several subsections within the main classifications.

The remainder of Chapter 2 expounds upon this multidimensional grid concept. First, the durable equipment replacement models are analyzed according to the elements of

the taxonomy: states of the system, decision actions, planning horizon, system knowledge, system objective, solution methods, and replacement models. Second, "sudden failure" replacement models are discussed in the context of the taxonomy scheme. Finally, the anticipated contributions of this research to logistics modeling are presented.

2.1 Durable Equipment Replacement Models

In this section, models are reviewed where the deterioration may be described as "normal wear and tear" (i.e. the equipment is durable). Also, at discrete points in time, a decision is made to repair, replace or restock the unit(s). System knowledge concerning costs or technological improvements may be complete or incomplete. With durable equipment problems, the system objective may be either cost minimization or profit maximization, and a variety of solution methodologies may be employed. Technological improvement, maintenance, salvage value, and/or taxes may or may not be considered. Therefore, in the subsequent sections, durable equipment replacement models are analyzed according to the elements of the multi-dimensional grid concept.

2.1.1 States of the System

With durable equipment replacement problems, most of the models are discrete time models in that a unit (or units) is monitored and a decision is made to repair, replace, and/or restock the unit(s). This discrete time process can be modeled using Markov decision models in which the state of the system is described by the level of deterioration and/or the number of spare parts available in inventory. Thus, at each state in a finite period there is a probability of equipment failure and a probability that no failure will occur. The Markov process is an excellent way to describe this birth-

death process as long as units fail randomly. The state by state evaluation of the unit life cycle possesses the Markov property, since it is only necessary to know the present state of an item in order to forecast future states. Thus, a Markov decision process is a stochastic sequential process.

The theory of finite Markov chains is discussed in Kemeny and Snell (64), and Jorgenson, McCall, and Radner (61), Howard (54), Bellman (7), Jardine (56), and White (133) discuss Markov processes in the context of the dynamic programming solution methodology. Howard (54) presents the classical automobile replacement problem in Chapter 5 of his book. Hastings (53) develops a modification of Howard's policy improvement routine for Markov decision problems, and also uses a dynamic programming formulation for a basic equipment replacement problem. Hastings (52) discusses the replacement problem more extensively in his book Dynamic Programming With Management Applications. Sasieni (104) studies the Markov chain process involved in the manufacture of rubber tires, but uses linear programming to solve the problem. Dreyfus (34) indicates that Sasieni oversimplifies the problem, and uses dynamic programming to optimally solve this replacement problem. Mine and Osaki (81) present several mathematical theories and techniques for Markov decision processes that include both linear programming and dynamic programming approaches.

There are numerous articles in the literature that discuss Markovian deterioration. Kolesar (67) develops a minimum cost replacement model under Markovian deterioration that uses control limit replacement rules. Rosenfield (97, 98) presents a model for Markovian deterioration in a system with uncertainty. For example, the precise state of the system may not be known with certainty, and an inspection cost is incurred to determine the precise system state. In this situation, the state is defined to be partially observable. Smallwood and Sondik (117) develop an algorithm for the optimal control of partially observable, finite-Markov processes. Weiss (132) observes that, in a semi-Markov process, the succession of states cannot be characterized by a single step Markov process. For example, a repair must be logically preceded by non-operability and inspection. Thus, he defines a set of composite states such as inspection-repair-operation or inspection-operation that may be described by a Markov process.

The literature on the Markov chain approach is quite diverse as model variations depend on the assumptions concerning planning horizon, system knowledge, system objectives, system constraints, and the number of units. Derman (29) discusses Markovian deterioration where the probabilities of replacements through undesirable states are bounded by prescribed numbers. In another paper, Derman (30) considers the problems in the optimal control of dynamic systems. In these

dynamic systems, the sequence of observed states is a stochastic process that depends upon the the sequence of decisions, since the decisions determine the probability laws that operate on the system. He uses linear programming and Markov chain theory in his solution methodology. Klein (65) also uses linear programming to develop inspection, maintenance, and replacement policies under Markovian deterioration. Sackrowitz and Samuel-Cahn (102) develop optimal inspection procedures for Markov chains. Ross (101) presents a Markovian replacement model that incorporates the stocking of spare parts. Moreover, Ross (100) also discusses a treatment of the quality control function under Markovian deterioration and presents a method for the estimation of transition probabilities from past records of the production process. Satia and Lave (105) also study Markovian decision processes where the transition probabilities that correspond to alternative decisions are not known with certainty. These authors use Max-Max and Max-Min optimal policies as well as a Bayesian formulation in two alternative replacement problem statements.

Truelove (127) defines strategic reliability to be the product of equipment availability and reliability over a fixed period of time. He then derives an approximation to the optimal solution for strategic reliability. Flehinger (40) defines a marginal testing policy as replacing all failure components as soon as they malfunction and, at regu-

lar intervals, conducting a test to locate those components that are still operating satisfactorily but that are expected to fail in the near future. She then examines the effects of marginal testing on system reliability. The Frisch multi-stream replacement model (41) uses a concept of nested Markov chains to model a population of repairable items. This model is discussed in more detail in the section "Replacement Models". Finally, Denardo and Fox (31) also examine multi-chain Markov decision processes.

2.1.2 Decision Actions

In durable equipment replacement analysis, decision actions involve repair, replacement, opportunistic replacement, spare part replacement, continuous monitoring, discrete inspections, and/or destructive inspections. With an opportunistic replacement policy, it may be "opportunistic" to perform two concurrent repairs rather than two separate repairs and exploit economies of scale. System uncertainty and the multitude of alternative decision actions may confound the decision maker. Martin (74) develops an early management decision game involving equipment replacement on the basis of incomplete, uncertain, and perhaps, inaccurate information. Chernoff and Moses (21), and White, Agee, and Case (134) propose a matrix decision model for considering future "state versus alternative" combinations. Probabilities could be assigned to each state of nature to represent

the uncertainty of occurrence. Thus, the matrix decision model represents a valuable organizational tool for the decision maker when selecting among equipment alternatives in the face of uncertainty.

2.1.3 Planning Horizon

The planning horizon for durable equipment models may be continuous or discrete, finite or infinite. Earlier replacement models by Hotelling (see Rapp (95)), and Preinreich (92) use continuous time with a finite horizon. Jones (59) develops an after-tax equipment replacement model that accommodates a range of planning horizons. Leung (71) presents both one-period and multi-period production function based replacement models. Bellman (8) and Dreyfus (33) use a finite horizon with discrete periods in their applications of dynamic programming to the durable equipment problem. Finally, Sethi and Chand (109) distinguish between a forecast horizon and a planning horizon. With a forecast horizon, it is not necessary to know the forecast for the entire horizon in order to determine the optimal first period replacement decision.

2.1.4 System Knowledge

Uncertainty about the future is the primary source of difficulty in equipment replacement problems. Often, in a stochastic environment, the decision maker has imperfect

system knowledge. Meyer (80) discusses the durable equipment problem with stochastic technological change and/or maintenance costs. Mayer (76) presents a synopsis of the problems encountered in the application of replacement theory. These problems are due to uncertainty concerning awareness of equipment investment opportunities, initial investment cost, technology change, equipment service life, salvage life, operation and maintenance costs, taxes, and depreciation schedules. Also, equipment selection alternatives can be based on the required investment, equipment service life, salvage value, minimum attractive rate-of-return, annual cost, or present worth of all revenues and receipts. Moreover, there may be unequal time periods of analysis which further complicate equipment replacement. Mayer suggests that all relevant factors be expressed in quantitative terms and that a post-audit be performed to determine whether anticipated benefits have been realized or whether action must be initiated to eliminate obstacles to the realization of anticipated benefits.

2.1.5 System Objective

The system objective in durable equipment replacement models may be either cost minimization or profit maximization. Hotelling (see Rapp (95)), Preinreich (92), Smith (118), Jones (59), Leung (71), Bellman (7), and Dreyfus (33) all use revenue, profit, or future worth maximization

approaches. Terborgh (124) and Clapham (24) use cost min-
imization approaches. Agee and Tanchoco (2) present a list
of direct, indirect, and intangible cost factors for the de-
cision maker to consider in his or her equipment replacement
analysis. Direct costs involve raw materials, equipment ac-
quisition cost, operating costs, etc. Indirect costs involve
general utilities, space utilization, inventory value of
spare parts, etc. Intangible cost factors include compat-
ibility with existing equipment, flexibility for future
change, operator morale, etc. Verheyen (128) gives an eco-
nomic interpretation of replacement models and concludes that
the moment of replacement is always determined when marginal
replacement costs are equal to the marginal costs of post-
poned replacement. However, uncertain system knowledge about
these various costs complicates the determination of the op-
timal moment of replacement.

2.1.6 <u>Solution Methods</u>

Both Klein and Rosenberg (66) and Sherif and Smith (118)
highlight durable equipment replacement problems and appro-
priate solution methods in their survey papers. Besides the
classical differential calculus approaches, numerous oper-
ations research models for the durable equipment replacement
problem appear in the literature. Bellman (7) was the first
to introduce the use of discrete dynamic programming to de-
termine the optimal service life of equipment. The theory

of dynamic programming (DP) is discussed in Bellman and Dreyfus (9), Cooper and Cooper (25), Dreyfus and Law (35), White (133), Hadley (49), Hastings (52), Kaufmann and Cruon (63), and Larson and Casti (68, 69). Various sections in these textbooks consider the classical equipment replacement problem. Articles by Bellman (8), Dreyfus (33, 37), and Schwartz, Scheler, and Cooper (107) further examine the DP approach to replacement analysis. Bellman considers two cases, one including and the other excluding technological change. Sasieni (104) uses a linear programming approach to a stochastic replacement problem. However, Dreyfus (34) indicates that Sasieni's method is oversimplified and that the stochastic replacement problem can be optimally solved using a dynamic programming formulation. Schwartz, et. al (107) present an article on the use of dynamic programming to create optimal repair and replace policies for naval aircraft. These authors use regression analysis to obtain estimates of the various cost functions in this realistic problem. Wagner (130) examines quantity discounts and uses a forward algorithm that incorporates cost curves that have non-decreasing marginal costs as a function of production output ("decreasing returns to scale").

Thompson and George (126) discuss a dynamic, continuous time model of a firm that encompasses operations and investments. Their model uses results from control theory in an attempt to maximize the discounted value of net profits from

production less the costs of interest and new capacity over a finite horizon plus the discounted value of capacity at the end of the period. Sethi and Chand (109) use planning horizon procedures to demonstrate that the forecast for the entire horizon is not necessary in order to determine the optimal first period replacement decision. The concept of a forecast horizon maintains that there exists an horizon T such that the optimal replacement decision for the first item of equipment (new or existing) based on the forecast of equipment technology until period T, remains optimal for any longer (than T) horizon, as well as for the infinite horizon problem.

Queueing theory can also be employed as an effective solution methodology in replacement analysis. Nahamias (85) gives a brief overview of spares provisioning using queueing models. The general objective of queueing models is to determine the length of the repair queue and the amount of time spent in the repair facility. With queueing theory, the analyst can determine the effects of repair/replace decisions on the operation of repair channels. Gross and Harris (46) use queueing theory to develop relationships for the failure rate and the rate at which units leave a repair facility. A modified version of their results is presented below:

      M = number of machines
      S = number of spares
      n = state of the system (number of machines in the repair queue)
      r = number of servers available (repairmen or

repair crews)

λ_n = failure rate when the state of the system is n

$$\lambda_n = \begin{bmatrix} M\lambda & 0 \le n < S \\ (M-n+S) & S \le n < M+S \end{bmatrix}$$

μ_n =   rate at which units leave the facility
        when the state of the system is n

$$\mu_n = \begin{bmatrix} n\mu & 0 \le n < r \\ r\mu & r \le n \end{bmatrix}$$

The Gross and Harris model is only valid when the rate of failure and time to repair are exponentially distributed with parameters λ and μ, respectively.

Taylor and Jackson (121) present the classical work on the application of a queueing repair model to the problem of determining suitable levels of spares inventories. These authors examine the problem of determining the number of spare engines required to maintain a fleet of aircraft at a certain efficiency level. They use a birth-death analysis and assume that when fewer than M machines are operational, all machines cease to operate. Taylor and Jackson derive a stationary distribution of the number of machines in the repair queue, and examine the probability that a total breakdown in the system will occur as a function of the number of spare machines.

Gross, Kahn, and Marsh (48) use infinite queueing theory to assist in the determination of an adequate number of spares and repair channels (servers) for replacing and re-

pairing components that randomly fail. Gross, et. al. assume that the failed components are replaced by spares (if available) and once repaired, in turn become spares. These authors use a multi-year horizon that allows for growth in component population size and component reliability. Their model objective is to minimize costs subject to an availability constraint. Availability is defined as the probability that the spares inventory is not empty given that a failure is about to occur. The relevant costs are: purchase cost of spares, purchase cost of service channel, repair cost, and investment cost in component reliability improvement program. In their modeling approach, the failure rate and time to repair are assumed to be exponentially distributed. Moreover, expected mean time between failure (MTBF) and mean time to repair (MTTR) are used in conjunction with a series queue to determine the number in repair. Instead of using a complicated integer-nonlinear program, Gross, et. al. (48) use a heuristic that only considers the purchase cost of spares and the purchase cost of service channels. The other costs are assumed to be negligible in comparison with these two costs. These authors use their results to provision servers and spares for a fleet of marine ship turbines on a year by year basis.

Gross and Ince (47) extend the classical machine repair model to allow for more than one stage in the repair phase. The multi-stage problem may involve the removal of a failed

machine, transportation to a repair facility, the repair it-
self, and transportation from the repair facility. These
authors assume stage 1 of the cyclic queue is with the ma-
chine in the operating phase. Since the authors model a cy-
clic queue, there is no assumption of an infinite input of
units. The decision variables in their model are the number
of repair channels and the total number of units in the pop-
ulation. The system objective is to adjust the decision
variables to achieve a desired availability of spares. Gross
and Ince derive both an exact model and a heuristic, and find
that the heuristic is computationally more efficient when a
higher availability is required.

Fabrycky, Malmborg, Moore, and Brammer (39) use finite
queueing theory to model repairable equipment population
systems (REPS). The decision variables in this model are the
population size, the age of the units, and the number of re-
pair channels. The REPS model also evaluates the case when
the MTTR and MTBF are design variables. Fabrycky, et.al.,
develop develop a single indenture, single echelon model that
assumes that the time between repairs and the service time
are exponentially distributed. The relevant costs in the
REPS model are:

> (1) population equivalent annual cost -considers
>   acquisition cost, salvage value, and interest
>   rate
>
> (2) repair facility annual equivalent cost -
>   considers cost of owning and operating a repair
>   facility by examining the initial cost of

the facility by channel, the salvage value
of the facility per channel, and the yearly
administrative, labor, and overhead cost
per channel

(3)   out of operation or down cost - considers
the cost of not having enough operable
units to meet demand.

Fabrycky, et.al., proceed to search for an optimum system
design through varying the design variables of MTBF and MTTR
and examining the resultant total system cost.   Also, the
service facility design is evaluated as a trade-off of the
waiting or out of operation cost against the cost of an ad-
ditional service channel.   The REPS model is discussed in
more detail inChapter 6, "Further Remarks".

Decision theory can also be utilized in the context of a
dynamic programming solution methodology for the equipment
replacement problem.   The basic concepts of decision theory
and utility theory are discussed in Bell, Keeney, and Raiffa
(6), Bunn (16), and Lifson (72).   The repair/replace decision
is a multi-criteria optimization problem that frequently in-
volves conflicting objectives.   Jones (58) presents a micro-
computer based package that facilitates the assessment of
multi-attribute value functions.   This package contains pro-
cedures to test independence conditions and to estimate pa-
rameters.   Both the classical approach (mid-value splitting
technique) of deriving the value curve and then finding the
scaling constants, and Edward's SMART technique of first
weighting the attributes and then deriving the value curve,

are programmed. Such a package could assist the decision maker with the determination of the expected value or the utility assessment of a particular decision alternative. Hence, the literature indicates a variety of solution methods - dynamic programming, linear programming, control theory, planning horizon theory, queueing theory, decision theory - for the durable equipment replacement problem.

2.1.7 <u>Replacement Models</u>

A survey of the literature indicates a variety of durable equipment replacement models. Thus, this categorization in the taxonomy is subdivided into a discussion of an early model, a reinvestment model, and models that incorporate technological change, maintenance, opportunistic replace-ment, and/or taxes. Moreover, multi-echelon or multi-level models that involve a hierarchy of repair facilities are also examined. Finally, the Frisch multi-stream replacement model (41) is discussed in detail. Thus, the intent of this sec-tion is to sketch the historical development of logistics modeling. As technological sophistication increases, logis-tics models become much more complex. Consequently, to fa-cilitate the discussion on replacement models, this categorization in the taxonomy is divided into the following sections:

A. Two Early Models

A. Two Early Models

One of the earliest economic replacement models was proposed by Hotelling in 1925 and is presented in Rapp (82). Hotelling's model can be formulated as follows:

$$\text{MAX} \quad B(T)$$
$$T$$

where

$$B(T) = \int_{0}^{T} Q(t)e^{-jt}\, dt + S(T)e^{-jt} - I$$

    $B(T)$ = present value of the payments in the
         investment at time T

    $Q(t)$ = net operating receipts at time t

      T = service life T of the investment

    $S(T)$ = salvage value at time T

      j = discount rate

      I = initial investment

(Rapp, p. I-2)

Hotelling assumes deterministic maintenance expenses, continuous time, complete or certain information about the future, a stationary economy, and a finite planning horizon without reinvestments. His system objective is to determine the service life T that maximizes the present value of the payments in the investment.

Preinreich (92) developed a constant chain approach to the replacement problem in 1940. The "constant chain" approach assumes that every reinvestment must be equal to the initial investment. This assumption of "equal links" in the replacement chain is necessary in order to simplify the number of equations. Thus, Rapp (95) presents the following modified version of Preinreich's model:

$$\text{MAX}_{T} \quad B(T)$$

where

$$B(T) = \sum_{v=0}^{\infty} e^{-jvt} \int_{0}^{T} Q(t)e^{-jt} + S(T)e^{-jt} - I$$

(Rapp, p. I-3)

Note: notation (except v) is the same as in Hotelling's model.

Similar to Hotelling's model, Preinreich's model assumes deterministic costs, continuous time, complete or certain information about the future, and no technological improvements. The system objective is to maximize the present value of the payments in the investment.

B. Technological Change, Taxes, Maintenance, Opportunistic Policies

A review of the literature indicates a variety of durable equipment replacement models concerning obsolescence (technological improvement), interest rate, salvage value, maintenance, and/or taxes. These models could be either stochastic or deterministic with respect to system parameters.

While he was Research Director of the Machinery and Allied Products Institute (MAPI) in 1949, Terborgh (124) developed a durable equipment model that accommodated technological change. The system objective of Terborgh's MAPI method is cost minimization. Terborgh assumes constant revenue and constant costs. These constant costs consisted of the capital cost of investment and the opportunity costs or "operating inferiority" of not using the most modern equipment. The system objective is thus to determine the service life of the investment such that the average annual costs are minimized. These minimized costs are what Terborgh terms "adverse minimum" for future investments. Terborgh further assumes that "operating inferiority" is deterministic or increases linearly over time. However, Terborgh's model does attempt to account for technological change and increasing operation and maintenance costs. Rapp (95) summarizes Terborgh's model as follows:

"adverse minimum" cost factors:

(1) $\dfrac{\alpha(T-1)}{2}$ = "operating inferiority" or opportunity costs of not using the latest equipment, expressed in terms of the average for T years where α represents the change in "operating inferiority" (α constant)

(2) $\dfrac{I}{T}$ = average investment cost for T years, where interest rate is not taken into account (I=investment cost)

(3) $\dfrac{jI}{2}$ = opportunity cost for capital used which has the value I at time=0 and the value zero after T years (j=discount rate)

Note: If salvage value (S) is considered, I is replaced by I-S in (2) and by I+S in (3).

Therefore, the average annual cost w is given by

$$w = \dfrac{\alpha(T-1)}{2} + \dfrac{I}{T} + \dfrac{jI}{2} \qquad (4)$$

and the "adverse minimum" is obtained by determining the service life T that minimizes w. By differentiating (4) with respect to T and setting the derivative equal to 0, we obtain

$$T = \dfrac{\sqrt{2I}}{\alpha} \qquad (5)$$

Thus, after substituting (5) in (4), the "adverse minimum" is

$$w = \sqrt{2I\alpha} + \dfrac{jI-\alpha}{2} \qquad (6)$$

(Rapp. pp. IV-14 - IV-15)

Terborgh's approach is presented in detail because it represents the first mathematical attempt to incorporate

technological change in replacement models. Terborgh (122, 123) extended his model in 1958 to consider taxes and presented an improved MAPI manual in 1967. Essentially, the MAPI method utilizes a series of charts to assist the analyst with investment computations. Meyer (80) expands the Terborgh model to incorporate a stochastic representation of technological change and/or maintenance costs. Jones (59) develops a replacement model for technological change that uses a future worth analysis, continuous discounting, discrete cash flows, a range of planning horizons, and incorporation of tax effects. Barr and Knight (5) examine the use of equipment operating characteristics to measure best-practice techniques in an attempt to analyze technological change in the durable goods industry. Leung (71) develops an equipment replacement model that incorporates input substitutions, expansion of output capacity, product-price volume relationship, and obsolescence and deterioration.

Smith (118) modifies the Preinreich model by relaxing the "constant chain" assumption. Smith assumes that operational income depends on the purchase time vT of new equipment. Rapp (95) presents the following version of Smith's durable equipment replacement model:

$$\underset{T}{\text{MAX}} \quad B(T)$$

where

$$B(T) = \sum_{v=0}^{\infty} e^{-vjT} \int_{0}^{T} Q(vT,t) e^{-jt} dt + e^{-jT} S(T) - I$$

and $Q(vT,t)$ = operating receipts at time t when the purchase date of the investment is vT

(Rapp, p. I-5)

Note: notation is the same as that used in Preinreich's model.

Thus, Smith observes that revenue will remain unaffected if the quantity and quality of production can be maintained as an asset deteriorates over time, and if cost reductions following from technical change do not lead to an alteration in the optimal output of a firm. Stapleton, Hemmings, and Scholefield (119) examine the effects of different kinds of technical change on the optimal life of assets. These authors hypothesize that a likely effect of technical progress is a lengthening of the optimal replacement cycle.

Clapham (24) develops a durable equipment replacement model that considers maintenance costs. Rapp (95) presents a modified version of Clapham's model as:

$$\underset{T}{\text{MIN}} \quad a(T)$$

where

$$a(T) = \frac{I}{T} + \frac{1}{T} \int_0^T f(t)dt$$

I=initial investment cost

T=service life

f(t)=maintenance expenditures at time t

(Rapp, I-6)

Thus, the system objective is to determine an optimal service life T that minimizes the initial investment cost and maintenance expenses.

Moreover, in a complex system with many units, the repair and/or replacement of one unit should be considered in relation to the other units. Opportunistic policies consider the interactions among units in that these policies exploit economies of scale in repair and/or replacement. In other words, two or more concurrent repairs may cost less than two separate repairs. Thus, when repairing one machine, it may be "opportunistic" to repair another machine at the same time. Radner and Jorgenson (94), and McCall (77) present a discussion of opportunistic replacement with continuous inspection. McCall concludes that the use of opportunistic policies facilitates inventory and maintenance management.

C. Multi-Echelon (Multi-Level) Replacement Models

Finally, the literature contains some informative articles on the multi-echelon replacement problem. The multi-echelon replacement problem involves a hierarchy of repair levels. For example, in the Navy's Level of Repair (LOR) system there are three levels of repair: an on-board ship repair, a dock (port) repair, and a central facility (depot) repair. Sherbrooke (11) introduces METRIC (Multi-Echelon Technique-for-Recoverable-Item-Control) - a mathematical model translated into a computer program that is capable of

determining base and depot stock levels for a group of recoverable items. METRIC is specifically designed for application at the weapon-system level, where a particular item may be demanded at several bases and the bases are supported by one central depot. Nark and Nair (86) develop a theory of multi-stage replacement strategies that is based on the grouping of units according to replacement cost and on the replacement of failures and of vacancies caused by the transfer of units operating in one stage to the proceeding stage. These authors contend that a multi-stage replacement strategy is more economical than a simple replacement strategy when there is a cost gradient in the replacement costs of items in the system (i.e. quantity discounts).

Porteus and Lansdowne (91) consider the multi-item, multi-location, multi-repair type supply and repair system. These authors present an optimal system design that consists of a provisioning of the number of spare parts for each item by location and specifying the expected repair times for each type of repair, by item and location. Their optimal design minimizes expected shortages within a budget constraint and includes procurement of spare parts and equipment and establishment of manpower levels for the repair facilities. Porteus and Lansdowne assume separable costs and use a Lagrangian approach to create an implementable algorithm for their model.

Zacks (136) develops a model for a two-echelon, multi-station inventory system. In his model, the higher echelon consists of a depot that procures parts from various manufacturers, and the lower echelon consists of several supporting ships (tender ships) for submarines. Zacks uses a cost structure that incorporates a penalty cost for shortages in his dynamic programming formulation of the problem.

Muckstadt (83) develops a model called MOD-METRIC, an extension of the METRIC model presented by Sherbrooke. He models a two-echelon system with two levels of parts (levels of indenture) - an assembly and its components. The model's objective is to compute spare part stock levels for both echelons and for the assembly and subassemblies that minimize expected backorders subject to an financial investment constraint. Muckstadt (83) demonstrates how MOD-METRIC can be used with the Air Force module repair concept to calculate spare engine and engine module stock levels. In another paper, Muckstadt (84) presents a model for a three-echelon, multi-item inventory system. This model is an extension of the two-echelon MOD-METRIC model. The modeled inventory system consists of a group of locations (bases) and a central depot, and a population of repairable items. The objective of the model is to determine the stock levels for the depot, for bases with maintenance centers, and for operating bases that minimize expected backorders for assembly subject to a financial constraint.

II. Literature Review   53

Finally, Graves and Keilson (45) present an "extended logistic system" that is defined as a well-designed configuration of equipment, modules, inventories, transportation, and repair and replacement facilities. Examples of "extended logistics systems" are a squadron of aircraft, a fleet of submarines, or a radar system. These authors maintain that complex, repairable systems have usually been designed using the tools of static inventory theory and reliability theory (steady state distributions). Graves and Keilson propose a methodology for the dynamic treatment of system behavior that uses persistence times or system failure times. These dynamic models can then incorporate real time data.

D. The Frisch Multi-Stream Replacement Model

Frisch (41) develops a conceptual model for a population of repairable items by using the concept of nested Markov chains (see Figure 1). The items are grouped into streams where each group has similar failure characteristics. Frisch uses a stationary Markov process (discrete time process).

> (A Markov process is stationary if the transition probability function depends only on the time difference,
>
> i.e. $P_{ij}^{n,n+1} = P_{ij}^{0,1} = P_{ij}$)

The Frisch model can be used to compute spare part requirements and assist the decision maker with the repair/replace alternative. Frisch utilizes two decision

variables in his model - quality and mode of fielding. He defines quality as "the deterioration of performance over time, measured against the design performance of the new product" (p. 468). Performance is defined as the output of a machine at its design point. Frisch defines mode of fielding as the method by which a population is built up. For example, various modes of fielding are:

> (1) Build the population at one time through one block procurement.
>
> (2) Build the population through uniform procurement amounts occurring at equal time intervals.
>
> (3) Build the population through decreasing procurement amounts occurring at equal time intervals.
>
> (4) Build the population through increasing procurement amounts occurring at equal time intervals.
>
> (5) Build the population strictly at the discretion of the user by procuring designated amounts at specified points in time.

Frisch also allows for varying the survival rate or the probability that an item will survive from one period to the next. After examining the effects of quality and mode of fielding, Frisch reports the following:

> (1) Low quality tends to promote constant replacement rates in the early stages of a system and hence there may be a low storage requirement.
>
> (2) High quality is detrimental to a stabilization and hence detrimental to economic replacement-production, and therefore requires a significant warehousing requirement.

Frisch proceeds to examine the effects of uncertainty on support requirements and on the repair/replace decision. He concludes that under complete certainty, a system should be repaired until it ceases to perform to standard. With uncertainty, a point is reached when the total system's life cycle cost can be reduced by a replacement rather than a repair. Frisch also demonstrates how his conceptual model may be used for a determination of the production rate of spare parts and/or spares. The demand for spares and/or spare parts is determined from the nested Markov chain concept, and a penalty cost can be associated with a shortage. Thus, one can evaluate the trade-off between a shortage cost and the cost saved by evening out the production of spare parts and/or spares. Moreover, one can also examine the trade-off of evening out procurement amounts versus production.

In his paper, Frisch presents his ideas for a logistics decision model. A flowchart of the decision process is presented is Figure 3.[11] Essentially, the modeling approach consists of two sub-models:

    (1)   Markov chain model calculates the physical behavior of the system - selected output from this submodel (capital cost, repair cost, shortage cost, inventory cost, total cost per period per stream) becomes the input for all future cost calculations

    (2)   Dynamic Programming model calculates cost inter-

---

[11]   Franz A.P. Frisch, "Mortality and Spareparts: A Conceptual Analysis", Proceedings of the 1983 Federal Acquisition Symposium , p. 479.

actions and supports the repair replace decision.

Thus, the proposed logistics decision model represents a comprehensive treatment of maintenance/replacement analysis. The output from the Markov chain sub-model could be isolated, since this information about the physical system is very valuable to the decision maker, or selected model output could serve as input to the Dynamic Programming sub-model. The Frisch multi-stream replacement model is very flexible in that it models a large population of different age groups and each stream in the Markov chain can have a different probability distribution of failure or different life expectancy.

Brammer (14) develops a microcomputer-based version of the Frisch Markov chain replacement model. Brammer's Maintenance Requirements Planning Model (MRPM) evaluates a population of repairable items where each end item is broken into repairable or replaceable components and then into subcomponents and so on until a spare part level is reached. This breakdown produces a maintenance tree. There is a maximum of 126 nodes that represent a major component and a family of subcomponents and spare parts (5 levels of indenture). Also, this package models alternative procurement policies, and different operating environments (support, combat, etc.).

Cost data requirements for the MRPM software include initial item cost, salvage value, procurement costs (adminis-

FEEDBACK

① DECISION
ABOUT
• MODE &
• QUALITY
OF ACQUISITION

DETERMINES THE
PHYSICAL BEHAVIOR·
OF THE ACQUIRED
POPULATION

② MODEL #1
NESTED MARKOV—
CHAIN MODEL
CALCULATES THE
PHYSICAL BEHAVIOR

THE OUTPUT OF
MODEL #1 IS THE
INPUT FOR ALL
COST CALCULATIONS

LIFE CYCLE COST
WAREHOUSING COST
TRAINING COST
ETC.

③ MODEL #2
DYNAMIC
PROGRAMMING
MODEL CALCULATES
COSTS AND
INTERACTIONS
OF COST

④ DECISION:
COST ACCEPTABLE

NO   IF YES:
IMPLEMENT

⑤ ACTION:
CHANCE DECISION

Figure 3.   Frisch Proposed Logistics Decision Model.

trative costs incurred each time an end item is procured), shortage costs, and interest rate. Various failure curves such as the uniform, exponential, normal, or bathtub functions are programmed into the package. If the user believes that these curves do not accurately represent the equipment failure characteristics, then it is possible to develop unique failure curves based on existing data. Also, the model uses MTTR (Mean Time To Repair) and MTBF (Mean Time Between Failure) in the development of the maintenance tree. Brammer's package outputs spare parts, warehouse space, and manpower requirements; availability, inventory demand profiles; repair levels - per STREAM, per PERIOD. Also, the period cost summary includes capital cost, repair cost, shortage cost, inventory cost, and total cost.

Thus, there are a diversity and a multiplicity of model types for the equipment replacement problem. Earlier models by Hotelling, Preinreich, and Terborgh possessed a simple elegance that led to easily implementable replacement policies. However, with the increased sophistication of technology, more complicated models such as the Frisch multi-stream replacement model were developed. However, there is a gradual development of replacement model building as new models extend previous work. Perhaps in the future, a comprehensive logistics "expert system" will be developed that models the accumulated knowledge of logistics experts.

2.1.8 Remarks

A review of the literature reveals that the various durable equipment replacement models can be readily classified according to the factors of the multi-dimensional grid. Although this taxonomy is quite broad, it does provide a more descriptive and realistic approach than the CERBS method proposed by Reisman and Buffa (96).

The inter-relationship between inventory problems and equipment replacement problems needs to be more fully explored. As McCall (78) observes, one should examine how the optimality of an inventory model is affected when demand is stochastically generated by equipment that is subject to a preventive maintenance program, or conversely, how is an optimal preventive maintenance policy derived when it is connected to a particular inventory policy. Moreover, the Wagner-Whitin algorithm (131) that is used to determine optimal inventory ordering policies in the presence of a time varying demand could also be used in an analogous sense for the determination of optimal repair/replace decisions in the presence of a time varying demand. Thus, in the inventory problem, one of the stochastic elements is demand, while in the maintenance problem, a stochastic element is equipment time to failure. Dynamic programming has been successfully used in the determination of optimal inventory policies (i.e. Wagner-Whitin algorithm), and has potential applications in the area of maintenance management. Moreover, the relation-

ship between a multi-item, multi-source (MIMS) procurement policy and a preventive maintenance program or a repair/replace policy could also be examined.

Hadley and Whiten (50, 51), Fabrycky and Banks (37), Wagner (129), Whitin (135), and Starr and Miller (120) give scholarly treatments to the various categories of inventory systems. Scarf, Gilford, and Shelly (106) present a compendium of multi-stage inventory models and solution techniques. Gluss (43) also examines the multi-stage inventory problem and develops an inventory solution for some specific demand distributions. He develops a penalty cost that consists of a fixed administrative cost and a cost proportional to the deficiency in the stock level. Peterson and Silver (88) discuss decision support systems for inventory/production management and present the rudimentary structure of an integrated inventory/maintenance system. Graves and Keilson (45) discuss an "extended logistics system" that involves a configuration of the acquisition, inventory, transportation, and maintenance (repair/replace) functions. In essence, their modeling approach involves the entire spectrum of the "material management" function.

Two case studies that appear in the literature deserve special note. Sinden (113) studies the replacement of durable equipment for facilities providing a service for a growing population (for example, a power plant, a transportation system , a telephone system, etc.). Thus in order to meet

service requirements, the facility must expand and replace its equipment from time to time. Consequently, Sinden develops a macroscopic model for the replacement of durable equipment. On the microscopic level, Eilon, King, and Hutchinson (36) present a study on the optimum replacement of fork lift trucks using two different replacement models.

Finally, dynamic programming is presented in the literature as a powerful technique that determines the optimal replacement policy when predictable technological changes are anticipated. However, it is a non-trivial task to predict technological changes. Consequently, there are a number of works in the literature that deal with the problem of technological forecasting. Linstone and Sahal (73) present a comprehensive collection of articles that discuss technological substitution or the process of substituting one technology for another (for example, the substitution of steam for sail). These articles discuss: some basic models for forecasting technological substitution, the determinants of the substitution rate, economic analyses, applications of technological substitution to energy production, and implications and challenges for the future.

Bright and Schoeman (15) present an interdisciplinary approach to technological forecasting. A number of authors from various fields have contributed their work and topics such as trend extrapolation, dynamic modeling, and forecasting resistance to technological change are presented. There

is an article by Fusfeld (42) that introduces the concept of a "technological progress function" that is analogous to the manufacturing progress function. The idea behind the technological progress function is that technological performance improves with learning as refinements and improvements are incorporated into production runs. Moreover, the research and development budget is often based upon a percentage of sales which is linked to the production quantity. In an article by Cetron and Dick (19), the Navy Technological Forecast (NTF) procedure is presented. The NTF involves three areas - scientific opportunities, technological capabilities, and probable system options. The NTF covers 75 broad functional areas of the Navy.

Martino (75) defines a technological forecast as "a prediction of the future characteristics of useful machines, procedures, or techniques" (p. 2). He subdivides the stages of the innovation process into the following categories (p. 6):

(a) scientific finding
(b) laboratory feasibility
(c) operating prototype
(d) commercial introduction or operational use
(e) widespread adoption
(f) diffusion to other areas
(g) social and economic impact.

Martino maintains that this division of the innovation process into stages assists the analyst in the determination and interpretation of a technological forecast. Various fore-

casting techniques such as the Delphi method, trend extrapolation, growth curves, analytical models, relevance trees, and mission flow diagrams are presented in his book. He also includes a discussion of the application of technological forecasting to planning and decision making as well as a section on presenting the forecast to others.

Jones (59) develops an after-tax equipment replacement model that incorporates a percentage improvement in technology, as well as linear and/or exponential effects of technological improvement on operating and salvage expenses. Chand and Sethi (20) also examine the effects of technological improvement, and use planning horizon procedures in their solution methodology for the machine replacement problem. These authors assume technological improvement over time and that there are several alternative replacement actions. These alternative actions are that an incumbent machine could be replaced by:

> (1) a new machine with different technologies (labor intensive versus capital intensive)
>
> (2) a used machine
>
> (3) repairs and/or improvements that affect the performance of the incumbent machine.

Chand and Sethi use a dynamic programming approach and the concept of a forecast horizon in the determination of the optimal replacement decision.

Ahmad and Christakis (3) argue that the assessment of technologies involve sociopolitical choices. These authors maintain that models for technological forecasting must be more than just a mechanism for identifying the introduction of technology. Ahmad and Christakis propose a model that incorporates the following features:

(1) anticipates the impact of alternative technologies on the biophysical and social environment

(2) evaluates the impact of alternative technologies with reference to socioeconomic norms

(3) interprets alternative technologies with reference to projected socioeconomic norms

(4) identifies and evaluates policy interventions to bring about desirable social change.

Finally, in a working paper by Sink, Mallak, and Luxhoj (115), the issue of the illusion of control in executive decision making is examined. These authors contend that although decision support systems enable executives to process the enormous amounts of data generated in the Information Age, perhaps such decision aids only present an illusion of control for decision makers and are just a part of the "magical rites of management". Thus, the decision maker must remember that model output is usually intended as a guide, and that intuitive processes or "gut feel" may help to refine or revise such output. In the next section, "sudden failure"

equipment models are analyzed according to the multi-dimensional grid concept.

2.2 "Sudden Failure" Equipment Replacement Models

A second major classification of equipment replacement problems is concerned with items that do not deteriorate from "normal wear and tear" but that experience "fatal failure" after a period of use. The time between installation and failure is not constant for any particular equipment type but follows some frequency distribution. For example, light bulbs can be classified as "sudden failure" equipment. Also, football stadium lights require an initial burn-in period in order to produce lights with longer expected lives and lower initial probability of failure. The ability of the lights to survive the initial "burn-in" period increases their chance for longevity. After this initial period, the probability of failure increases with age.

The bulk of the literature that is reviewed focuses on durable equipment replacement models. However, Churchman, Ackoff, and Arnoff (22) give an excellent introduction to replacement models for "sudden failure" of items. A taxonomy of models can be developed that is based on the multidimensional grid concept. Although this taxonomy is essentially similar to the taxonomy developed for durable equipment replacement models, the primary difference is that deterioration is not a factor with "sudden failure" equipment. The principal problem is to develop a replacement policy for items that have not failed as opposed to the replacement of durable equipment that has deteriorated in per-

formance. Thus, the analyst must be able to accurately estimate the probability distribution of failures for industrial equipment. Renewal theory is concerned with the failure and replacement of such equipment. Cox (26) presents a discussion of renewal theory that includes replacement strategies. Dobb (32) discusses renewal theory in terms of probability theory. Proschan (93) develops a mathematical model for the determination of optimal spare part kits using renewal theory.

2.2.1 <u>States of the System</u>

With renewal theory, the states of the system are that an item is in service or it has failed. Jorgenson, McCall, and Radner (61) observe that the probabilistic mechanism describing changes of state from good to failed may be characterized by the equipment's reliability function. A reliability function indicates the probability that equipment is good after a certain time has elapsed from the installation date. Time to failure is a random variable whose distribution is referred to as the equipment's failure distribution. The failure rate of equipment at time t is the probability that the equipment will fail in the next interval of time given that it is good at the start of the interval (i.e. conditional probability). Moreover, the maintainability of equipment is defined as the probability that the equipment will be restored to specified conditions within a

period of time T when the maintenance is performed according to certain procedures.

Thus, probability density functions, cumulative distribution functions, reliability functions, failure rates and maintainability assist the analyst in determining the transition of equipment from state "good" to state "failed". Jorgenson, et. al. (61) present a discussion on failure distributions in Chapter 7 of their book that includes the exponential, normal, log-normal, Weibull, and Gamma distributions. Jardine (56) also gives an introduction to the statistical preliminaries required in the analysis of equipment subject to "sudden failure".

2.2.2 Decision Actions

Essentially, replacement policy in the case of "sudden failure" involves service replacements made after failure and planned replacements made before failure. Jorgenson, et. al. (61) present some simple replacement strategies in Chapter 11 of their book that are based on these two decision actions. These authors then develop some strategies that involve idle time and component wear. Jardine (56) discusses replacement decisions, inspection decisions, overhaul and repair decisions, organizational structure decisions, reliability decisions, and scheduling and sequencing decisions. He also discusses how component redundancy can be utilized to reduce the proportion of time that equipment is inoperable

due to all components being in a failed state if equipment operation only requires one component to function. Also, the decision maker may decide to use economies of scale and replace similar items in groups rather than individually, since group replacement sometimes lowers costs. Organizational structure decisions include determination of the optimal size of the maintenance crew.

2.2.3 Planning Horizon

In general, the planning horizon for "sudden failure" equipment replacement problems is assumed to be a long period of time and the intervals between preventive replacements are assumed to be relatively short. Thus, the problem is to determine the optimal interval between preventive replacements that minimize total expected replacement cost. Cox (26) discusses alternating renewal processes that are characterized by alternating sequences of running-times and repair-times.

2.2.4 System Knowledge

With "sudden failure" equipment, it is imperative that the analyst be able to accurately estimate the equipment failure distribution. Uncertainty regarding failure characteristics usually diminishes with increased item usage. Jorgenson, et. al. (61) present a discussion of estimation procedures for the form and parameters of the time-to-failure

distribution in Appendix A of their book. Also, there may be uncertainty as to initial investment costs, operation and maintenance costs, etc.

2.2.5 System Objective

In the "sudden failure" equipment replacement problem, the system objective is usually the minimization of expected costs. These costs are a function of replacement cost, cost of equipment failure, and the probability of failure. A fundamental requirement of a pragmatic replacement policy is that the replacement cost after failure be greater than the replacement cost before failure. This cost difference is the source of savings required to compensate for the expense of reducing failure probability by replacement of surviving items. The replacement cost for a failed item involves purchase cost, labor cost, cost of downtime, and safety costs. Agee and Tanchoco (2) list other cost factors that are involved in any economic analysis. Jardine (56), Cox (26), Jorgenson, et. al. (61), and Churchman, et. al. (22) all develop cost minimization models. Jardine (56) also develops a preventive maintenance model where the system objective is to minimize downtime.

2.2.6 Solution Methods

Solution methodologies for the "sudden failure" equipment replacement problem involve the use of mortality curves,

Monte Carlo techniques, simulation, graphical techniques, renewal theory, Laplace transforms, enumerative techniques, and the calculus. These methodologies are displayed in Jardine (56, 57), Cox (26), Churchman, et. al. (22), and Jorgenson, et. al. (61).

2.2.7 Replacement Models

Jardine (56) presents numerous models for equipment that is subject to "sudden failure". He develops models for instantaneous replacement, fixed interval preventive replacements, and preventive replacement that depend on equipment age. Other models consider downtime, group replacement, and multi-stage replacement. A multi-stage replacement model is for the situation where there is a group of similar items that can be divided into sub-groups depending upon item replacement cost. Thus, some items may be more expensive to replace than others, since failure in a strategic position can have serious consequences. Truelove (127) defines strategic reliability as the product of availability and reliability over a fixed period of time. He then demonstrates an approximation method for the strategic reliability and preventive maintenance problem. Churchman, et. al. (22) develop cost minimization models that incorporate idle time and component wear.

Preventive maintenance models for single component equipment, equipment with several parts, equipment operating

characteristics, and opportunistic policies are developed by Jorgenson, et. al. (61). Barlow and Hunter (4) use renewal theory to develop optimum preventive policies for simple equipment and for large, complex systems. For example, for large, complex computer systems, preventive maintenance is usually scheduled after a certain number of accumulated hours. Failures are repaired as quickly as possible between maintenance periods. For simple equipment, repair (or replacement) at the time of failure may correspond to a general overhaul. Thus, Barlow and Hunter develop optimum maintenance policies and unique solutions for each case that depend on the equipment failure distribution. Hunter and Proschan (55) also use renewal theory in the case when a constant failure rate precedes equipment wearout. These authors develop a model for the distribution and expected value of the number of planned replacements, the number of failures, and the total number of removals due to either planned replacement or failure replacement. Thus, their model results can be used to determine the number of spare parts to stock or the budget required to maintain equipment.

2.2.8 Remarks

Thus, the multi-dimensional grid concept can also be used to develop a taxonomy of "sudden failure" equipment replacement models. The literature that is reviewed indicates

a diversity of model types that incorporate various assumptions concerning downtime, failure distributions, and costs.

2.3 Chapter Summary and Conclusions

The literature on economic replacement models is reviewed and a taxonomy of models is presented using a multi-dimensional grid concept with eight factors to distinguish among a variety of model types. Two major classifications of equipment replacement models based on life patterns are determined to be:

(1) items that deteriorate with time, and

(2) items that fail suddenly.

The first categorization pertains to durable equipment and the second to "sudden failure" equipment. Within these major classifications, each equipment type is further analyzed according to the remaining factors of the multi-dimensional grid. These factors are states of the system, decision actions, planning horizon, system knowledge, system objectives, solution methods, and replacement models.

A bulk of the literature that is reviewed discusses durable equipment replacement problems, since this is the most common type of industrial equipment. The literature reveals that many of the earlier models by Hotelling (see Rapp (95)), Preinreich (92), and Terborgh (124) possessed a simple elegance that led to easily implementable policies. However, the increasing sophistication of technology and and the explosion of data requires the development of much more complex models that depend on the computer for implementation.

Finally, the second part of the literature review ana-
lyzes "sudden failure" equipment replacement models according
to the factors of the multi-dimensional grid concept. Again,
there is a wide diversity of model types that can be applied
under different operating conditions and equipment failure
characteristics. It should be noted that the distinction
between durable equipment and "sudden failure" equipment may
not always be clear. There is a crossover between the two
groups when MTBF, MTTR, and other failure characteristics are
known for durable equipment models. Renewal theory that is
used as a solution method for "sudden failure" equipment may
also be used for the durable equipment problem. Thus, in
reality, there may not be such a dichotomous classification
of replacement models.

A review of the literature and subsequent analysis of the
taxonomy results indicate that a future research area is the
study of multi-echelon (multi-repair levels), multi-part
interaction replacement models. This area is very difficult
to handle mathematically, especially when the interactions
that occur are due to stochastic dependence among parts and
dynamic economic factors. More research is also needed in
the application of dynamic programming to replacement analy-
sis, especially in the multi-part, multi-echelon case.

In conclusion, the multi-dimensional grid concept facil-
itates a systematic classification or taxonomy of equipment
replacement models. Perhaps in the future, an interdisci-

plinary approach to replacement analysis that incorporates various aspects of queueing theory, decision theory, linear programming, dynamic programming, and sociopolitical and socioeconomic factors will be attempted. For as Preinreich (92) observed in 1940, an optimal replacement policy is crucial to the operational and economic vitality of any industrial enterprise.

2.4 Contribution of this Research to Logistics Modeling

Again, multiplicity and diversity of product types and the increase in technological sophistication complicate modern logistics modeling. The Frisch multi-stream replacement concept represents one attempt at modeling the physical behavior of repairable items by grouping end items into streams according to similar failure characteristics. Moreover, the multi-stream concept can be utilized by the decision maker to facilitate repair/replacement analysis. Consequently, the development of a computerized methodology that mathematically exploits the nature of the multi-stream concept represents a significant advance in assisting logisticians with the fundamental question of whether to repair or to replace incumbent equipment (i.e. the "defender" asset).

This general methodology accommodates both stochastic and/or deterministic demand; different hazard models; a budget constraint; repair capacity constraint; discounting; technological improvement; and model implementation issues. In the new model, physical and non-physical constraints are separated, so that any repair policy (physical) or budgetary policy (non-physical) can be incorporated into the modeling approach. Technological improvement is addressed by allowing for a percentage improvement in productivity and a percentage reduction in operating costs. The model can assist the decision maker with assessing the impact of different technologies on the operating environment. Implementation issues

are addressed by providing guidelines for effective model use at all organizational levels. Finally, the new model enables the decision maker to perform either single- or multi-parameter sensitivity analysis and perhaps examine the inter-relationships between inventory and maintenance policies. Thus, the contribution of this research to modern logistics is that it attempts a holistic treatment of the repair/replace decision.

III. A GENERAL MODELING APPROACH

3.1 Introduction

In this chapter, a general model for the multi-stream replacement problem is introduced. In the general equipment replacement problem, a finite planning horizon may be partitioned into stages such that an end item deteriorates toward a final stage where it is no longer economically or operationally feasible to continue to repair the item, or the item experiences fatal failure. This multi-stage deterioration process is very amenable to a dynamic programming solution methodology where the output from one stage becomes the input to the next stage.

In the multi-stream replacement problem, a concept of nested Markov chains is used to model the physical behavior of a population of repairable items. The population is grouped into streams depending upon such parameters as item age, the number of item operational hours, or the environment in which the item operates (see Figure 1, Chapter 1). It is assumed that similarly aged items within the stream are at the same level of deterioration. In the modeling approach described in this chapter, a dynamic program is formulated where the state function is characterized by two parameters - item age and current operational status of the equipment. If a constant hazard model is applicable (i.e. failure rate

is constant), then the transition probabilities are stationary. With non-constant hazard models (i.e. failure rate is non-constant), the transition probabilities are non-stationary. Each stream is either a Markov or an approximate Markov chain, since there is a sequence of probabilistic transitions in which the transition probabilities are dependent only on the current state of the system for constant hazard models, or on the current state and item age for non-constant hazard models. The grouping of streams form nested Markov chains that represent a population of repairable items.

The dynamic programming modeling approach has its genesis in the Logistics Decision Model (see Figure 3, Chapter 2) proposed by Frisch (41). Again, the Frisch decision model is composed of the following two sub-models:

1. Markov chain sub-model calculates the physical behavior of the system - selected output of this model (capital cost, inventory cost, repair cost, shortage cost, total cost per period per stream) becomes the input to the dynamic programming sub-model.

2. Dynamic Programming sub-model determines cost calculations and supports the repair/replace decision.

Consequently, in this research, the development of a generalized solution methodology for supporting the equipment repair/replace decision depends upon the nested Markov chain

concept or multi-stream replacement model developed by Frisch

for the modeling of the physical behavior of a logistics

system. Therefore, since the Frisch multi-stream replacement

model has been previously discussed (see Section 2.1.7(D)),

this chapter on the modeling approach focuses specifically

on the development of the dynamic programming sub-model.

However, to facilitate the discussion, the multi-stream re-

placement sub-model will be elaborated upon as necessary.

The modeling approach for the _physical_ system uses the

concept that an individual component of equipment has unique

failure characteristics as described by Mean Time Between

Failure (MTBF) and Mean Time To Repair (MTTR). Also, besides

the major component failure probabilities, there is also a

probability of fatal failure. There is a hierarchy of fail-

ure probabilities, and the failure probabilities at higher

levels in the maintenance tree are determined by the failure

rate probability distributions of the lowest indenture level

components that have _known_ failure rate distributions.

Figure 4[12] graphically depicts this hierarchy of failure

probabilities in the maintenance tree. Brammer (14) utilizes

the nested Markov chain concept to develop a microcomputer-

based package for the physical system sub-model. He develops

---

[12]   Kenneth W. Brammer, "A Transient State Maintenance Re-
        quirements Planning Model", M.S. Thesis, Virginia
        Polytechnic Institute and State University (1985), p. 70.

a Maintenance Requirements Planning Model (MRPM) that incorporates the maintenance tree concept.

In the next section, the basic features of the dynamic programming approach are outlined. After this, modeling assumptions are presented and discussed. The dynamic programming approach is then further elaborated upon with a discussion of decision trees and planning horizon theory. Essentially, decision trees aid in structuring the problem, and planning horizon theory eliminates the need for the full horizon of data in the economic analysis. A concise problem statement and system objective are also presented, and the states of the system, decision actions, and stages of the dynamic program are summarized. There is a separate section on model notation that offers a brief explanation of model terminology. A general mathematical model is then developed that is subsequently embellished to include technology effects. There is a brief discussion of the estimation of transition probabilities for the states of equipment condition. Model development is followed by a two stream numerical example. The results of the numerical analysis are then summarized in the repair/replace decision matrix. The numerical analysis is then followed by brief discussions on repair facilities and discounting. Finally, the chapter is summarized, and pertinent conclusions are presented.

END ITEMS CAN BE MODELED
AS A FAMILY OF COMPONENTS.
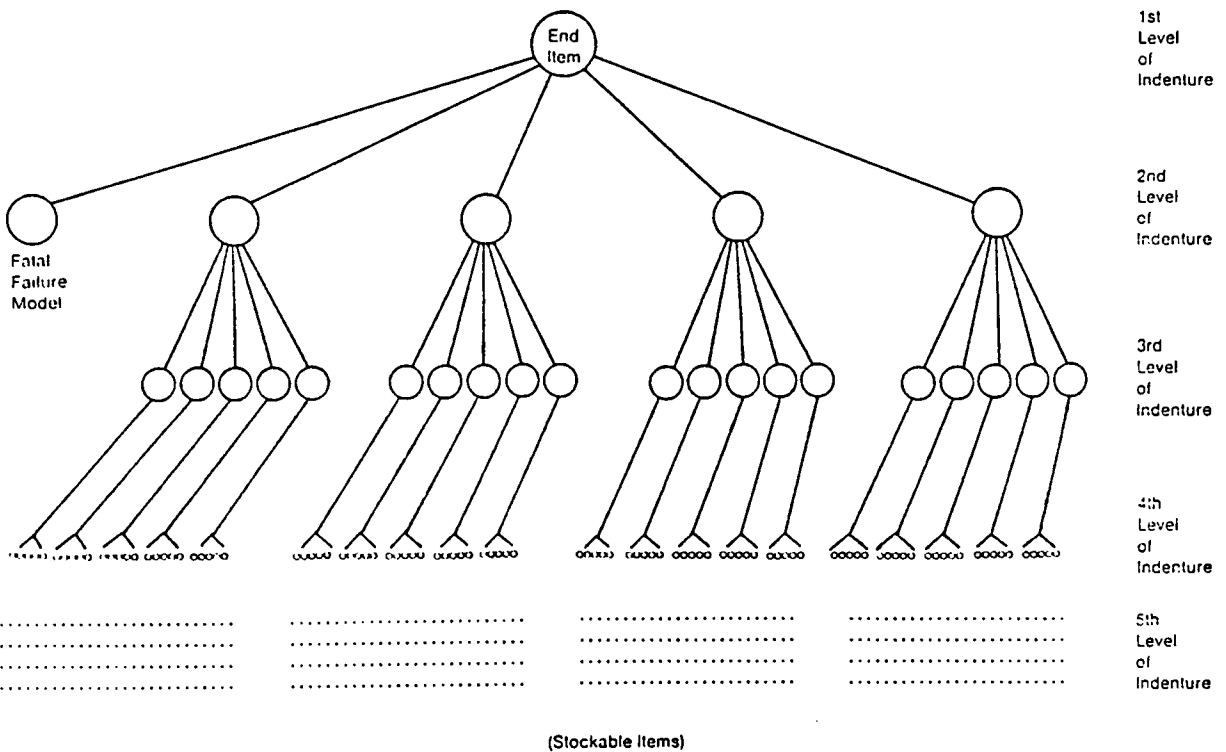
Figure 4. Sample Maintenance Tree.

3.2 Basic Features of Dynamic Programming

In this section, some of the basic features and terminology associated with the dynamic programming approach are presented. These features are listed and then elaborated upon as necessary. Thus, the basic features of the dynamic programming approach are:

1. The problem can be divided into stages with a policy decision required at each stage.

2. Each stage has a number of states associated with it.

3. The effect of the policy decision at each stage is to transform the current state into a state associated with the next stage.

4. Given the current state, an optimal policy for the remaining stages is independent of the policy adopted in the previous stages.

5. The solution procedure begins by finding the optimal policy for each state of the last stage.

6. A recursive relationship is available that identifies the optimal policy for each state with $(N-J)$ stages $(J=0,2,...N-1)$.

7. Using this recursive relationship, the solution procedure moves backward stage by stage, each time finding the optimal policy for each state of that stage, until it finds the optimal policy when starting at the initial stage.

A typical i^{th} stage can be represented as in Figure 5.

DP APPROACH
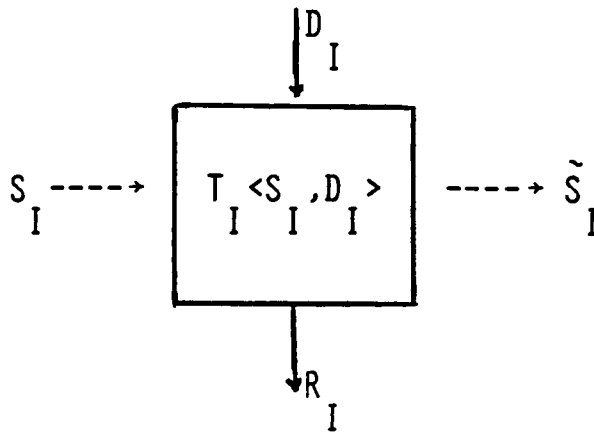
FACTORS: (1) S_I = INPUT (INITIAL) STATE

(2) $T_I <\cdot>$ = STAGE TRANSITION FUNCTION OR "STAGE -

COUPLING FUNCITON"

(3) $\tilde{S}_I$ = OUTPUT (FINAL) STATE

(4) D_I = DECISION

(5) R_I = STAGE RETURN (MEASURES THE UTILITY OF A

STAGE AS A FUNCTION OF THE INPUT STATE AND

DECISION)

Figure 5. A Stage in Dynamic Programming.

36

The following five factors characterize each stage:

1. s_i = input state; called the "initial state" since it gives a description of the system at the beginning of the stage.

2. $T_i <\cdot>$ = stage transition function; sometimes called the "stage-coupling function" that expresses each component of the output state as a function of the input state and stage decision.

3. s_i = output state; called the "final state" since it gives a description of the system at the end of the stage:
$$s_i = T_i <s_i, d_i>.$$

4. d_i = decision; controls the operation of the stage.

5. r_i = stage return; a variable that measures the "utility" of the stage as a function, $R_i <\cdot>$, of the input state and decision:
$$r_i = R_i <s_i, d_i>.$$

Thus, the equipment replacement problem with a finite horizon is very amenable to a dynamic programming solution methodology, since the planning horizon can be divided into stages where decisions are to be made. In this multi-stage deterioration process, the output from one stage becomes the input to the next stage. Therefore, dynamic programming exploits the multi-stage structure of the multi-stream replacement problem by decomposing the N-dimensional multi-stream problem into N-single dimensional problems. The dynamic programming approach and the principle of optimality is then applied to each stream, and the results of the individual cost calculations for each stream can then be merged

or aggregated to yield a period by period replacement analysis.

To review, the principle of optimality states that:

> An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.[13]

In other words, the principle of optimality maintains that an optimal policy or decision strategy consists of optimal subpolicies. Thus, the logistician attempts to determine the "best thing to do" in each period in order to best utilize his or her resources. The equipment replacement problem can be discussed in the context of a dynamic programming solution methodology as follows:

stages: discrete points in time where decisions are made

states: initial - equipment either "good" or "failed"
             final - equipment either "good" or "failed"

decisions: either repair or replace end item

returns: repair or replacement costs

objective: minimize total equipment life cycle costs subject to a budget constraint and a repair capacity constraint

Decision variables are the number of end items to replace and the number of end items to repair per _stream_ , per _period._ The use of discrete dynamic programming is particularly ap-

---

[13] Bellman and Dreyfus, p. 15.

propriate, since there are a finite number of states at each stage, a finite number of decisions are possible at each stage, and a finite number of stages typically exist in the system representation. In the next section, modeling assumptions are introduced and analyzed as to their influence on the general modeling approach described in this dissertation.

3.3 Modeling Assumptions

In this section, model assumptions are presented and discussed. These assumptions may be structural, descriptive, realistic, or limiting (simplifying) in nature. A structural assumption is an analytical construct that is necessary in modeling a physical system. A descriptive assumption merely describes an attribute or a characteristic of the modeling approach. Realistic assumptions attempt to incorporate an essence of reality into the model. Finally, although limiting or simplifying assumptions impose constraints on model application, these assumptions are necessary for efficient model development. It is important to note that the only model of reality is reality itself. However, the various types of assumptions facilitate model construction. Note that some of the assumptions pertinent to the physical system (Markov sub-model) that are necessary for the development of the dynamic programming sub-model are elucidated. Those assumptions specific to the dynamic programming modeling ap-

proach are then analyzed according to the four basic types of assumptions:

1. Each stream in the nested Markov chain contains a homogeneous group of end items.

   This is a structural assumption that is necessary in the construction of the model for the physical system. Similarly aged items with the same failure characteristics are grouped together into streams. This assumption eliminates item-by-item tracking.

2. Minimal repair returns the end item to the state of repair it was in just prior to failure.

   This is a descriptive assumption. Although it may be possible for repaired equipment to achieve the same functional performance as new equipment, the reliability of repaired equipment generally deteriorates with successive repairs. Also, maintenance costs generally increase with equipment age.

3. The failure of any component on the maintenance tree results in an immediate failure of the end item.

   This is a limiting assumption of the sub-model for the physical system. This assumption could be relaxed by separating sub-components into critical and non-critical categories.

4. Failure probabilities are not dynamic.

   This is a limiting assumption of the sub-model for the physical system. This assumption could be relaxed by incorporating real time data into the model. Thus, it would then be possible to construct failure distributions that reflect the probability of failure after a repair has been performed.

5. Components fail independently of the failure of other components.

   This is a structural assumption of the sub-model for the physical system, and reflects the horizontal independence of component failure

in the maintenance tree.

6. Upon fatal failure, an end item must be permanently removed from service.

   This is a realistic assumption, and a salvage value is attached to end items. For example, a fatal failure occurs in a combat zone when the end item is rendered non-operational or destroyed. In a non-combat environment, a fatal failure occurs when a critical component fails and cannot be replaced, or the end item reaches its retirement age.

7. Several levels of repair facilities are available.

   This is a realistic assumption, since operationally, there are different types of repair that require various levels of maintenance. Moreover, the cost of repair at the different levels of repair - on-site, warehouse, central depot, etc. - may differ.

8. Mean Time to Repair (MTTR) includes the total amount of time that elapses between failure of an end item or component and the time when the equipment is again operational.

   This is a simplifying assumption. Thus, in this modeling approach, MTTR includes diagnostic time, travel time to and from the repair facility, queueing time, and the time for the actual repair. This assumption could be refined by separately analyzing the various MTTR elements.

9. Replenishment of end items through procurement is instantaneous.

   This is a simplifying assumption. However, this assumption could be refined by incorporating lead time into the procurement policy.

10. Acquisition cost, spare part procurement cost, general operation and maintenance costs, and repair costs are all treated as beginning of period costs.

    This is a simplifying assumption that ensures a systematic treatment of costs in the repair/replace analysis.

11. There is a budget constraint and a repair capacity

constraint.

This is a realistic assumption. The equipment replacement problem is a multi-criteria optimization problem with conflicting objectives. However, in this modeling approach, it is further assumed that both constraints are never binding in the same period (i.e. a feasible solution does exist).

12. Demand per stream is known in each period and no shortages are allowed.

This is a simplifying assumption. The modeling approach does incorporate a time varying demand, but the demand distribution is known. Demand is defined as the number of end items required in a given period to ensure mission success in that period.

13. There may be more than one quality-price combination of end items in a given period.

This is a realistic assumption in that it accommodates the possibility of technological progress when selecting among equipment alternatives.

14. Taxation effects are not considered.

This is a simplifying assumption. In this modeling approach, all pertinent costs are considered to be before taxes. Jones (59) develops a replacement modeling analysis that considers taxation effects.

15. Quantity discounts are considered.

This is a realistic assumption. In reality, there may be a cost gradient associated with varying purchase amounts or repair amounts.

16. An interest rate is not considered over the planning horizon.

This is a simplifying assumption. In reality, there may be either a constant or a variable interest rate to be considered in the replacement analysis.

17. Machine output capacity is fixed.

This is a simplifying assumption. In this modeling approach, production expansion effects are not considered. Technological improvement is reflected

by a percentage increase in capital cost and a percentage decrease in general operation and maintenance expenses. The effect of technological progress is explained in further detail in the section, "A Mathematical Model with Technology Effects".

Thus, in the foregoing section, a distinction is made among structural, descriptive, realistic, and limiting (simplifying) assumptions. In order to understand the capabilities of the modeling approach, it is first necessary to analyze the assumptions inherent in model building and how these various types of assumptions facilitate model development. In the next section, a dynamic programming formulation of the multi-stream equipment replacement problem is presented.

3.4 A Dynamic Programming (DP) Approach

The subsequent modeling approach is particularly influenced by the works of Bellman and Dreyfus (9), Jardine (56), Bunn (16), Wagner and Whitin (131), Chand and Sethi (20, 109), Shooman (112), Singh and Billinton (114), Cinlar (23), Jones (59), and Jones and Tanchoco (60). Essentially, the modeling approach utilizes dynamic programming, decision trees, and planning horizon theory. The basic features of dynamic programming that were developed by Bellman and Dreyfus (9) were previously explained in Section 3.2. Bunn (16) defines a decision tree as a representation of the "structure of a decision problem in terms of the sequence and

causal relationships between various decisions and uncertain outcomes" (p. 84). Planning horizon theory is presented in Wagner and Whitin (131) and Chand and Sethi (20, 109). Therefore, prior to a discussion of the dynamic programming replacement model, the concepts of decision trees and a planning horizon are examined in more detail.

3.4.1 Decision Trees

Bunn (16) and Jardine (56) discuss decision trees rather extensively. An example of a decision tree that could be used in replacement analysis is presented in Figure 6. In this representation of a repair/replace decision process, the circles represent the possible states of equipment, and the squares represent the occurrence or non-occurrence of the event equipment failure.

The decision tree indicates that there are two possible equipment conditions at the start of a period (i.e., i = good (G) or failed (F)). Also, j, the equipment condition at the end of the period, can be either good (G) or failed (F). Note that there are two possible decisions (d):

R = Repair

P = Purchase (Replace).

Note that if the equipment is in state "good" at the start of the period, and a decision is made to replace or purchase (P), then there is a probability (p^P_{GG}) that the

Figure 6.   Example of a Decision Tree.
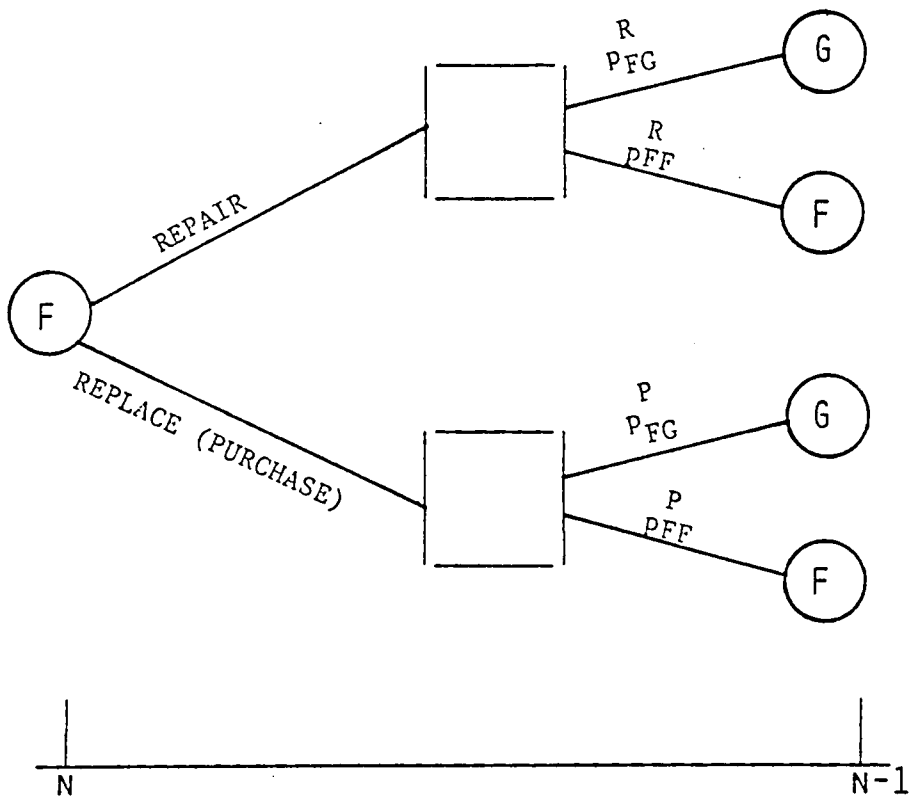
LEGEND:

○   = STATES OF EQUIPMENT CONDITION

▢   = OCCURRENCE OR NON-OCCURRENCE OF EQUIPMENT CONDITION

95

equipment will be in state "good" after the purchase, and a probability (p^P_{GF}) that the equipment will be in state "failed" after the purchase. When purchasing a new piece of equipment, it is expected that there exists a high probability that the equipment will be operational after installation. In reality, this is not always the case, and there is a small probability that the new equipment will not be operational after installation. In effect, a defective piece of equipment has been purchased, and it must be returned to the vendor. However, in this modeling approach, this probability is considered to be negligible and is not incorporated in model computations. This feature could be incorporated in the modeling approach, but the trade-off is an increased number of computations versus a slightly more realistic model. This is where the intuition, judgment, and experience of the logistician in assessing the quality of the vendor's product may significantly influence model output.

If the equipment is in state "failed" at the start of the period, and the decision is made to repair (R), then there is a probability (p^R_{FG}) that the equipment will be in state "good" at the end of the period, and a probability (p^R_{FF}) that the equipment will be in state "failed" at the end of the period. Upon repair, it is expected that the equipment will again be operational. There is a small probability that the repair may not be effective, and that the equipment remains in a non-operational state. In this case, the equip-

ment experiences a fatal failure, and must be permanently removed from service. However, in this modeling approach, this probability is considered to be negligible, and is not incorporated in model computations.

If the equipment is in state "failed" at the start of the period, and the decision is made to replace or purchase (P) a new piece of equipment, then there is a probability (p^P_{FG}) that the equipment will be in state "good" at the end of the period, and a probability (p^P_{FF}) that the equipment will be in state "failed" at the end of the period. Again, it is expected that there is a high probability that a new piece of equipment is operational after installation, but in reality, there is a small probability that defective equipment has been purchased. This probability is considered to be negligible, and is not incorporated in model computations.

Thus, decision trees can be utilized to assist in structuring the decision process in any replacement analysis. The probability that the equipment will go from state i to state j in one period if decision d is taken (p^d_{ij}) is called the item's <u>state transition</u> probability. The evaluation and quantification of these state transition probabilities is a non-trivial task. These probabilities could be estimated from past production and maintenance records. Also, decision theory that considers the subjective evaluations of decision makers could be utilized to arrive at these probabilities. The use of decision theory in replacement analysis will be

discussed in more detail in the section "Estimation of Transition Probabilities". In the next section, the basics of planning horizon theory are presented.

3.4.2 Planning Horizon Theory

The rudiments of planning horizon theory are presented in Wagner and Whitin (131) and elaborated upon in Chand and Sethi (20, 109). Wagner and Whitin develop an algorithm that determines an optimal inventory ordering policy. Their algorithm uses the following two key properties:

Property 1: A replenishment can only occur when the inventory level is zero.

Property 2: There is an upper limit, termed the forecast horizon, as to how far in advance a given period's demand may be included in an earlier replenishment quantity. Basically, the carrying costs become so excessive that it becomes less expensive to have a replenishment arrive at the start of the period under analysis instead of including that period's requirements in a replenishment from previous periods.

It is property 2 that is referred to as the planning horizon theorem. Thus, these disjoint planning horizons eliminate the need for the full horizon of data, and significantly reduce the computational requirements in any economic analysis. Chand and Sethi (20) use planning horizon procedures in their replacement analysis of several competing technologies.

Wagner and Whitin (131) use planning horizon theory in the development of an optimal inventory model. However, their approach could be used in an analogous fashion in the development of a model to support the repair/replace decision. Hence, there is an upper limit, or forecast horizon, as to how far in advance a given period's demand may be included in any previous replenishment. This property can be used to embellish and expand the standard purchase option by allowing for a future period's requirements to be carried in inventory. The subsequent modeling approach offers 3 different purchase options. In the next sections, the problem statement, system objective, states of the system, decision actions, and stages of the dynamic programming approach are briefly summarized.

3.4.3 Problem Statement

In this problem, equipment is subject to failure as described by the above set of assumptions and the multi-stream modeling assumptions that are discussed in Section 2.1.7. On failure, one of two possible decisions are available: repair or complete replacement of the failed equipment. Moreover, the technological environment is improving over time, and it is assumed that there are linear technology effects on capital costs and exponential technology effects on operating expenses for both the "defender" and "challenger"

assets. Decisions are to be made at discrete points in time, and there is a finite planning horizon.

3.4.4 System Objective

The system objective is to determine a policy that assists management in determining what action to take at each decision point to minimize the total cost of operation and maintenance subject to a budget constraint and a repair capacity constraint over the next n periods of time. Thus, it is desired that all demands be met at minimum cost.

3.4.5 States of the System

In this modeling approach, there are two possible states of equipment conditions at the start of a period (i.e. i = "good" (G) or "failed" (F)). Moreover, j, the condition at the end of the period, is also either "good" (G) or "failed" (F). There may not be such a dichotomous classification of equipment condition in reality. For example, although a non-critical component has "failed", the equipment may still be operational. The definition of equipment condition "good" requires further refinement in order to be of practical value. Perhaps the equipment condition could be classified as condition 1, condition 2, etc. when referring to the various levels of operability. An inspection is normally required to ascertain the precise state of equipment condition. Weiss (132) examines semi-Markov processes and defines a set

of composite states such as "inspection-repair-operation" or "inspection-operation" or "inspection-operation-undetected non-operability" that may be used in describing a conventional Markov process. Rosenfield (97, 98) studies semi-Markov processes in the presence of uncertainty. The modeling approach in this dissertation only examines a dichotomous classification of equipment condition ("good" or "failed") in the development of a general solution methodology. The issue of preventive maintenance in the context of a population model is addressed in Chapter 6, "Summary and Conclusions".

3.4.6 Decision Actions

There are three possible decisions (d) for the stated problem:

    R = Repair

    P = Purchase

    K = Keep ("do nothing").

Note that there are numerous pieces of equipment being evaluated, since the modeling approach uses the concept of nested Markov chains. Thus, the decision analysis also includes the number of units to replace or purchase, N_p, the number of units to repair, N_r, or the number of units to "keep", N_k, in each period. This can be accomplished by applying a DP approach to each stream or Markov chain. Note that the "do nothing" alternative is a viable option. If the condition

of equipment is in state "good" at the start of a period, then the logistician may decide that it may be too costly to purchase a new piece of equipment, and simply decide to "do nothing" or maintain the status quo, based on the economic analysis. This is where the modeling approach could be expanded to include the decision alternative of preventive maintenance. However, the reader is reminded that only the three decision actions of purchase, repair, and keep are incorporated in the model developed herein.

3.4.7 Stages

In this DP approach to the multi-stream replacement problem, the stages are the discrete periods in time where decisions are to be made. Note that there is a finite planning horizon.

3.5 Model Notation

In this section, the notation used in the mathematical model is introduced and explained. Moreover, the recurrence relation that is used in the dynamic program to evaluate stage-by-stage replacement or repair costs is also developed.

p^d_{ij} = probability that the equipment will go from state i to state j in one period if decision d is taken. This probability is referred to as the end item's state transition probability.

d_t = demand per stream for an end item in period t

CC_t = inventory cost per unit per period for end items carried forward to meet demand in period t+1

P_t = purchase cost per unit per period of new equipment (first cost of end item less salvage value for a retired end item)

RC_t = repair cost per unit per period (labor, transportation, and overhead costs that are incurred, on the average, each time an end item is serviced by a repair facility)

OD_t = operating cost per unit per period of the existing asset or the "defender" end item

OC_t = operating cost per unit per period of the "challenger" end item

I_t = inspection cost per unit per period

n = total number of periods

B_t = Cumulative Budget Limit with t periods to go

BUD_t = Period Budget Limit with t periods to go

$M_{v,t}$ = Repair Capacity or Maintenance Limit for a level v repair with t periods to go (number of units)

$R(t)$ = Reliability value with t periods to go

G = current age of the stream of end items

λ = estimated rate of technological improvement

N_p = Number of units to purchase per period

N_r = Number of units to repair per period

N_k = Number of units to keep per period

TC^d = Total Cost associated with a particular decision d (d = Purchase, Repair, or Keep)

a_t = age of the equipment with t periods to go

$X_t(a_t,i)$ = decision (R,P,K) with t periods to go that will yield $f_t(a_t,i)$

In general, the policy cost with t periods to go for an item of age a_t in state i is $f_t(a_t,i)$. The procedure works backward through time. Note that a_t refers to the equipment age with t periods to go, and i refers to the equipment condition at the start of the period (i = "good" (G) or "failed" (F)). Figure 7 graphically depicts the variable a_t. Suppose that the initial population age, G, equals 2 periods and the planning horizon is 3 periods. If a decision is made to either keep or repair the equipment in the current period depending on whether the operational status is in state "good" or "failed", respectively, then the population ages one pe-

riod by the start of the next period. If a decision is made to purchase new equipment, then the aging process regenerates, and the population age reverts to age zero, and by the start of the next period, the equipment is of age one. For example, a_2, or the population age with 2 periods to go in the analysis, may be either 3 or 1 depending on whether a non-replacement or replacement decision occurred in the previous period (i.e. 3 periods to go). Thus, as Figure 7 demonstrates, the aging variable a_t forms an upper triangular matrix.

The cost of the first decision, with t periods to go is c^d_{ij} if action d is chosen and results in state j. Note that d corresponds to the decision actions of purchase (P), repair (R), or keep (K). However, there is a probability, p^d_{ij}, attached with arriving in state j. Since there are multi-outcomes that could result if decision d is made, the cost of the first decision is then

$$f'_t(a_t, i) = \sum_{j=1}^{S} c^d_{ij} \, p^d_{ij} \qquad (1a)$$

where S is the number of possible states of equipment at the end of the period. In the general model development, S = 2, since there are two possible states of equipment condition at the end of a period (i.e. j = "good" (G) or "failed" (F)). However, as previously discussed, the probability that the condition of equipment is in state "failed" at the end of the

PERIODS TO GO: t	3	2	1
POPULATION AGE: a_t	a_3	a_2	a_1
	2	3	4
		1	2
			1

Figure 7. Aging Variable a_t.

period is assumed to be negligible in comparison with the probability that the condition of equipment is in state "good" at the end of the period. In the subsequent analysis, $S = 1$. In other words, it is assumed that the equipment can only be in state "good" at the end of the period.

At the end of the period, the equipment condition is in state "good" (G) with $t-1$ periods left in the replacement analysis. The minimum expected cost over this remaining time is $f_{t-1}(a_t, G)$. However, note that state "good" (G) occurs with probability p^d_{ij} and the costs are:

$$f^2_t(a_t, i) = \min_d [p^d_{iG} f_{t-1}(a_t, G)] \quad (1b)$$

The total cost over t periods is the sum of (1a) and (1b) and is given by:

$$TC = f_t(a_t, i) = f'_t(a_t, i) + f^2_t(a_t, i)$$

$$= f_t(a_t, i) = c^d_{iG} p^d_{iG} + p^d_{iG} f_{t-1}(a_t, G) \quad (2)$$

Since the system objective is to minimize the total cost TC, the logistician must select the best decision d for an item of age a_t when in state i with t periods to go that minimizes (2). The resulting minimum total cost $f_t(a_t, i)$ and

best decision d are obtained by the following <u>recurrence re-</u><u>lation:</u>

$$f_t(a_t,i)= \min_{d} [c^d_{iG}p^d_{iG} + p^d_{iG}f_{t-1}(a_t,G)] \qquad (3)$$

$$t \geq 1$$

3.6 <u>Reliability, Availability, and Transition Probabilities</u>

The subsequent mathematical model uses the concepts of reliability, availability, and transition probabilities to describe the failure dynamics of a population of end items. Shooman (112), Kapur and Lamberson (62), Singh and Billinton (114, Billinton and Allan (10), Osaki and Hatoyama (87), Carter (18), Calabro (17), Messinger (79), and Blanchard (12, 13) all give extensive treatments to these topics. The intent of this section is to review some of the fundamentals and to explain their significance to the modeling approach. The probability of failure for an end item (or system) is given by

$$P(T \leq t) = F(t)$$

where T is a random variable that defines the failure time of the end item (or system) and F(t) is the failure distribution function. The reliability or survivor function is the

complement of the failure distribution function and is given by

$$R(t) = 1 - F(t) = P(T \geq t)$$

where R(t) is defined as the probability that the end item (or system) has not failed by time t. The reliability or survivor function describes the failure dynamics between periods, and is used to determine the number of units surviving at time t. In the subsequent mathematical model, the function $R(a_t)$ defines the reliability for an item of age a with t periods to go in the analysis. Note that 1-R(t) gives the unreliability, or the probability that the system has failed with t periods to go in the analysis.

The hazard function h(t) is used to describe the instantaneous rate of failure and is given by

$$h(t) = \frac{f(t)}{R(t)}$$

where f(t) is the probability density function which is the derivative of F(t) or the cumulative distribution distribution function, and R(t) is the reliability function. Note that f(t), h(t), and R(t) are all interrelated, and that once one value is known, the other two can be readily determined. Although the modeling approach does not work directly with the hazard function, the computer program that supports the modeling effort presents the user with the option of select-

ing from among five different hazard models. The five hazard models are the constant hazard, linearly increasing, piecewise linear bathtub, Weibull, and the exponential models. The computer program then uses the appropriate reliability function that corresponds to the selected hazard model. The reliability functions that correspond to the selected hazard model are presented in Chapter 4, "Population Model Implementation".

The availability function A(t) is defined as the probability that the end item (or system) is operational at time t, which distinguishes it from the reliability function R(t) which gives the probability that an end item (or system) has operated over the interval 0 to t. In the subsequent mathematical model, the total costs with t periods to go for state "good" are multiplied by the availability function value with t periods to go to determine the expected costs for state "good". Similarly, the total costs for state "failed" with t periods to go are multiplied by the unavailability (1 - A(t)), or the probability that the end item (or system) is non-operational with t periods to go, to determine the expected costs for state "failed". The expected costs for states "good" and "failed" are then aggregated to determine the period cost with t periods to go in the analysis. If a constant hazard model is selected to describe the failure dynamics of a stream of end items, then the availability function A(t) is given in Shooman (112) as:

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t}$$

where

μ = 1/MTTR
λ = 1/MTTF
MTTR = Mean Time To Repair
MTBF = Mean Time Between Failure
MTTF = Mean Time To Failure = MTBF - MTTR.

Again, in the subsequent mathematical model, A(t) represents the availability with t periods to go in the analysis. The determination of availability functions for non-constant hazard models is a non-trivial problem, and is not addressed in this dissertation (see section 6.4, "Areas for Future Research"). Messinger (79) presents some approximation methods in his dissertation, such as the use of Monte Carlo simulation, that offer potential for the determination of time-dependent availability function values for non-constant hazard models. However, for the modeling approach in this dissertation, the "inherent availability" as defined by Blanchard (12, 13) is used to determine an availability value for non-constant hazard models. Blanchard (11, 12) defines "inherent availability" as

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

where

$$MTBF = \text{Mean Time Between Failure}$$
$$MTTR = \text{Mean Time To Repair}.$$

Thus, the "inherent availability" is a function of the system design parameters MTBF and MTTR.

For the modeling approach presented in this chapter, if a constant hazard model is selected, then the transition probabilities from state to state given a particular decision action d are stationary, and are not time-dependent. If a non-constant hazard model is selected to describe the failure dynamics of a stream of end items, then the transition probabilities are non-stationary and time-dependent. However, in this modeling approach, if a non-constant hazard model is applicable, then the transitions from state to state are modeled as an approximate Markov process. Singh and Billinton (114) present a development of time-dependent transition probabilities for a two state Markov process. The results that are used in the modeling approach of this chapter are

$$P_{GG} = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t}$$

$$P_{FG} = \frac{\mu}{\lambda + \mu} - \frac{\mu}{\lambda + \mu} e^{-(\lambda+\mu)t}$$

where

$$\mu = 1/MTTR$$
$$\lambda = 1/MTBF$$
$$MTBF = \text{Mean Time Between Failure}$$
$$MTTR = \text{Mean Time To Repair}.$$

In the subsequent mathematical model, if a non-constant hazard model is used to describe the failure dynamics of a stream of end items, then the transition probabilities are as follows:

$$p^P_{GG} = p_{GG}$$
$$p^P_{FG} = p_{GG}$$
$$p^K_{GG} = p_{GG}$$
$$p^R_{FG} = p_{FG}$$

Note that for the Purchase (P) decision, the probability p_{GG} is applicable to both states since the service rate from state "failed" to state "good" is not dependent on the Mean Time To Repair, but rather on the new system design parameters of the end item that is purchased. Furthermore, the estimated rate of technological improvement, λ, is applied to the old design parameters MTBF and MTTR in an attempt to capture the anticipated improvement in MTBF and MTTR for a new end item. In the next section, the concepts that are developed in the foregoing sections are synthesized into a formal mathematical model for the economic evaluation of a population of repairable units.

3.7 A Mathematical Model

In the foregoing sections the terminology, structure, and notation of a dynamic program to support the repair/replace decision for a population of end items is developed. This dynamic program has a state function that is characterized by two parameters - item age and current operational status of the equipment. The model can be mathematically stated as follows:

$$f_t(a_t, i) = \min_{d} [C^d_{iG} \, p^d_{iG} + p^d_{iG} \, f_{t-1}(a_t, G)] \qquad (4)$$

such that

$$\sum_{a=0}^{t+G} \sum_{i=G}^{F} TC^d_{iG} \le B_t \qquad (a)$$

$$\sum_{v=1}^{r} p_v \, N_r = N_v \le M_{v,t} \qquad (b)$$

$TC^d_{iG}, \ N_r, \ N_v, \ B_t, \ M_{v,t} \ge 0$

t = 1, 2, 3, ... n   (period(s) to go in analysis)

i = G or F   (current operational status)

a = 0, 1, 2, ... t+G (item age, G = current item age)

v = 1, 2, 3, ... r   (level of repair)

In words, constraint (a) states that the Total Cost associated with a particular decision d (d = Purchase, Repair, or Keep) must be less than or equal to the cumulative budget

allocation with t periods to go in the analysis. Constraint
(b) states the following:

(probability of a level v repair)(total number of repairs) =
(number of level v repairs) which must be less than or equal
to the maintenance capacity for a level v repair with t pe-
riods to go in the analysis.

In this modeling approach, there are several levels of
repair facilities available. Thus, p_v denotes the probabil-
ity that a type v repair is required. A diagram of a multi-
repair type of repair supply system is presented in Figure
8.

Flexibility can be introduced to the above dynamic pro-
gram by allowing the decision maker to suppress alternatives
that are not available to him or her due to budget con-
straints. For example, if the decision with two periods re-
maining is to purchase new equipment, but no funds are
available at that time for acquisition, then it is possible
to suppress the purchase decision at this period and continue
on a sub-optimal path. A supplemental cost of deviating from
the optimal path can be readily determined. Also, if the
total number of expected repairs exceeds the repair capacity
constraint, then this decision can be suppressed by continu-
ing along a sub-optimal path. Moreover, the decision maker
may be able to reduce repair time, re-route repairs, or hire

more maintenance personnel if the budget allows. Note that equation (3) can be solved recursively with the initial condition:

$$f_0(a_t, i) = 0. \qquad (5)$$

The foregoing sections develop a general dynamic programming approach that can be used in a repair/replace analysis with deterministic demand. In reality, there is often a time varying or stochastic demand for end items. Wagner and Whitin (131) develop an algorithm for the determination of optimal inventory ordering policies in the presence of a time varying demand. Their approach can be used in an analogous fashion for the determination of optimal maintenance policies. For example, the setup costs in the Wagner-Whitin algorithm correspond to the purchase costs of new equipment; production and holding costs in an inventory system correspond to maintenance, repair, salvage, and operating costs in a maintenance system. Moreover, there is a link between an inventory policy and a maintenance policy that can be captured in a dynamic model. Current inventory levels of end items in a maintenance department can be dynamically incorporated into an approach similar to the Wagner-Whitin algorithm by the following relation:

$$E_t = E_{t-1} + \sum_{k=0}^{t} Q^d_k - \sum_{k=0}^{t} d_k \qquad (6)$$

$$t = 1, 2, 3, \ldots n$$
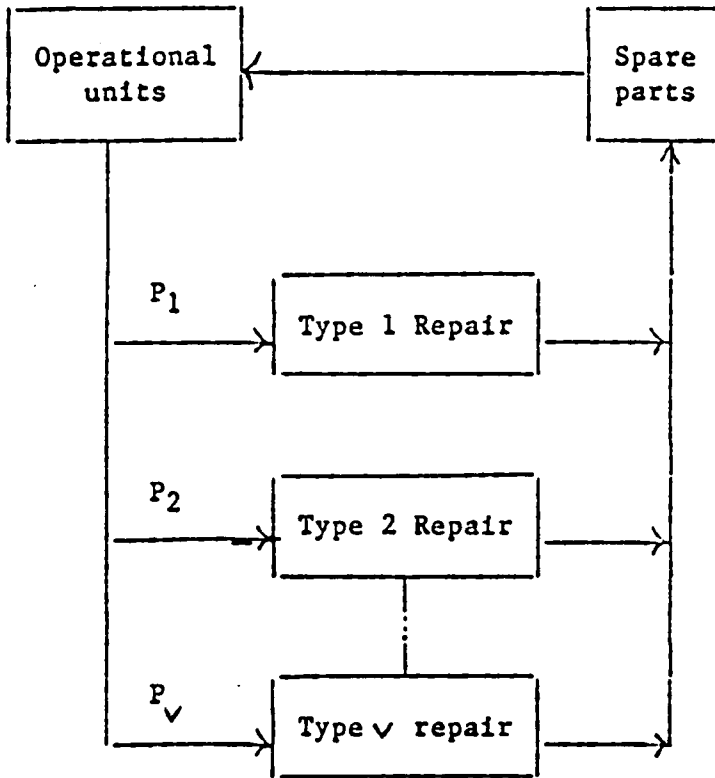
Figure 8. Multi-Repair Type Maintenance System.

where E_t denotes the beginning maintenance inventory of end items with t periods to go and Q^d_k represents the quantity purchased, repaired, or kept in any given period. Note that E_o represents the initial condition or the ending maintenance inventory of end items (i.e. there are no periods to go in the analysis). In this manner, the inventory of end items currently in the warehouse can be economically accounted for in the repair/replace financial analysis. This inventory/maintenance link is further addressed in the section "Areas for Future Research".

The functional equation that represents the minimum cost policy for t periods to go is given by:

$$)=min \begin{bmatrix} (P): R(a_t)\{I_t d_t + [d_t P_t + OC_t(d_t)(1)]p^P_{iG} + p^P_{iG} f_{t-1}(1,G)\} \\ (R): \\ R(a_t)\{I_t d_t + [RC_t(d_t)(1) + OD_t(d_t)(1)]p^R_{FG} + p^R_{FG} f_{t-1}(a_t+1,G)\} \\ (K): R(a_t)\{I_t d_t + [OD_t(d_t)(1)]p^K_{GG} + p^K_{GG} f_{t-1}(a_t+1,G)\} \end{bmatrix}$$

$$t \geq 1$$

such that

$$N_{p,t} + N_{r,t} + N_{k,t} = d_t$$

$$\sum_{a=0}^{t+G} \sum_{i=G}^{F} TC^d_{iG} \leq B_t$$

$$\sum_{v=1}^{r} p_v N_r = N_v \leq M_{v,t}$$

$$f_o(a_t, i) = 0$$

$$TC^d_{iG}, N_{p,t}, N_{r,t}, N_{k,t}, d_t, N_v, B_t, M_{v,t} \geq 0$$

t = 1, 2, 3, ... n   (period(s) to go in analysis)

i = G or F   (current operational status)

a = 0, 1, 2, ... t+G   (item age, G = current item age)

v = 1, 2, 3, ... r   (level of repair)

Note that TC^d_{iG} corresponds to the <u>appropriate</u> total costs associated with a particular decision d (d = Purchase, Repair, Keep). For example, the decision to purchase incurs a purchase or acquisition cost, as well as operating costs for the "challenger" asset. The decision to repair incurs a repair cost and operating costs for the "defender" or present asset. The decision to keep incurs only operating costs of the "defender" asset. Note also that for the purchase alternative, the population age can be at most one period old from the previous period (i.e. $f_{t-1}(1,G)$), since the aging process regenerates upon replacement. However, for both the repair and keep alternatives, the population age increases by one period from the previous period (i.e. $f_{t-1}(a_t+1,G)$), since both these alternatives involve continuous (non-replacement) aging.

As discussed in section 3.4.1, a simplifying assumption is that the state transition probabilities, p_{GF} and p_{FF}, are negligible in comparision with the transition probabilities p_{GG} and p_{FG} Consequently, the products $[p_{GF}(f_{t-1}(a_t+1,F))]$ and $[p_{FF}(f_{t-1}(a_t+1,F))]$ are negligible in comparison with the products $[p_{GG}(f_{t-1}(a_t+1,G))]$ and $[p_{FG}(f_{t-1}(a_t+1,G))]$, respectively, in their application to the appropiate decision action.

Note that for the Purchase alternative in state "good", only the product $[p^P_{GG}(f_{t-1}(1,G))]$ is pertinent, and for state "failed" only the product $[p^P_{FG}(f_{t-1}(1,G))]$ is rele-

vant. With the Repair alternative, the initial state of equipment condition can only be in state "failed", since the possibility of preventive maintenance is not examined. Moreover, the transition probability p^R_{FF} is negligible in comparison with the transition probability p^R_{FG}. Consequently, the product $[p^R_{FF}(f_{t-1}(a_t+1,F))]$ is negligible in comparison with the product $[p^R_{FG}(f_{t-1}(a_t+1,G))]$. An analogous argument can also be applied to the Keep alternative. With the Keep alternative, the initial state of equipment condition can logically only be in state "good". It would not be reasonable to "keep" a defective end item. Therefore, the only legitimate state transition probability in this modeling approach for the Keep alternative is p^K_{GG}. Consequently, only the product $[p^K_{GG}(f_{t-1}(a_t+1,G))]$ is pertinent.

In the next section, the above mathematical model is embellished to incorporate technology effects, since in reality, a dynamic technological environment exists. The decision maker may be confronted with the choice of competing technologies in his or her selection of equipment.

3.8 A Mathematical Model With Technology Effects

Since the repair/replace decision is made in a dynamic environment with a constantly changing technology, it is prudent to consider technology effects in the general modeling approach. In this modeling approach, it is assumed that technology is improving at a gradual rate expressed as a

percentage. Moreover, the technology effects on capital cost and operating expenses are assumed to be linear and exponential, respectively. Such a treatment of technology effects is presented in Jones (59). Suppose that gradual technological improvement is forecasted as developing at a rate of λ with a linear effect on capital cost and an exponential effect on operating costs.

The basic model can then be embellished in the following manner:

$$
f_t(a_t, i) = \min \begin{bmatrix}
(P): \\
R(a_t)\{I_t d_t + [(d_t)P(1-\lambda a_{t.}) + OCe^{\lambda a}t(d_t)(1)]p^P_{iG} + p^P_{iG}* \\
f_{t-1}(1,G)\} \\
\\
(R): \quad R(a_t)\{[I_t d_t + RC_t(d_t)(1) + ODe^{\lambda a}t(d_t)(1)]p^R_{FG} + p^R_{FG}* \\
f_{t-1}(1,G)\} \\
\\
(K): R(a_t)\{[I_t d_t + ODe^{\lambda a}t(d_t)(1)]p^K_{GG} + p^K_{GG}f_{t-1}(a_t+1,G)\}
\end{bmatrix}
$$

$$t \geq 1$$

such that

$$N_{p,t} + N_{r,t} + N_{k,t} = d_t$$

$$\sum_{a=0}^{t+G} \sum_{i=G}^{F} TC^d_{iG} \leq B_t$$

$$\sum_{v=1}^{r} p_v N_r = N_v \leq M_{v,t}$$

$$f_o(a_t, i) = 0$$

$$TC^d_{iG}, N_{p,t}, N_{r,t}, N_{k,t}, d_t, N_v, B_t, M_{v,t} \geq 0$$

$t = 1, 2, 3, \ldots n$	(period(s) to go in analysis)
$i = G$ or F	(current operational status)
$a = 0, 1, 2, 3, \ldots t+G$	(item age, G = current item age)
$v = 1, 2, 3, \ldots r$	(level of repair)

Thus, the above modeling approach allows for the incor-
poration of linear and exponential technology effects. Dif-
ferent functions could be used if the rate of technological
improvement or technological substitution is known with cer-
tainty. Technology effects can be demonstrated by the dif-
ference   between   labor-intensive   and   capital-intensive
equipment.

Labor-intensive equipment does not reflect state-of-the-
art technical advancements, and usually involves a lower ac-
quisition cost than capital-intensive equipment. Generally,
there is a high degree of automation associated with
capital-intensive equipment.   In reality, the purchase of
used equipment that may reflect a moderate degree of techni-
cal sophistication is usually a feasible decision alterna-
tive. The various levels of technological sophistication in
equipment alternatives involve differing levels of operating
characteristics. Therefore, the general operation and main-
tenance costs associated with each technology alternative
also vary. The differences in technology for equipment se-
lections are thus reflected in differing cost matrices of
acquisition cost, and general operation costs. In the next
section, the idea of using planning horizon theory to
embellish the basic model with alternative purchase options
is addressed.

3.9 Planning Horizon Theory and Alternative Purchase Options

The above mathematical model is further embellished to incorporate three different purchase options, P1, P2, or P3. With Purchase Option 1 (P1) the decision maker can purchase 1 period's supply of end items. With Purchase Option 2 (P2), the decision maker can purchase 2 period's supply and carry the next period's supply in inventory. Purchase Option 3 (P3) recommends that the decision maker purchase 3 period's supply and carry the next 2 period's supply in inventory. For example, with 1 period to go, only Purchase Option 1 is available to the decision maker. With 2 periods to go, Purchase Option 2 is available to the decision maker in addition to Purchase Option 1, provided there is sufficient warehouse space to carry 1 period's supply in inventory. If the inventory carrying capacity is exceeded, then only Purchase Option 1 is available for consideration. With 3 periods to go in the analysis, Purchase Option 3 is now available to the decision maker in addition to Purchase Options 1 and 2, provided that there is sufficient warehouse space to carry 2 period's supply in inventory. If the inventory carrying capacity is exceeded, then only Purchase Options 1 and 2 are available to the decision maker. Moreover, if there is inadequate warehouse space to carry 1 period's supply of end items, then Purchase Option 2 is also not available for consideration. With more than 3 periods to go in the analysis, only Purchase Options 1, 2, and 3 are potentially available

to the decision maker. In other words, the modeling approach limits the warehouse carrying capacity to a maximum of 2 period's supply of end items, even though the warehouse space may be available. This constraint is necessary in order to assure that the mathematical computations are tractable.

Recall that with planning horizon theory there is an upper limit as to how far in advance a period's replenishment may be carried forward in a replenishment from previous periods. There comes a point in time when the carrying costs become so prohibitive that it becomes less expensive to have that period's replenishment arrive at the start of the period, rather than to carry that period's supply in inventory. The embellished modeling approach incorporates planning horizon theory in the sense that rather than the carrying costs becoming prohibitive, the warehouse carrying capacity acts as the limiting factor.

The three Purchase Options can be mathematically formulated as follows:

(P1):
$$R(t)\{I_t d_t + [(d_t)P(1-\lambda t) + (d_t)(1)OCe^{\lambda t}]p^P_{iG} + p^P_{iG} f_{t-1}(1,G)\}$$

(P2):
$$R(t)\{I_t d_t + [(d_t + d_{t-1})P(1-\lambda t) + (d_t)(1)OCe^{\lambda t}]p^P_{iG} + CC_t(d_{t-1})\}$$

(P3):
$$R(t)\{I_t d_t + [(d_t + d_{t-1} + d_{t-2})P(1-\lambda t) + (d_t)(1)OCe^{\lambda t}]p^P_{iG} + CC_t(d_{t-1} + d_{t-2})\}.$$

3.10 Estimation of Transition Probabilities

The evaluation of state transition probabilities for equipment is a non-trivial task. The intent of this is to highlight some possible estimation procedures that are available in the literature, and to briefly discuss how decision theory can be used to test subjective probability estimates for consistency. In reality, there is usually an inspection cost that is incurred in order to determine the precise state of the equipment condition. Also, as discussed in Section 3.4.5, there may be several levels of operability within the "good" classification for equipment. Satia and Lave (105) present both a heuristic and a Bayesian approach for the determination of transition probabilities in the face of uncertainty. Ross (100) describes a procedure for the estimation of transition probabilities from past records of the production process. Historical records on equipment repair characteristics could also aid in the evaluation of the probability of a type v repair, p_v, if several levels of repair facilities are available.

Moreover, decision theory could be utilized to test the subjective estimations of probability by a logistician. The principles of correspondence and coherence provide the necessary conditions in a test of rationality. According to Bunn (16), the principle of correspondence maintains that "any belief by an individual should correspond to indisputable fact" (p. 70). Bunn states that with the prin-

ciple of coherence, "all the beliefs and reasons for actions of an individual should be coherent (i.e. there should be no contradictions in his belief-structure)" (p. 70-71). Therefore, decision theory uses the five postulates of coherence -- orderability, substitutability, decomposability, continuity, and monotonicity - to test the rationality of the decision maker. Jones (58) provides a software package that could be utilized by the logistician to evaluate his or her estimates of state transition probabilities. Decision theory is discussed extensively in Bell, Keeney, and Raiffa (6), Bunn (16), and Lifson (72). The subsequent modeling approach does not use any of the estimation procedures for transition probabilities that are available in the literature, but the mathematical model could be embellished to incorporate such techniques. Essentially, the modeling approach depends on historical data that has been collected on the stream of end items for the determination of transition probabilities. In the next section, the dynamic programming solution procedure is illustrated with a two stream replacement model that incorporates technology effects.

3.11 A Numerical Example

In this section, a numerical example is presented for a two stream replacement problem. Stream 1 consists of operating environments A and B, and stream 2 is composed of only operating environment A. Tables 1 and 2 contain data for streams 1 and 2, respectively. State transition probabilities for streams 1 and 2 are presented in Tables 3 and 4, respectively. Note that the transition probabilities for streams 1a and 1b are stationary (i.e. time-independent), since a constant hazard model is used to describe the failure dynamics of streams 1a and 1b. However, the transition probabilities for stream 2a are non-stationary (i.e. time-dependent), since a non-constant hazard model (Weibull) is used to describe the failure dynamics of stream 2a. This example demonstrates a two period financial analysis. Repair capacity constraints for each stream in each period (M_t) are presented in Table 5. Note that there are two levels of repair (LOR) facilities available. A level 1 repair corresponds to a field repair, and a level 2 repair corresponds to a local facility repair. The items in both stream 1a and 1b require a type 1 repair, while the items in stream 2a require a type 2 repair. The budget constraint for each stream in each period (BUD_t) is also presented in Table 5.

Note that the numerical example is intended as an illustration of the modeling approach and that the data has been fabricated. However, the data that is required for the model

would come from historical maintenance records for a partic-
ular group of end items. For example, the model is demon-
strated in Chapter V, "Population Sensitivity Analyses", with
data that has been collected on the U.S. Navy's Side Loadable
Warping Tug (SLWT).

Table 1. Stream 1 Data

Operating Environment:	A		B	
Period definition:	months		months	
Hazard Model:	constant		constant	
Initial Age:	0		1	
Level of Repair:	1		1	
MTBF	10		10	
MTTR	1		1	
Rate of Tech. Imp.	.20		.20	
Periods to go: t	2 (JAN)	1 (FEB)	2 (JAN)	1 (FEB)
d_t	38	46	27	15
cc_t	1.1	1.1	1.1	1.1
I_t	1	1	1	1
RC_t	120	120	45	45

Op. Environment A	Op. Environment B
$OC(t) = 65e^{.2a_t}$	$OC(t) = 33e^{.2a_t}$
$OD(t) = 180e^{.2a_t}$	$OD(t) = 125e^{.2a_t}$
$P(t) = 500(1-.2a_t)$	$P(t) = 325(1-.2a_t)$
$R(t) = e^{-.1a_t}$	$R(t) = e^{-.1a_t}$

Table 2.   Stream 2 Data

| Operating Environment: A |
| Period definition: months |
| Hazard Model: weibull |
| Initial Age: 1 |
| Level of Repair: 1 |
| MTBF   20 |
| MTTR   2 |
| Rate of Tech. Imp.   .20 |

Periods to go: t	2 (JAN)	1 (FEB)
d_t	115	120
CC_t	1.1	1.1
I_t	1	1
RC_t	46	46

$$OC(t) = 47e^{.2a_t} \qquad P(t) = 109(1-.2a_t)$$

$$OD(t) = 93e^{.2a_t} \qquad R(t) = e^{-1/6a_t^{1/2}}$$

**Table 3. Streams 1a and 1b Transition Probabilities
(Constant Hazard Model)**

Condition at Start of Period	Decision	Condition at End of Period Good (G)
Good (G)	Purchase (P)	$p^P_{GG} = .99$
	Keep (K)	$p^K_{GG} = .97$
Failed (F)	Purchase (P)	$p^P_{FG} = .99$
	Repair (R)	$p^R_{FG} = .96$

Table 4. Stream 2a Transition Probabilities
(Weibull Hazard Model)

Condition at Start of Period	Decision	Condition at End of Period Good (G)	
		Period(s) to go	
		2	1
Good (G)	Purchase (P)	p^P_{GG} = .97	.95
	Keep (K)	p^K_{GG} = .96	.94
Failed (F)	Purchase (P)	p^P_{FG} = .97	.95
	Repair (R)	p^R_{FG} = .61	.38

Table 5. Repair Capacity, Maintenance Inventory Carrying Capacity, and Budget Limits

REPAIR CAPACITY (Maintenance levels of end items)

Periods to go: t	2	1	
streams 1a,1b: stream 2:	6 32	5 32	(LOR 1) (LOR 2)

MAINTENANCE INVENTORY CARRYING CAPACITY (number of items)

Periods to go: t	2	1
streams 1a,1b: stream 2a:	10 122	11 124

BUDGET

Periods to go: t	2	1

stream 1:
   OE   A
   OE   B
	$27000
	8500
		$20000
		4000

stream 2: OE A	4000	13000

3.11.1 STREAM 1 Calculations

First, the DP solution methodology is applied to stream 1. In this example, the initial condition is $f_0(a_t, i) = 0$. Gradual technological improvement is forecast as developing at a rate of 20% ($\lambda = .20$) with a linear effect on purchase cost and an exponential effect on operating costs. In this example, the periods refer to the months of January and February. Note that the repair capacity constraints and the budget constraints for each stream in each period (Table 5) apply to each iteration of the following computational procedure. The initial age of the population is 0 (i.e. new equipment). Thus, when the initial condition of the equipment is "good" ($i = G$), and with one period to go in the analysis, or at the start of February, there are two possible decision actions for stream 1a.

$$f(a_t, G) = \min \begin{bmatrix} \text{Purchase (P1): } R(a_t)\{I_t d_t + [500(1-.2a_t)(d_t) + \\ \qquad\qquad (OCe^{.2t})(d_t)(1)]p^P_{GG}\} \\ \text{Keep (K): } R(a_t)\{I_t d_t + [(ODe^{.2a}t)(d_t)(t)]p^K_{GG}\} \end{bmatrix}$$

Consider the decision to purchase, then:

$$I_t(d_t)[P(1-.2a_t)(d_t)+(d_t)(t)OCe^{.2t}]p^P_{GG}$$

$$= 1(46)+ 500(1-.2(1))(d_1)p^P_{GG}+65e^{.2t}(d_1)(1)p^P_{GG}$$

$$= .9048[1(46)+400(46)(.99)+79.4(46)(1)(.99)] = \$19795.10$$

Consider the decision to keep the equipment, then:

$$I_t d_t + [(ODe^{\lambda a}t)(d_t)(t)]p^K_{GG} = I_1 d_1 + [(ODe^{.2(1)})(d_1)(1)p^K_{GG}$$

$$= .9048[1(46)+(219.8)(46)(1)(.97)] = \$8915.42$$

Thus,

$$f_1(1,G) = \min \begin{bmatrix} (P): & 19790.32 \\ (K): & 8915.42 \end{bmatrix} = \$8915.42$$

and $X_1(1,G) = K$. With one period to go in the analysis, and with the initial condition of equipment in state "good" (i = G), the decision action is the keep ("do nothing") alternative in order to meet the anticipated demand of 46 units (no shortages are allowed). Next, the beginning inventory of end items that is required to meet the anticipated demand given the decision to keep the end items is calculated from the following relationship (i.e. equation (6)):

$$E_t = E_{t-1} + \sum_{k=0}^{t} Q_k - \sum_{k=0}^{t} d_k$$

$$= 0 + 46 - 46 = 0.$$

Note that the beginning maintenance inventory, E_0, equals 0.

When the initial condition of equipment is in state "failed" (i = F) with one period to go in the analysis:

$$(R): R(1)\{I_1 d_1 + [RC(d_1)(1)+(d_1)(1)OD_1]p^R_{FG}\}$$

$$(P1): R(1)\{I_1 d_1 + [P(1-.2(1))(d_1)(1) + OCe^{.2(1)}(d_1)(1)]p^P_{FG}\}$$

$$f_1(1,F)=\min \begin{bmatrix} (R) & : & .9048[1(46)+120(46)(1)(.96)+(219.8) \\ & & *(46)(1)(.96)] = 13618.66 \\ \\ (P1): & .9048[1(46)+400(46)(.99)+(79.4) \\ & & *(46)(1)(.99)] = 19795.10. \end{bmatrix}$$

The expected number of repairs, $[(1-R(t))*d_t]$, is computed to be $(1-.9048)(46) = 4.37$ which is less than the repair capacity of 5 units. Note that $(1-R(t))$ is termed the unreliability, or the probability that the system will have failed by time t. Since the repair capacity constraint is not violated, $X_1(1,F) = R$. Consequently, with one period to go in the analysis (February) and with the initial condition of equipment equipment in state "failed" ($i = F$), the decision action is to "repair" the end items in order to meet the anticipated demand of 46 units for this period. This decision action results in a cost of $13618.66. The required beginning inventory level of end items in the maintenance department for the start of February is:

$$E = E_0 + \sum_{k=0}^{t} Q_k - \sum_{k=0}^{t} d_k$$

$$= 0 + 46 - 46 = 0.$$

Thus, this beginning inventory level of zero end items becomes the ending inventory level at the start of the next period in the analysis (January).

With two periods to go in the analysis (January and February), there are now <u>two</u> purchase options available to the decision maker.

Option 1: Purchase enough end items (38) to satisfy only January's demand, then proceed in the "best way" from the start of February with zero inventory of end items.

Option 2: Purchase enough end items (84) to meet the demand requirements for both January and February.

Thus, with two periods to go in the analysis, and with the initial condition of equipment in state "good" (G):

$$f_2(0,G)=\min \begin{bmatrix} (K) & : & 1[1(38)+(38)(180)(1)(.97)+(.97) \\ & & *(8915.42) = 15320.76 \\ \\ (P1): & 1[1(38)+500(38)(.99)+65(38)(1)(.99) \\ & & +(.99)(8915.42)] = 30119.57 \\ \\ (P2): & 1(.98)[1(38)+500(84)(.99)+65(38)(1) \\ & & *(.99)+(1.1)(46)] = 43231.62 \end{bmatrix}$$

and $X_2(0,G) = K$.

Thus, the best decision action is the "keep option 1" which is to keep enough end items to meet the anticipated January demand of 38 units, and then proceed in the "best way" from February. This decision action

results in a cost of $15320.76. Note that a 2% dis-
count is applied to purchase option 2. Next, the re-
quired beginning inventory of end items for the start
of January is:

E = 0 + 38 - 38.

Therefore, the beginning of the next period in the
analysis (December), is then entered with an ending
inventory level of zero end items.

In the mathematical formulation of the model pre-
sented in section 3.7, note that a simplifying assump-
tion is that the products $[p_{GF}(f_{t-1}(a_t+1,F))]$ and
$[p_{FF}(f_{t-1}(a_t+1,F))]$ are negligible in comparison with
the products $[p_{GG}(f_{t-1}(a_t+1,G))]$ and
$[p_{FG}(f_{t-1}(a_t+1,G))]$. For example, when i = F with two
periods to go in the analysis (January and February),
the value $f_1(1,G)$ = $8915.42 is multiplied by p^R_{FG} =
.96 for the repair option and by p^P_{FG} = .99 for the
purchase option. Therefore, with two periods to go and
i = F:

$$f_2(0,F)=\min \begin{bmatrix} \text{(R)} & : & 1[1(38)+120(38)(1)(.96)+38(1)(180) \\ & & *(.96)+(.96)(8915.42)] = 19540.80 \\ \\ \text{(P1)}: & & 1[1(38)+500(38)(.99)+65(38)(1)(.99) \\ & & +(.99)(8915.42)] = 30119.57 \\ \\ \text{(P2)}: & & 1(.98)[1(38)+500(84)(.99)+65(38)(1) \\ & & *(.99)+(1.1)(46)] = 43231.62. \end{bmatrix}$$

The expected number of repairs, $[(1-R(t)*d_t]$, is computed to be $(1-1)(38) = 0$ which is less than the repair capacity of 6 units with 2 periods to go in the analysis. Consequently, $X_2(0,F) = R$. Thus, with two periods to go in the analysis, and the initial condition of equipment in state "failed" ($i = F$), the decision action is to repair 38 units in order to meet the demand requirements of January. This decision action results in a cost of $19540.80. Maintenance inventory requirements are determined to be:

$E = 0 + 38 - 38 = 0$.

Next, the above calculations are applied to operating environment B in stream 1 in a similar fashion. Thus, utilizing operating environment B cost data in Table 2 and the transition probabilities from Table 3, similar results are obtained for stream 1b. Note that since the initial population age is one month old, we can reach February (one period to go) with a population that is either 1 or 2 months old, depending on whether the decision is to purchase or to keep in January.

With one period to go in the analysis (February), and with the initial condition of equipment in state "good" ($i = G$):

$$(P1): \ .9048[1(15)+(260)(15)(.99)+(40.3)$$

$$f_1(1,G) = \min \begin{vmatrix} *(15)(1)(.99)] = 4048.48 \\ \\ (K) : .9048[1(15)+(153)(15)(1)(.97)] \\ = 2023.84 \end{vmatrix}$$

and $X_1(1,G) = K$. Thus, at the beginning of February, with one period to go in the analysis, and with the initial condition of equipment in state "good" ($i = G$), the decision action (d) is to keep the end items in order to meet an anticipated demand of 15 units in this period. The cost is \$2023.84. The required beginning inventory of end items is calculated from the following equation (6):

$$E = 0 + 15 - 15 = 0.$$

Therefore, the beginning of the next period in the analysis (January) is then entered with an ending inventory level of zero end items.

With one period to go in the analysis (February), and with the initial condition of equipment in state "good" ($i = G$), a population of age 2 is evaluated:

$$f_1(2,G) = \min \begin{bmatrix} (P1): .8187[1(15)+(195)(15)(.99)+(49.2) \\ *(15)(1)(.99)] = 2981.19 \\ \\ (K) : .8187[1(15)+(186.5)(15)(1)(.97)] \\ = 2233.88 \end{bmatrix}$$

and $X_1(2,G) = K$. Thus, at the beginning of February, with one period to go in the analysis, and with the initial condition of equipment in state "good" (i = G), the decision action (d) is to keep the end items in order to meet an anticipated demand of 15 units in this period. The cost is \$2233.88. The required beginning inventory of end items is calculated from the following equation (6):

$$E = 0 + 15 - 15 = 0.$$

Therefore, the beginning of the next period in the analysis (January) is then entered with an ending inventory level of zero end items.

When the initial condition of equipment is in the state "failed" (i = F) and with one period to go in the analysis:

$$f_1(1,F) = \min \begin{bmatrix} (P1): & .9048[1(15)+(260)(15)(.99)+(40.3) \\ & *(15)(1)(.99)] = 4048.48 \\ \\ (R) : & .9048[1(15)+(45)(15)(1)(.96)+(152.7) \\ & *(15)(1)(.96) = 2589.43. \end{bmatrix}$$

The expected number of repairs is computed to be (1-.9048)(15) = 1.42 which is less than the repair capacity of 5 units. Therefore, $X_1(1,F) = R$. With one period to go in the analysis (February), and with the initial condition of equipment in state "failed" (i =

F), the decision action is to "repair" the end items in order to meet the anticipated demand of 15 units for this period. The cost is then $2589.43. The beginning inventory of end items that is required is calculated from equation (6) to be:

$$E = 0 + 15 - 15 = 0.$$

Thus, the beginning of January is entered with an ending inventory level of zero for end item 2.

When the initial condition of equipment is in the state "failed" (i = F) and with one period to go in the analysis, a two month old population is evaluated as follows:

$$f_1(2,F) = \min \begin{bmatrix} \text{(P1): } .8187[1(15)+(195)(15)(.99)+(49.2) \\ \qquad *(15)(1)(.99)] = 2981.18 \\ \\ \text{(R) : } .8187[1(15)+(45)(15)(1)(.96)+(152.7) \\ \qquad *(15)(1)(.96)] = 2741.50 \end{bmatrix}$$

and $X_1(2,F) = R$. Therefore, with one period to go in the analysis (February), and with the initial condition of equipment in state "failed" (i = F), the decision action is to "repair" the end items in order to meet the anticipated demand of 15 units for this period. The cost is then $2741.50. The beginning inventory of end items that is required is calculated from equation (6) to be:

$$E = 0 + 15 - 15 = 0.$$

Thus, the beginning of January is entered with an ending inventory level of zero units.

With two periods to go in the analysis (January and February), there are again two purchase options that are available to the decision maker.

Option 1: Purchase enough end items (27) to satisfy only January's demand, then proceed in the "best way" from the start of February with zero inventory of end items.

Option 2: Purchase enough end items (42) to meet the demand requirements for both January and February.

The initial age of the population in January is 1 month old. Thus, with the operational status of the equipment in state "good":

$$f_2(1,G) = \min \begin{bmatrix} (K) & : .9048[1(27)+(152.7)(27)(1)(.97)+(.97) \\ & *(2233.88)] = 5603.49 \\ \\ (P1): & .9048[1(27)+(195)(27)(.99)+(40.3) \\ & *(27)(1)(.99)+(.99)2023.84] = 7528.09 \\ \\ (P2): & .9048(.98)[1(27)+(195)(42)(.99)+(40.3) \\ & *(15)(1)(.99)+(1.1)(15)] = 7758.71 \end{bmatrix}$$

and $X_2(1,G) = K$.

Thus, the best decision action is the "keep" option which is to keep the end items in January to meet an anticipated demand of 27 units, and then proceed in the best way from February. This action results in a cost

of \$5603.49. Note that for the keep alternative, $f_1(2,G) = \$2233.88$, and for purchase option 1, $f_1(1,G)$ = \$2023.84, since non-replacement and replacement aging apply, respectively. The required beginning inventory level is:

$$E = 0 + 27 - 27 = 0.$$

The beginning of December is then entered with an ending inventory level of zero units.

When the initial condition of equipment is in state "failed" ($i = F$), at the beginning of January with two periods to go in the analysis (January and February):

$$f_2(1,F)=\min \begin{bmatrix} (R) : .9048[1(27)+(45)(27)(1)(.96)+(152.7) \\ \quad *(27)(1)(.96)+(.96)(2233.88)] = 6682.19 \\ \\ (P1): .9048[1(27)+(195)(27)(.99)+(40.3) \\ \quad *(27)(1)(.99)+(.99)(2023.84)] = 7528.09 \\ \\ (P2): .9048(.98)[1(27)+(195)(42)(.99)+(40.3) \\ \quad *(15)(1)(.99)+(1.1)(15)] = 7758.71. \end{bmatrix}$$

The expected number of repairs is $(1-.9048)(27) =$ 2.57 which is less than the repair capacity of 6 units. Therefore, $X_2(1,F) = R$, and the best decision action is to repair enough end items in January to meet the anticipated demand of 27 units , and proceed in the "best way" from February. This action results in a cost of \$6682.19. Note that as described in section 3.7, only the products (.96)(2233.88) and

(.99)(2023.84) apply to the repair and purchase options, respectively, where $f_1(2,G) = \$2233.88$ and $f_1(1,G) = \$2023.84$. The beginning inventory level is:

$$E = 0 + 27 - 27 = 0.$$

The beginning of December is then entered with an ending inventory level of zero units.

3.11.2 STREAM 1 Policy Determination

Now that all possible decision options have been enumerated, a policy recommendation can be determined. Table 6 graphically depicts a feasible repair/replace policy for streams 1a and 1b. Note that in stream 1a the initial age of the population is 0 (i.e. new equipment). Therefore, with 2 periods to go in the analysis (or at the start of the planning horizon) and with the operational status of the equipment in state "good", the decision action is to keep the stream of end items. Consequently, the equipment ages by one month and with one period to go in the analysis, the decision action is to keep the incumbent one month old stream of end items. A similar analysis can be performed for state "failed". Note that for operating environment B, the initial population age is two months old. Therefore, with one period to go, the equipment can be either 1 or 2 months old de-

pending on the decision action that is implemented with 2 periods to go in the analysis (or at the start of the planning horizon). With 2 periods to go in the analysis, and the operational status of the equipment in state "good", the decision action is to keep the one month old stream of end items. Consequently, the stream ages by one month, and the decision action with one period to go is to keep the two month old stream. A similar analysis can be performed for state "failed". A set of decision actions form a policy and the cost of the policy in each period is presented under the recommended decision action.

**Table 6. STREAM 1 Policy Recommendation
(Both Operating Environments)**

Operating Environment: A Operational Status: Good		
	Period(s) to go	
Age of Incumbent Population	2	1
0	$X_2(0,G)=K$ $15320.76	
1		$X_1(1,G)=K$ $8915.42
Operational Status: Failed		
0	$X_2(0,F)=R$ $19540.80	
1		$X_1(1,F)=R$ $13618.66
Operating Environment: B Operational Status: Good		
1	$X_2(1,G)=K$ $5603.49	$X_1(1,G)=K$ $2023.84
2		$X_1(2,G)=K$ $2233.88
Operational Status: Failed		
1	$X_2(1,F)=R$ $6682.19	$X_1(1,F)=R$ $2589.43
2		$X_1(2,F)=R$ $2741.50

3.11.3 STREAM 2 Calculations

Since this is a multi-stream replacement problem, stream 2 contains items with different failure characteristics than the items that are grouped together to form stream 1. Note that stream 2 only contains one operating environment. Cost data for stream 2a were presented in Table 2, and the transition probabilities for stream 2a were given in Table 4. The cost calculations for stream 2 are performed in an analogous fashion to those of stream 1. Note that the initial population age is two months old, which means that the population age can be either 1 or 3 months with 1 period to go depending on whether the decision is to purchase or to repair/keep.

When the initial condition of equipment in stream 2a is "good" ($i = G$) at the beginning of February, and with one period to go in the analysis (working backwards):

$$f_1(1,G)=\min \begin{bmatrix} \text{(P1):} & .8465[1(120)+(103.2)(120)(.95)+(57.4) \\ & *(120)(1)(.95)] = 15599.64 \\ \\ \text{(K)} : & .8465[1(120)+(138.7)(120)(1)(.94)] \\ & = 13345.38 \end{bmatrix}$$

and $X_1(1,G) = K$ and the decision action is to keep the end items in order to meet an anticipated demand of 120 units in February. This decision results in a cost of $13345.38. The required beginning inventory is:

$$E = 0 + 120 - 120 = 0.$$

Therefore, the beginning of the next period in the analysis (January) is entered with an ending inventory level of zero units.

Stream 2a is now evaluated for a population age of 3 months old. With the operational status in state "good" ($i = G$) at the beginning of February, and with one period to go in the analysis (working backwards):

$$f_1(3,G)=\min \begin{bmatrix} (P1): & .7492[1(120)+(51.6)(120)(.95)+(85.6) \\ & *(120)(1)(.95)] = 11807.99 \\ \\ (K) : & .7492[1(120)+(19.47)(120)(1)(.94)] \\ & = 14405.86. \end{bmatrix}$$

$X_1(3,G) = P1$, and the decision action is to keep the end items in order to meet an anticipated demand of 120 units in February. This decision results in a cost of $11807.99. The required beginning inventory is:

$$E = 0 + 120 - 120 = 0.$$

Therefore, the beginning of the next period in the analysis (January) is entered with an ending inventory level of zero units.

With the initial condition of equipment in state "failed" (i = F) at the start of February with one period to go in the analysis:

$$f_1(1,F)=\min \begin{bmatrix} \text{(P1): } .8465[1(120)+(87.2)(120)(1)(.95) \\ \qquad +(57.4)(120)(1)(.95)] = 14055.62 \\ \\ \text{(R) : } .8465[1(120)+(46)(120)(.38)+(113.5) \\ \qquad *(120)(1)(.38)] = 7374.78. \end{bmatrix}$$

The expected number of repairs, $[(1-R(t)*d_t]$, is computed to be $(1-.8465)(120) = 18.42$ and is less than the repair capacity of 32 units. Therefore, $X_1(1,F) = R$, and the best decision is to repair the end items in order to meet an anticipated demand of 120 units in February. The cost of this decision is $7374.78. The required beginning inventory for the start of February is:

$$E = 0 + 120 - 120 = 0.$$

The beginning of the next period in the analysis (January) is then entered with an ending inventory level of zero end items.

Next, the population age of 3 months old is evaluated. With the operational status of equipment in state "failed" (i = F) at the start of February with one period to go in the analysis:

$$f_1(3,F) = \min \begin{bmatrix} (P1): & .7492[1(120)+(43.6)(120)(.95)+(85.6) \\ & *(120)(1)(.95)] = 11124.72 \\ \\ (R): & .7492[1(120)+(46)(120)(.38)+(169.4) \\ & *(120)(1)(.38)] = 7448.73. \end{bmatrix}$$

The expected number of repairs is computed to be $(1-.7492)(120) = 30.09$ which is less than the repair capacity of 32 units. Therefore, $X_1(1,F) = R$, and the best decision is to repair the end items in order to meet an anticipated demand of 120 units in February. The cost of this decision is \$7448.73. The required beginning inventory for the start of February is:

$$E = 0 + 120 - 120 = 0.$$

The beginning of the next period in the analysis (January) is then entered with an ending inventory level of zero end items.

As in stream 1 with two periods to go in the analysis (January and February), there are <u>two</u> purchase options available to the decision maker.

Option 1: Purchase enough end items (115) to satisfy only January's demand, then proceed in the "best way" from the start of February with zero inventory of end items.

Option 2: Purchase enough end items (235) to meet the demand requirements for both January and

February.

In the economic analysis for January, the initial population age is 2 months old. Thus, with the operational status of equipment in state "good" ($i = G$):

$$f_2(2,G)=\min \begin{bmatrix} (P1): & .7900[1(115)+(65.4)(115)(1)(.97)+(70.1) \\ & *(115)(1)(.97)+(.97)(13345.38)] = 22258.28 \\ \\ (P2): & .7900(.98)[1(115)+(235)(65.4)(1)(.97)+ \\ & (70.1)(115)(1)(.97)+(1.1)(120)] = 17786.92 \\ \\ (K) : & .7900[1(115)+(138.7)(115)(1)(.96) \\ & (.96)(14405.86)] = 23113.12. \end{bmatrix}$$

In this case, the minimum cost corresponds to Purchase option 2, which means to purchase 235 units to supply the demand requirements for both January and February. With this option, February's requirements of 120 units will need to be carried in inventory at a cost of $(120)(1.1) = \$132$. The inventory carrying capacity constraint of 122 units with 2 periods to go is not violated. Therefore, $X_2(2,G) = P2$. and, the best decision action is to purchase enough end items (235) to meet the demand requirements for both January and February. The cost of this decision is $17786.92. Note that the values $f_1(1,G) = \$13345.38$ and $f_1(3,G) = \$14405.86$ are the returns from the previous period for the purchase and keep options, respectively. The required beginning inventory of end items in the maintenance department for the start of January is:

$$E = 0 + 235 - 115 = 120.$$

The beginning of the next period in the analysis (December) is then entered with an ending inventory level of 120 units.

When the initial condition of equipment is in state "failed" ($i = F$) at the beginning of January, with two periods to go in the analysis (January and February):

$$f_2(2,F)=\min \begin{bmatrix} \text{(P1): } .7900[1(115)+(65.4)(115)(1)(.97)+(70.1) \\ *(115)(1)(.97)+(.97)(13345.38)] = 22258.28 \\ \\ \text{(P2): } .7900(.98)[1(115)+(65.4)(235)(1)(.97)+ \\ (70.1)(115)(1)(.97)+(1.1)(120)] = 17786.92 \\ \\ \text{(R) : } .7900[1(115)+(46)(115)(1)(.61)+(138.7) \\ *(115)(1)(.61)+(.61)(11807.99)] = 16016.92 \end{bmatrix}$$

The expected number of repairs is computed to be $(1-.79)(115) = 24.15$, which is less than the repair capacity of 32 units. Therefore, $X_2(2,F) = R$ or repair enough end items in January to meet the demand requirements of 115 units. The cost of this decision is $16016.92. As discussed in section 3.7, the products $(.97)(13345.38)$ and $(.61)(11807.99)$ represent the returns form the previous period for the purchase and repair options, respectively, where $f_1(1,G) = \$13345.38$ and $f_1(3,G) = \$11807.99$. The required beginning inventory level for the start of January is:

$$E = 0 + 115 - 115 = 0.$$

The beginning of the next period in the analysis (December) is then entered with an ending inventory level of 0 units.

3.11.4 STREAM 2 Policy Determination

As with stream 1, now that the all possible decision actions have been enumerated, a repair/replace policy can be ascertained for stream 2. This policy is graphically depicted in Table 7. As before, a policy is a set of decision actions. For example, with the operational status of equipment is state "good", and with the initial population age of 2 months old, the decision action is P2, which means to purchase 2 periods' supply and carry one period in inventory. The cost of this decision action is $17786.92. Note that with one period to go, the population age can be either 1 or 3 months old, depending on the decision action that is implemented with 2 periods to go in the analysis. In this case, the recommended action is P2, and the new equipment ages one month by the next period. Consequently, the population age is now one month old, and the decision action is to keep the one month old stream of end items at a cost of $13345.38. A similar

analysis can be performed for state "failed". However, note that if the decision is made to repair the month old equipment with two periods to go, then the equipment ages by one month, and with one period to go, only a population of three months old need be considered.

Table 7.   STREAM 2 Policy Recommendation

Operating Environment: A		
Operational Status: Good		
		Period(s) to go
Age of Incumbent Population	2	1
1		$X_1(1,G)=K$ $13345.38
2	$X_2(2,G)=P2$ $17786.92	
3		$X_1(3,G)=P1$ $11807.99
Operational Status: Failed		
1		$X_1(1,F)=R$ $7374.78
2	$X_2(2,F)=R$ $16016.92	
3		$X_1(1,F)=R$ $7448.73

3.11.5 Stream Aggregation

Streams 1 and 2 can now be aggregated to determine period by period costs. First, the costs corresponding to states "good" and "failed" must be aggregated for each stream per operating environment. The costs per operating environment are then aggregated to determine period by period stream costs. As discussed in section 3.6, the availability function gives the probability that an end item (or system) is operational at time t. Since a constant hazard model is used to describe the failure dynamics of streams 1a and 1b, the availability is computed as follows:

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t}$$

where

$\mu = 1/MTTR$
$\lambda = 1/MTTF$
MTBF = Mean Time Between Failure
MTTR = Mean Time To Repair
MTTF = Mean Time To Failure.

Thus,

| | Period(s) to go | | |
	2	1	0
Availability	.9108	.9329	1
Unavailability	.0892	.0671	0

Note that the unavailability is the complement of the availability (i.e. 1-A(t)). The calculations for stream 1 are as follows:

STREAM 1

Period to go: 1

Operating Environment A:
    (.9329)(8915.42)+(.06710(13618.66) = 9231.01
Operating Environment B:
    (.9108)(2233.88)+(.0892)(2741.50) = 2279.16

                                Total... $11510.17

Periods to go: 2

Operating Environment A:
    (1)(15320.76)+(0)(19540.80)   = 15320.76
Operating Environment B:
    (.9329)(5603.09)+(.0671)(6682.19) = 5675.87

                                Total... $20996.63.

The calculations for stream 2 are performed in an analogous fashion. However, note that a non-constant hazard model (Weibull) describes the failure dynamics for stream 2. In this case, as discussed in section 3.6, the "inherent availability" is used to compute the probability of the end item (or system) being operational at time t. The "inherent availability" is calculated as follows:

$$A_i = \frac{MTBF}{MTBF + MTTR.}$$

In this case, the availability is not time-dependent and is computed to be .9091. The unavail-

ability, or the probability that the system is not operational at time t, is .0909. The stream aggregation calculations for stream 2 are as follows:

Period to go: 1

Operating Environment A:
   (.9091)(13345.38)+(.0909)(7448.73) = 12809.37

Periods to go: 2

Operating Environment A:
   (.9091)(17786.92)+(.0909)(16016.92) = 17626.03.

Note that these policy costs represent aggregated returns. Consequently, the values must be compared to the cumulative budgetary constraint to determine if the financial resources are binding. In all cases but one the budget constraint is non-binding. However, for stream 2 with 2 periods to go, the policy cost is $17626.03 which exceeds the cumulative budgetary constraint of $17000.00. A supplemental cost of $626.03 must be expended if this policy recommendation is to be implemented. Note that the modeling approach does not recommend an alternative policy if the supplemental funds can not be allocated. This is a deficiency in the model.

3.11.6 Stream Summary

The aggregated stream costs can now be summarized as follows:

Period to go: 1

Stream 1:	$11510.17
Stream 2:	12809.37
Total....	$24319.54

Periods to go: 2

Stream 1:	$20996.63
Stream 2:	17626.03
Total....	$38622.66.

Note that stream 1 accounts for 47.32% of the expected future costs with 1 period to go, and stream 2 accounts for 52.68% of the costs. With two periods to go, stream 1 represents 54.63% of the expected future costs, and stream 2 accounts for 45.37% of the costs. Thus, it would appear that the costs for stream 1 are increasing with time, and stream 2 costs are decreasing with time.

3.11.7 Population Summary

The expected future costs of the population of two streams can now be computed. These aggregated costs are:

Period(s) to go	Expected Future Costs
2	$38622.66
1	$62942.20
	Total... $62942.20.

Thus, for a population of two primary or main streams, the expected future costs for a planning horizon of two months are $62942.20.

It is important to remember that the above calculations reflect an economic analysis coupled with the imposition of physical and financial constraints. Although a decision action may recommend that two months supply of a particular end item be carried forward in the maintenance inventory to meet an anticipated demand, the physical reality of warehouse space limitations may render such an alternative infeasible. Suppose that the analysis indicates that the "best" decision alternative is to purchase two months supply of gyrocompasses in order to meet both January and February's anticipated demand. The budget constraint and the repair capacity constraint are not violated, and the decision action appears to be feasible. However, it may not be possible to carry forward the extra month's supply of gyrocompasses due to a constraint on warehouse storage capacity (cubic feet or number of units). The physical reality of storage capacity must also be considered with the economic analysis. The separation of constraints into physical and non-physical facilitates insights into actual policy implementation.

Note that at the present time, if the supplemental funds of exceeding the budget are not allocated, then the modeling approach does not offer an alternative policy. This is a deficiency in the model which could be improved by tracing a "sub-optimal" path through the period by period dynamic programming calculations. However, this requires modification of both the current modeling approach and the accompanying software package.

The results of the dynamic programming calculations can now be summarized in a decision matrix format. This decision matrix provides the logistician with a concise summary of action programs in a repair/replace analysis.

3.11.8 Repair/Replace Decision Matrix

In this section, a decision matrix is presented that assists the decision maker with determining decision strategies for the multi-stream replacement problem. The decision matrix for stream 1 is presented in Table 8 and the matrix for stream 2 is presented in Table 9. Note that if the foregoing model and stream parameters are inputted into the software package, "A Dynamic Repair/Replace Population Model" or DRRPM, there will be a slight discrepancy in DRRPM output values from the values in the Repair/Replace Decision Matrix due to the increased accuracy of computer calculations.

Table 8.   STREAM 1 Decision Matrix

Periods to go: t	2		1		
State of equipment at start of period: i	G	F	G	F	
Avail./Unavail.	.9329	.0671	1	0	
Starting Maintenance Inventory: E_t	0	0	0	0	OE A
	0	0	0	0	OE B
Decision Action to take at start of period: $X_t(i)$	K	R	K	R	OE A
	K	R	K	R	OE B
Level of Repair:		1		1	OE A
		1		1	OE B
Demand: d_t	38	38	46	46	OE A
	27	27	15	15	OE B
Requirements:	38	84	46	46	OE A
	27	27	15	15	OE B
Policy Cost: f_t	15320.76	19540.80	8915.42	13618.66	OE A
	5603.49	6682.19	2233.88	2741.50	OE B
Ending Maintenance Inventory: E_{t-1}	0	0	0	0	OE A
	0	0	0	0	OE B

Legend: G = Good   P1 = Purchase option 1
          F = Failed   P2 = Purchase option 2
          R = Repair   P3 = Purchase option 3
          K = Keep

Table 9. STREAM 2 Decision Matrix

Periods to go: t	2		1			
State of equipment at start of period: i	G	F	G	F		
Avail./Unavail.	.9091	.0909	.9091	.0909		
Starting Maintenance Inventory: E_t	0	0	0	0	OE	A
Decision Action to take at start of period: $X_t(i)$	P2	R	K	R	OE	A
Level of Repair:		2		2	OE	A
Demand: d_t	115	115	120	120	OE	A
Requirements:	235	115	120	120	OE	A
Policy Cost f_t	17786.92	16016.92	13345.38	7448.73	OE	A
Ending Maintenance Inventory: E_{t-1}	120	0	0	0	OE	A

Legend: G = Good   P1 = Purchase option 1
          F = Failed   P2 = Purchase option 2
          R = Repair   P3 = Purchase option 3
          K = Keep

Note that these decision matrices yield the best decision at any point in time. For example, with two periods remaining in the economic analysis, and with the current operational status of the stream of end items in state F ("failed"), then the policy decision for operating environments A and B of <u>stream 1</u> is to repair in both cases. Note that a level 1 or a field repair is required. The policy costs of these decisions are $19540.80 and $6682.19, respectively. Moreover, with two periods remaining in the analysis, and if operating environment A of <u>stream 2</u> is in state G ("good") with two periods to go, then the decision of "purchase option 2" results in a policy cost of $17786.92.

In the next section, a suggested modeling approach for the activities in a network of repair facilities is presented. Essentially, the repair activity for each stream is separately determined, and then these disaggregated activities are later merged to ascertain the system repair activity.

3.11.9 Repair Facilities

Hunter and Proschan (55) observe that the probability of at least n failures during [0,t] and the $E_F(t)$, the expected number of failures during (0,t) can be obtained by using the Poisson distribution.   With Markovian or approximate Markovian deterioration, the probability of failure during any interval of time is independent of the number of preceding failures.   Thus, with the multi-stream or nested Markov chain model, independent Poisson processes can be merged to produce a Poisson process as shown in Figure 9.

Stream 1
$N_1(t)$

Output Stream
$N_S(t)$
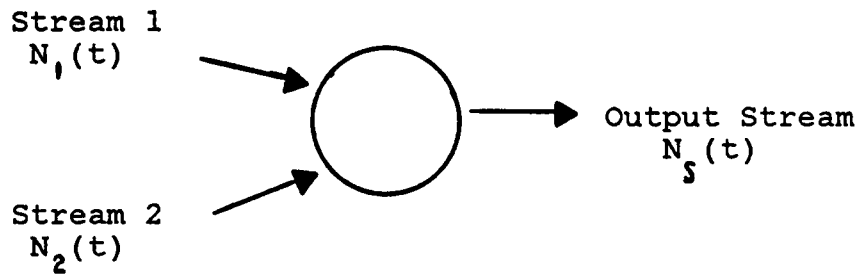
Stream 2
$N_2(t)$

Legend: $N_1(t)$ = # of failures in stream 1

$N_2(t)$ = # of failures in stream 2

$N_S(t)$ = # of failures in system

Figure 9. Merging Two Repair Processes

Thus, the Poisson process could be used to model the re-
pair situation where a count is made of the number of events
(failed equipment) occurring in a given period of time. The
state at time t would correspond to the number of failures
by time t. From Figure 7, let $N_1(t)$, $N_2(t)$, and $N_s(t)$ cor-
respond to the numbers of failures occurring in stream 1,
stream 2, and the system, respectively. Then,

$$N_s(t) = N_1(t) + N_2(t)$$

where $N_1(t)$ and $N_2(t)$ are Poisson distributed random vari-
ables. $N_s(t)$ is also a Poisson process, since it is the sum
of Poisson processes. Moreover, if λ_1 and λ_2 are the rates
of occurrence of the stream 1 and stream 2 failure process,
then

$$E[N_1(t)] = \lambda_1 t$$

$$E[N_2(t)] = \lambda_2 t$$

$$E[N_s(t)] = E[N_1(t) + N_2(t)]$$

$$= E[N_1(t)] + E[N_2(t)]$$

$$= \lambda_1 t + \lambda_2 t$$

$$= (\lambda_1 + \lambda_2)t.$$

Thus, the rate of occurrence of the system failure process is the sum of the rates of failure occurrence in the individual streams.

3.11.10 Discounting

The foregoing multi-stream model could be embellished to incorporate a discount rate α ($0 \le \alpha \le 1$). The discounting factor attempts to capture the influence of the time value of money. Thus, equation (4) can be re-stated as:

$$f_t(a_t,i) = \min_{\alpha} \, [\alpha C^d_{iG} p^d_{iG} + \alpha p^d_{iG} f_{t-1}(a_t,G)]$$

$$t \ge 1$$

such that

$$\sum_{a=0}^{t+G} \sum_{i=G}^{F} TC^d_{iG} \le B_t$$

$$\sum_{v=1}^{r} p_v N_r = N_v \le M_{v,t}$$

$$TC^d_{iG}, \ N_r, \ N_v, \ B_t, \ M_{v,t} \ge 0$$

$t = 1, 2, 3, \ldots n$ (period(s) to go in analysis)

$i = G$ or F (current operational status)

$a = 0, 1, 2, \ldots t+G$ (item age, G = current item age)

$v = 1, 2, 3, \ldots r$ (level of repair).

In the next section, the modeling approach is summarized and pertinent conclusions are presented.

3.12 <u>Chapter Summary and Conclusions</u>

In this chapter, a general modeling approach for the multi-stream replacement problem was introduced. The modeling approach accommodates both constant hazard and non-constant hazard models, since a dynamic program was formulated where the state function was characterized by two parameters - item age and current operational status of the equipment. The assumptions pertinent to the modeling approach are explained. Since a dynamic programming solution methodology was employed, the fundamentals of dynamic programming are discussed in the context of the repair/replace decision. Model notation was presented, and both a general mathematical model and a mathematical model with technology effects are developed. The rate of technological improvement was incorporated in the model by allowing for both linear and exponential effects on acquisition cost and operating expenses, respectively. The modeling approach was demonstrated via a two stream numerical example that has both a budget constraint and a repair capacity constraint. There are two levels of repair considered in the example, and the economic analysis was for two periods. However, the essence of the modeling approach was captured in this example, and planning horizon theory was invoked to offer three different purchase options. The repair/replace decision matrix was presented

as an organizational tool for the logistician in summarizing and economically evaluating a feasible maintenance policy during a specified planning horizon. A modeling approach for the network of repair facilities was proposed and the issue of discounting was also addressed.

The solution of the multi-stream replacement problem is a non-trivial problem. As the above modeling approach demonstrates, a dynamic programming solution methodology can be utilized to develop a feasible policy to meet a stochastic demand during a finite horizon. Furthermore, an approach analogous to the Wagner-Whitin algorithm can be used to examine the interrelationships between a maintenance policy and an inventory policy for a stream of end items. It was also seen that interdependencies between inventory/maintenance systems do exist, and can be captured in a dynamic program. Dynamic programming has ready-made sensitivity analysis, and has the flexibility to incorporate a budget constraint and a repair capacity constraint.

In the next chapter, population model implementation is discussed. As the number of streams of end items increases, the problem can become intractable. Fortunately, the computational power of the computer can be used to create an implementable decision support system. A computerized model is subsequently developed and demonstrated in the next chapter.

IV. POPULATION MODEL IMPLEMENTATION

4.1 Introduction

In this chapter, the software package that was developed to support the general modeling approach of the previous chapter is described. This mainframe package is entitled "A Dynamic Repair/Replace Population Model" or DRRPM. The computer model was developed at Virginia Tech using the facilities of the Virginia Tech Computing Center. The package runs on the VM2 system which is controlled by an IBM 3084 processor. The Program Operator's Manual that accompanies the DRRPM software is contained in Appendix I.

The mainframe package is interactive in nature. The user is prompted for various stream input parameters that are listed in Table 10, and these values are subsequently processed in the main module. Stream output is then made available for user viewing and analysis through several options. The user can view either detailed stream by stream output, a stream summary, or a population summary. If a personal computer is used as a terminal and is connected on-line to a printer, printouts of all input and output screens can be readily obtained by simply pressing "SHIFT PrtSc".

In the next section of this chapter, population model data requirements are discussed. A table of input parameters is presented. The problems associated with data collection

are also addressed. The capabilities and limitations of the computer model are then elucidated with flowcharts and explanations of the main program and sub-routines. Areas for program expansion are then addressed, and appropriate levels of model application are highlighted. Finally, the computerized model is summarized and pertinent conclusions are presented.

4.2 Population Model Data Requirements

The data requirements for the "Dynamic Repair/Replace Population Model" or DRRPM are rather extensive, principally due to the nature of logistics problems. The computerized model is capable of evaluating 12 primary or main streams with 2 operating environments per stream for a planning horizon of 12 periods. For example, streams 1a,1b, and 2a are the equivalent of 2 primary streams. A table of stream input parameters for just one stream and one operating environment is presented in Table 10.

As can be seen from Table 10, data requirements involve the input of both system and stream input parameters. System parameters include period definition, number of periods, number of streams, and retirement age of the population. These parameters establish a framework for the overall population of end items. Note that the user can define the period to be weeks, months, or years, and all subsequent input parameters must be entered in terms of the defined period to

ensure proper dimensionality. Stream parameters involve once per stream and period by period parameters. The parameters that are required once per stream are: stream number, operating environment, stream name, current population age, present purchase price, salvage value, repair cost, present operating costs for both the "defender" and "challenger" assets, maintenance inventory carrying cost, inspection cost, estimated rate of technological improvement, transition probabilities, hazard model, Mean Time Between Failure (MTBF), and Mean Time To Repair (MTTR). The parameters that are required on a period by period basis are: forecasted demand, budget limit, repair capacity, and maintenance inventory carrying capacity.

Brammer (14) observes that data collection in logistics systems is a non-trivial task, and that maintenance data may not be readily available. He lists sources of logistics data as in-house maintenance records, outside source maintenance records, manufacturer information or test data, and independent source test data.[14] In the past, manual data collection systems have been utilized; however, automated data collection systems are very popular today. Norfolk Southern Corporation, a member of the railroad industry, currently

---

[14] Brammer, p. 138.

utilizes the Computer Aided Reporting System or CARS.[15] CARS revolves around a hand-held Motorola computer that prompts railroad workers for repair information and transmits the information by radio waves to a main computer that prints the proper code on repair shop reports. Such a system coupled with bar-coding has significant potential as a data collection system in other logistics applications. In the next section, the "Dynamic Repair/Replace Population Model (DRRPM)" is explained in more detail.

---

[15] D. Rosenthal, "On the High-Tech Track", <u>Roanoke Times and World News,</u> Jan. 19, 1986, p. EC1.

Table 10. Population Model Data Requirements

System parameters:

Period definition	Number of streams
Number of periods	Retirement age of population

Once Per Stream Parameters:

Stream Number	Operating Cost of the "defender"
Operating Environment	Operating Cost of the "challenger"
Stream Name	Inventory Carrying Cost
Current Population Age	Inspection Cost
Purchase Price	Rate of Tech. Improvement (%)
Salvage Value	Level of Repair
Repair Cost	Transition Probabilities
MTBF	Hazard Model
MTTR	

Period By Period Data:

Forecasted Demand
Budget Limit
Repair Capacity (number of units)
Maintenance Inventory Capacity (number of units)

4.3 Computer Model Development: A Modular Approach

As Figure 10 demonstrates, the "Dynamic Repair/Replace Population Model", or DRRPM, was developed in modules. The overall driver for DRRPM is programmed in EXEC2. The input module is programmed in EXEC2 and controls the flow of a series of input screens. These input screens prompt the user for both system and stream parameters. The input screens were designed utilizing IBM's Display Management System or DMS. Stream input data files are created upon completion of user input. The main module is programmed in FORTRAN 77 and initially reads data from the stream input files. This data is then used to perform the dynamic programming calculations and the resultant output is stored in stream output files. The display module is programmed in EXEC2 and leads the user through a series of output screens, so that both stream and population data can be viewed and analyzed. As with the input module, the screens for the output module are created using IBM's Display Management System or DMS.

4.3.1 DRRPM Operation

Figure 11 sketches the DRRPM processing flow. The user simply types "program" to initiate the computerized model. The EXEC2 driver for the overall computer model is entitled "PROGRAM" and contains a series of EXEC2 statements that control subsequent processing. The EXEC2 input module is entitled "INPUT" and leads the user through a series of in-

EXEC2 (DRIVER)

EXEC2

INPUT MODULE

DMS

DATA FILES

↓

FORTRAN 77

DYNAMIC PROGRAMMING CALCULATIONS

OUTPUT FILES

↓

EXEC2

DISPLAY MODULE

DMS
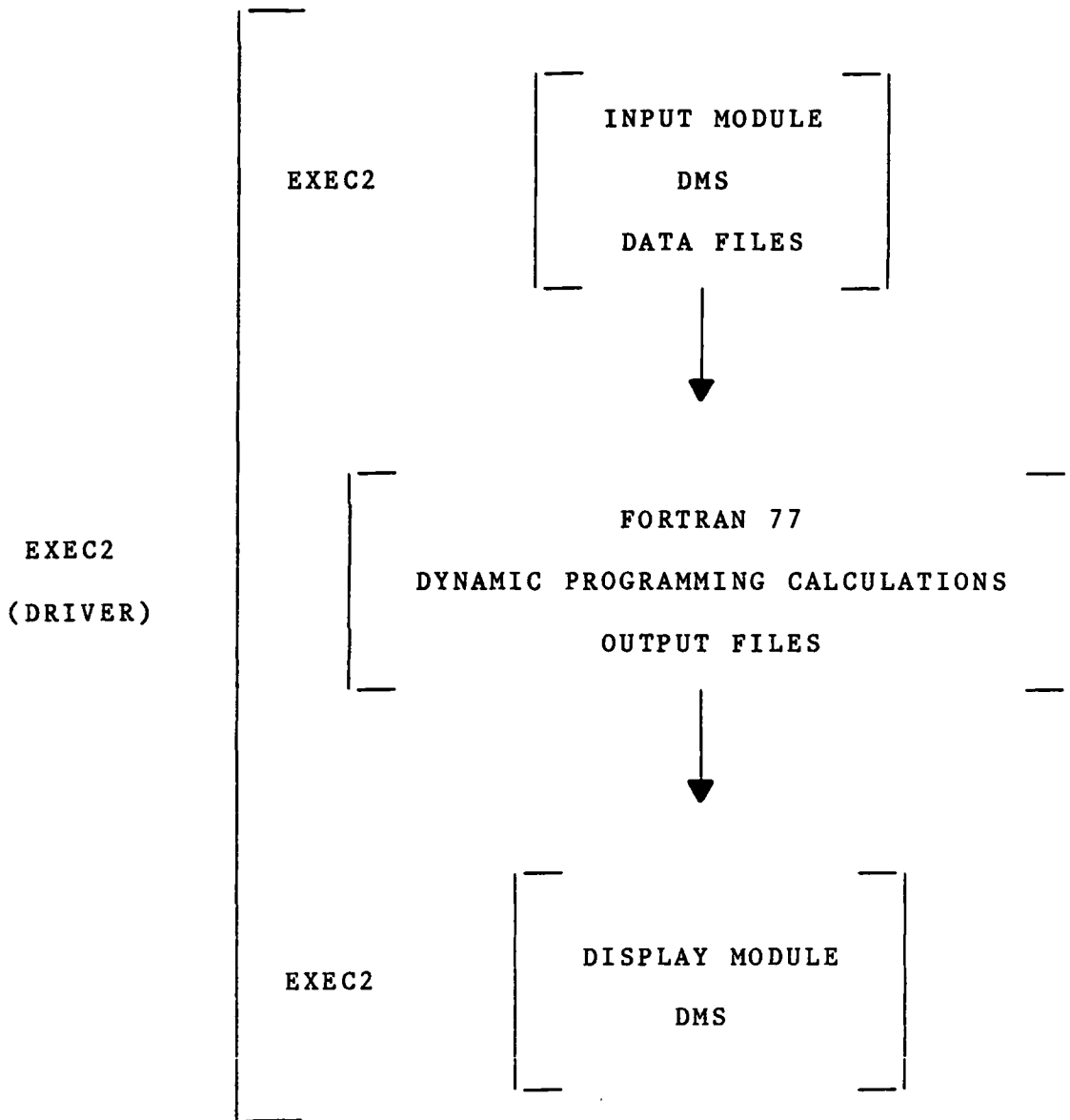
Figure 10.   A Modular Approach.

troductory screens so that data can be entered for each stream. Data options include: a sample case study, the use of existing data, or all new inputs. "NAVY" is an EXEC2 program that defines 68 files that are potentially used for DRRPM processing. Fifteen of the 68 files are used to store data for a sample case study. The main module is entitled "MAIN" and is programmed in FORTRAN 77. This module reads data from stream input files to perform the dynamic programming calculations. "OUTPUT" is the EXEC2 driver for the the series of output screens, and "PRINTER" is the EXEC2 driver that controls printer options. Printer options include: stream by stream output, a stream summary, or a population summary. The source code for each module is listed in Appendix III (Appendices B.1 - B.5).

4.3.2 MAIN Module Operation

In this section, the MAIN FORTRAN 77 module is explained in more detail, and explanations of sub-routines for the MAIN module are also presented. A flowchart of the MAIN module is presented in Figures 12 - 14. As the flowchart indicates, system constraints that establish a framework for model operation are initially read from a data file. Next, stream input data are then read from data files. The return value is initialized to zero, and the loop for the dynamic programming calculations is then entered.

```
┌─────────────┐
│             │
│   PROGRAM   │     :    EXEC2   DRIVER FOR THE
│             │
└─────────────┘          OVERALL COMPUTER MODEL
       │
       ▼
┌─────────────┐
│             │
│   INPUT     │     :    EXEC2   STREAM INPUT
│             │
└─────────────┘          DRIVER
       │
       ▼
┌─────────────┐
│             │
│   NAVY      │     :    EXEC2   FILE DEFINITIONS
│             │
└─────────────┘          DRIVER
       │
       ▼
┌─────────────┐          FORTRAN77   MAIN MODULE -
│             │
│   MAIN      │     :    PERFORMS DYNAMIC PROGRAMMING
│             │
└─────────────┘          CALCULATIONS
       │
       ▼
┌─────────────┐
│             │
│   OUTPUT    │     :    EXEC2   STREAM OUTPUT
│             │
└─────────────┘          DRIVER
       │
       ▼
┌─────────────┐
│             │
│   PRINTER   │     :    EXEC2   PRINTER OPERATIONS
│             │
└─────────────┘          DRIVER
```
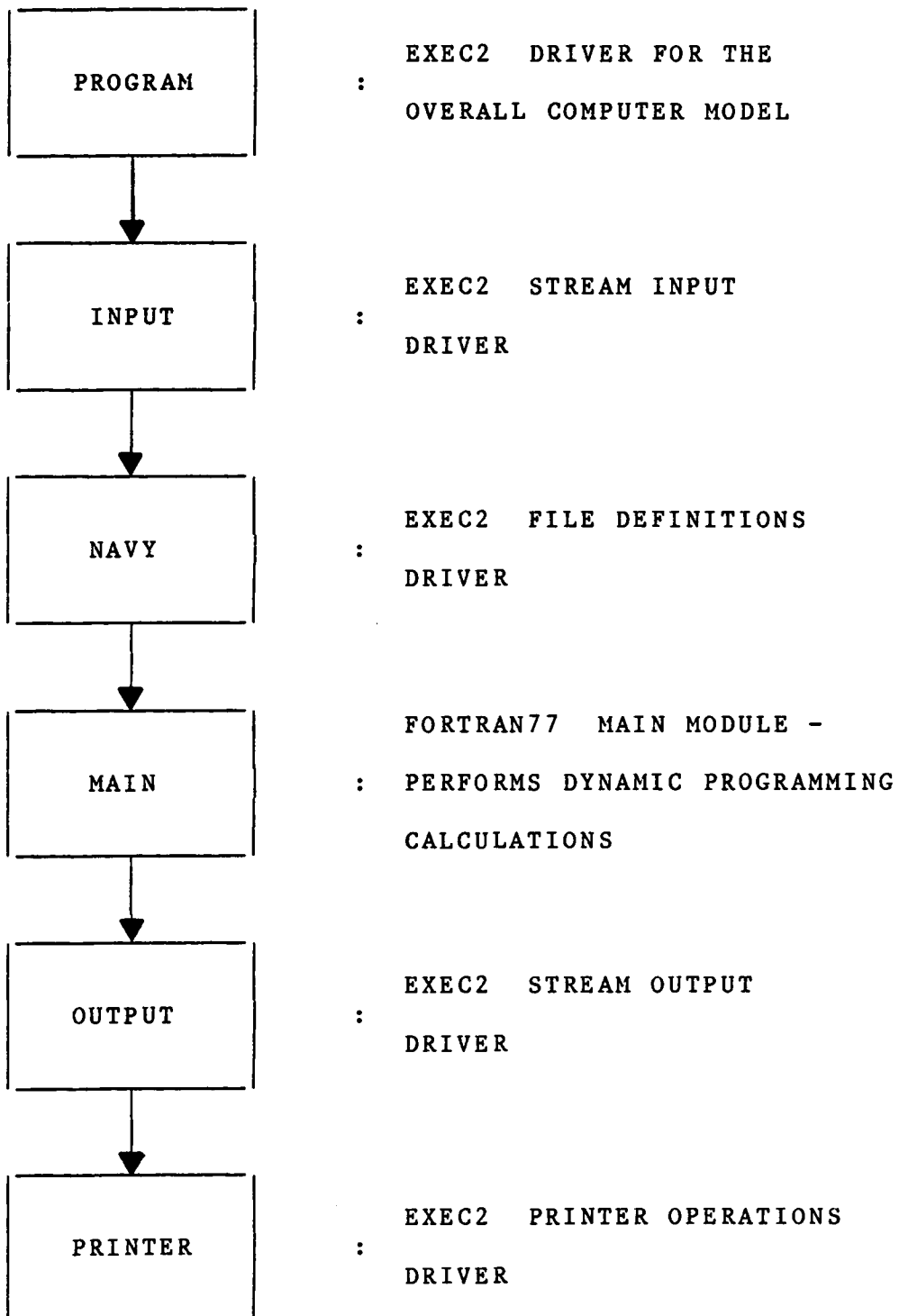
Figure 11.   DRRPM Processing Flow.
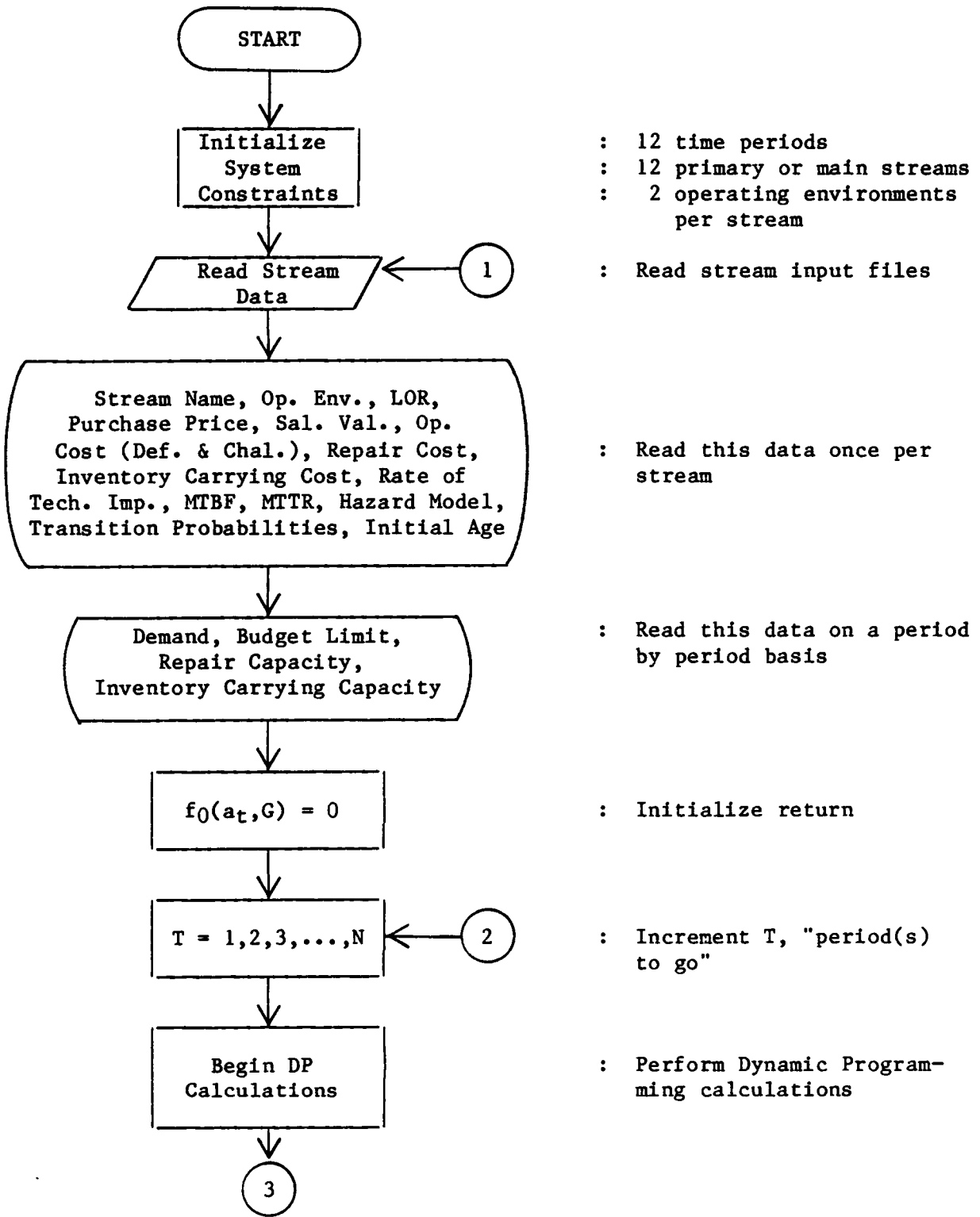
Figure 12. Flow Chart for MAIN FORTRAN 77 Module.

The flow chart contains the following elements:

- START
- Initialize System Constraints
  - : 12 time periods
  - : 12 primary or main streams
  - : 2 operating environments per stream
- Read Stream Data ← (1)
  - : Read stream input files
- Stream Name, Op. Env., LOR, Purchase Price, Sal. Val., Op. Cost (Def. & Chal.), Repair Cost, Inventory Carrying Cost, Rate of Tech. Imp., MTBF, MTTR, Hazard Model, Transition Probabilities, Initial Age
  - : Read this data once per stream
- Demand, Budget Limit, Repair Capacity, Inventory Carrying Capacity
  - : Read this data on a period by period basis
- $f_0(a_t,G) = 0$
  - : Initialize return
- $T = 1,2,3,\ldots,N$ ← (2)
  - : Increment T, "period(s) to go"
- Begin DP Calculations
  - : Perform Dynamic Programming calculations
- (3)

185

Note that the variable t represents "period(s) to go" in the analysis, since backward recursion is used. Next, the inventory carrying capacity is evaluated to determine if the warehouse can store one or two periods' supply of maintenance inventory. If this constraint is violated, then, where applicable, either Purchase option 2 (P2) or Purchase option 3 (P3) is discarded. The operational status "good" is evaluated first and the minimum of either the Purchase or Keep options is selected and becomes the "best thing to do" or $f_{t-1}(a_t+1,G)$. As discussed in section 3.7, $f_{t-1}(a_t+1,G)$ also applies to state "failed" due to a simplifying assumption.

The operational status "failed" is evaluated next. However, prior to this state evaluation, it is first determined if the repair capacity is violated. If so, then the repair option is discarded, and only the purchase option is considered. Otherwise, both the purchase and repair options are evaluated, and the minimum of the two alternatives is selected. If there are more "periods to go" in the analysis, then the dynamic programming calculations continue. If there are no more periods to be evaluated the costs for state "good" and "failed" are aggregated. The state "good" costs are multiplied by the availability, or the probability that the system is operational at time t, and the state "failed" costs are multiplied by the unavailability, or the probability that the system is non-operational at time t, in order to determine an expected future cost.
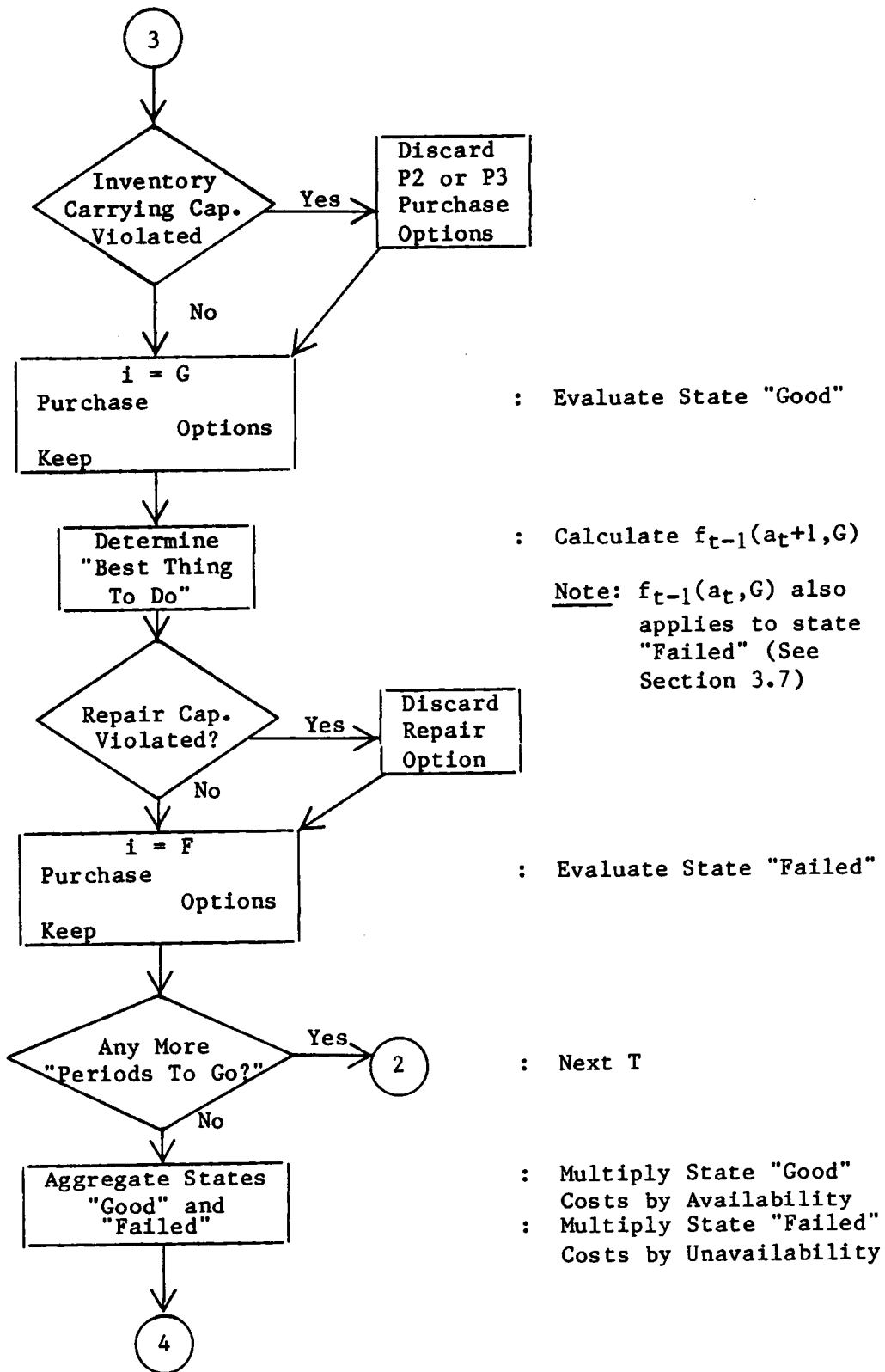
Figure 13. Flow Chart for MAIN FORTRAN 77 Module (Cont'd.)

DRRPM accommodates 2 operating environments per stream. Consequently, the stream costs for each operating environment are aggregated to determine the primary or main stream cost. After all decision options for each period have been enumerated, a repair/replace policy and policy costs can be determined based on the initial population age and initial decision action. Note that if the cumulative budget constraint is violated, then DRRPM computes a supplemental cost of exceeding the budget. If there are more streams, DRRPM then reiterates the above computational procedure. Once all streams in the population have been evaluated, then the streams can be aggregated on a period by period basis to determine a period by period population cost. Display options include stream by stream output, a stream summary, and a population summary. Note that the user can obtain printouts of all input and output screens by simply pressing "SHIFT PrtSC" if connected on-line to a small printer.

4.3.3 Explanation of Sub-routines in MAIN

Figure 15 presents a brief description of each sub-routine that is used in the MAIN module. The sub-routine HAZARD computes a Reliability function value, $R(a_t)$, for the selected hazard model, where a_t represents the age of the item with t periods to go. Although the user selects from among five pre-defined hazard models, DRRPM works with the corresponding reliability function to describe the probabil-
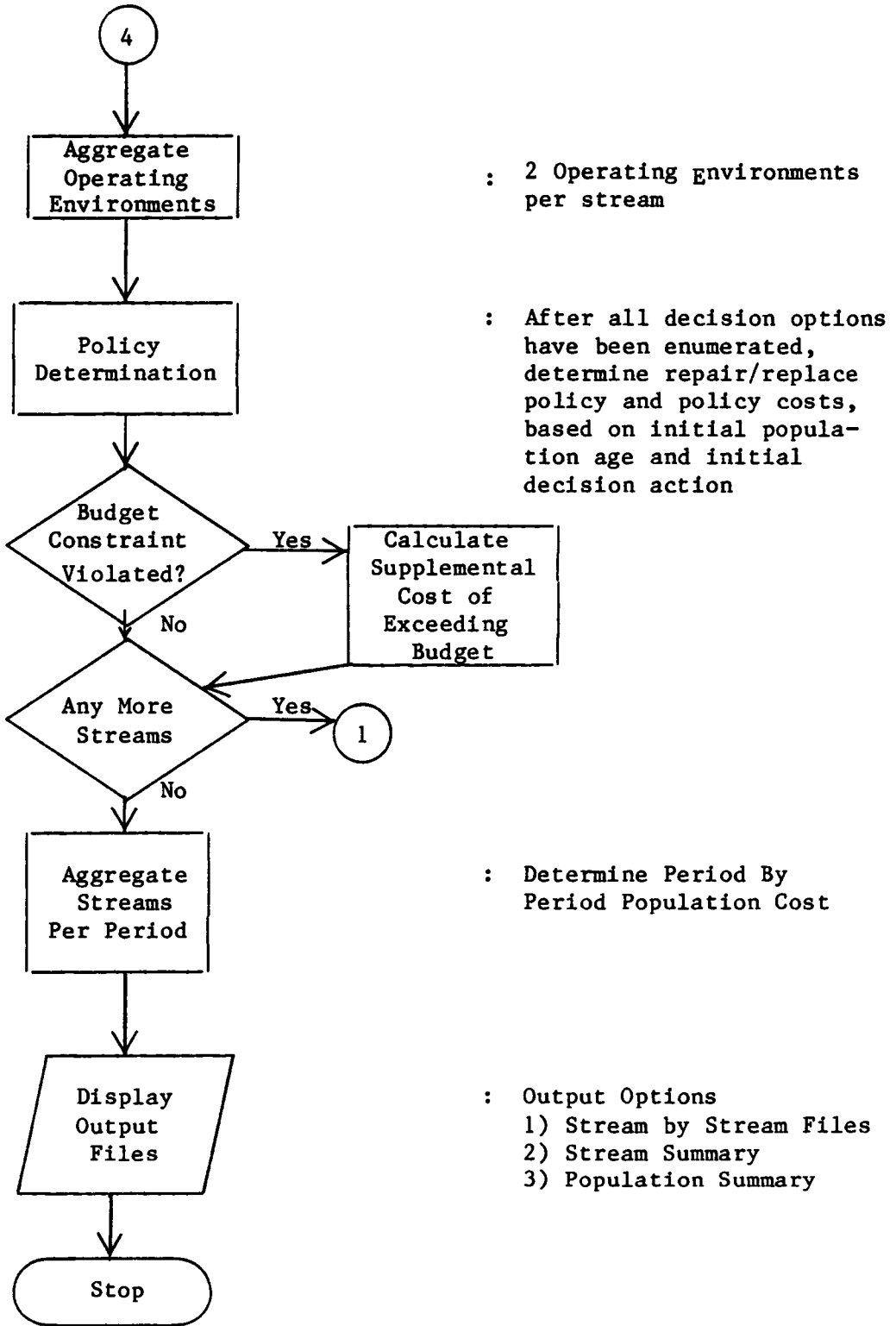
Figure 14. Flow Chart for MAIN FORTRAN 77 Module (Cont'd.)

ity that the system has not failed with t periods to go. The five hazard models and the corresponding reliability functions that are used in DRRPM are presented in Table 11. Note that these reliability functions are specific to DRRPM in that certain parameters and interval limits are linked to Mean Time Between Failure (MTBF) in an attempt to eliminate the need for additional user input.

The sub-routine TRANS computes time dependent state transition probabilities for non-constant hazard models. Mathematical formulations of the time-dependent transition functions are presented in section 3.6. If a constant hazard model is selected to describe the failure dynamics of a stream of end items, then DRRPM uses the stationary transition probabilities that are inputted by the user. AVAL computes the availability function value, $A(t)$, for a constant hazard model. A_i, or the "inherent availability" that is used in DRRPM for non-constant hazard models is computed in the MAIN FORTRAN 77 module. The sub-routine BUDGET calculates a supplemental cost of exceeding the cumulative budget constraint. REQ determines policy requirements for each period. Finally, sub-routine ZERO fills stream output files with zeros if there are no computed values as a result of MAIN module calculations. For example, suppose data is available for only 3 of the 12 possible planning periods. Sub-routine ZERO then fills the data locations for the remaining 9 periods in the stream output files with zeros. The source code

for all sub-routines is listed in Appendix III (Appendices B.1 - B.5).

Table 11. DRRPM Reliability Functions

Hazard Model	Reliability Function

1. Constant

$$R(a_t) = e^{-(1/\text{MTBF})a_t}$$

2. Linearly Increasing

$$R(a_t) = e^{-(.025a_t^2)/2}$$

3. Piece. Lin. Bathtub

$0 \le a_t \le \text{MTBF}$

$$R(a_t) = e^{-((.05a_t)-((0.25/\text{MTBF})*(a_t^2)/2))}$$

$\text{MTBF} < a_t$ and $a_t \le (3*\text{MTBF})$

$$R(a_t) = e^{-((.05*\text{MTBF})-((.025/\text{MTBF})*(\text{MTBF}^2/2)))}e^{-(.025*}$$
$$(a_t-\text{MTBF}))$$

$(3*\text{MTBF}) < a_t \le (4*\text{MTBF})$ or $a_t > (4*\text{MTBF})$

$$R(a_t) = e^{-(.05*\text{MTBF})-((.025/\text{MTBF})*(\text{MTBF}^2)/2))}$$
$$+e^{-(0.025*((3*\text{MTBF})-\text{MTBF}))}e^{(-(.025*(a_t-(3*\text{MTBF}))))}$$
$$+e^{-((.025*(a_t-(3*\text{MTBF})+((.05/\text{MTBF}))*((a_t-(3*\text{MTBF}))^2)/2))}$$

4. Weibull

$a_t < (4*\text{MTBF})$ or $a_t \ge (4*\text{MTBF})$

$$R(a_t) = e^{(-(1/6)(a_t^{1/2}))}$$

5. Exponential

$a_t < (4*\text{MTBF})$ or $a_t \ge (4*\text{MTBF})$

$$R(a_t) = e^{-((.05*e^{((.025*a_t)-1)}))}$$

4.3.4 DRRPM Capabilities and Limitations

As previously discussed, DRRPM is capable of determining a period by period repair/replace policy and the corresponding policy cost. DRRPM is capable of analyzing 12 primary or main streams with 2 operating environments per stream. There is a limit of 12 planning periods which could be 12 weeks, months, or years. These are the principal restrictions; however, DRRPM could be modified to accommodate more streams and a longer planning horizon as long as sufficient computer memory is available. The trade-off is that the increased processing capability necessitates more input by the user.

As discussed in section 3.3, a simplifying assumption is that there is zero lead time. The computer model could be expanded to incorporate lead time, as well as a shortage cost. Also, the time value of money is not considered in the computations of the various cost factors. DRRPM could be easily modified to incorporate an interest rate in cost calculations. Also, DRRPM could be modified to incorporate inflationary effects. The computer model does accommodate 3 different purchase options, and could be embellished to allow more purchase options. DRRPM does accommodate gradual technology effects; however, these effects are assumed to be linear and exponential with respect to purchase price and operating expenses, respectively. Perhaps the effect of a

HAZARD	Computes R(t), Reliability function value, for selected Hazard Model.

TRANS	Computes time-dependent transition probabilities for non-constant hazard models. <u>Note</u>: Transition probabilities for a constant hazard are inputted by the user.

AVAL	Computes A(t), Availability function value, for constant hazard model. <u>Note</u>: A_i, "inherent availability," for non-constant hazard models is computed in the MAIN FORTRAN 77 module.

BUDGET	Computes supplemental cost of exceeding budget.

REQ	Determines Policy Requirements for the period.

ZERO	Fills stream output files with zeros if there are no computed values.

Figure 15. MAIN FORTRAN 77 Sub-routines.

sudden technological change could be incorporated into the computerized model.

4.3.5 Areas for DRRPM Expansion

There are three main areas where the computerized model could be expanded. First, both stream and population output could be linked to a graphics package so that the user could view the period by period policy changes in graphic form, rather than viewing a series of tables. In this way, the logistician could readily determine the "big picture" and quickly ascertain the effect on availability of stream input changes. Second, perhaps stream output files could be linked to a statistical package so that a complete statistical analysis of population dynamics could be obtained. Third, perhaps a module could be attached to DRRPM so that a Monte Carlo simulation could be performed to determine time-dependent availability for non-constant hazard functions (see Messinger (79)). Presently, DRRPM utilizes the time independent A_i, or the "inherent availability", for non-constant hazard models.

4.3.6 DRRPM Level of Application

The "Dynamic Repair/Replace Population Model" has potential application at the operational, tactical, or strategic levels within an organization. The detailed stream by stream output can be used at the operational level to determine ac-

tual repair/replace policy requirements and anticipated costs. This output can be used to schedule the various repair facilities. Note that DRRPM allows for the incorporation of three levels of repair. Goldman and Slattery (44) give an extensive treatment of the various costs and repair strategies for a network of repair facilities. The effect of single- or multi-parameter sensitivity analysis on availability, reliability, or policy recommendation can be readily determined by the operations manager. For example, the operations manager could examine the effect of an increase in operating expenses on future repair/replace policy recommendations. The computerized model assists the decision maker with systematic resource allocation while ensuring system availability. DRRPM also allows the operations manager to analyze either an entire system, such as a ship, or a subsystem, such as a propulsion system on a ship. A case study of a pump sub-system for the U.S. Navy's Side Loadable Warping Tug (SLWT) is presented in the next chapter.

At the tactical level within an organization, the stream summary provides a concise recapitulation of stream costs on a period by period basis. The logistician at this level can evaluate what percentage of expected future cost for a period is attributed to a certain stream. If this percentage is unacceptable, some measures could be currently undertaken to reduce the anticipated cost, such as perhaps hiring some part-time or seasonal repair personnel.

At the strategic level within an organization, the population summary offers top management a concise summary of period by period population costs. Management can then decide whether to alter the current maintenance strategy or continue on the present course.

4.4 Chapter Summary and Conclusions

In this chapter, the computerized model that is developed to support the general modeling approach of the previous chapter is described. "A Dynamic Repair/Replace Population Model" or DRRPM is a mainframe package that is capable of analyzing 12 primary or main streams with 2 operating environments per stream for a maximum planning horizon of 12 periods. A modular approach is used in the development of the computer model, and each of the modules is explained in the chapter. Moreover, all sub-routines associated with the MAIN program are also described. The source code for all modules is presented in Appendix III (Appendices B.1 - B.5).

It is seen that data requirements for the population model are rather extensive, due to the nature of logistics problems. The capabilities and limitations of DRRPM are addressed. DRRPM assists the logistician with the analysis of a multi-stream multi-repair network of end items subject to certain system restrictions. DRRPM processing capability could be increased given sufficient computer memory, but population data requirements would increase significantly. Three areas of possible program expansion are: linkage to a graphics package, linkage to a statistical analysis package, and the addition of a module to simulate time-dependent availability for non-constant hazard models.

DRRPM has potential application at the operational, tactical, and strategic levels within an organization. The de-

tailed stream by stream output enables the operations manager to perform single- or multi-parameter sensitivity analyses and to ascertain the effect of parametric variations on repair/replace policy recommendations, policy costs, reliability, and availability. The stream summary assists logisticians at the tactical level with the analysis of cost patterns for a system. Finally, the population summary presents top management with a concise recapitulation of expected future costs on a period by period basis. This cost summary can assist in the determination of appropriate maintenance programs and facilitate systematic resource allocation.

In the next chapter, different scenarios are developed to demonstrate the various features of the computerized model. These scenarios involve single- and multi-parameter sensitivity analyses on the pump sub-system for the U.S. Navy's Side Loadable Warping Tug (SLWT).

V. POPULATION SENSITIVITY ANALYSES

5.1 Introduction

In this chapter, the results of parametric variations on population input data are presented. Both single- and multi-parameter sensitivity analyses are performed. The population under analysis is the pump system for the U.S. Navy's Side Loadable Warping Tug (SLWT). This pump system, which consists of the freshwater, seawater, and hydraulic pumps, is a part of the propulsion sub-system for the SLWT. Eight different scenarios that involve single-parameter sensitivity analysis are developed in an attempt to demonstrate the various features of the software package, "A Dynamic Repair/Replace Population Model" or DRRPM. Moreover, two scenarios are developed that involve multi-parameter sensitivity analysis in an attempt to demonstrate the multi-dimensional capabilities of DRRPM.

In the next sections, a description of the population is presented, and the population database is described. The results of the population base case are then compared with the single- and multi-parametric variations. The relationship of each scenario to the overall computerized model is discussed. Finally, the chapter is summarized, and pertinent conclusions are presented.

5.2 Population Description

The population under evaluation is the pump system for the U.S. Navy's Side Loadable Warping Tug (SLWT). A picture of the SLWT is presented in Figure 16.[16] The pump system is a part of the propulsion sub-system for the SLWT and consists of three pumps: freshwater, seawater, and hydraulic pumps. The intent of analyzing a sub-system of an end item is to demonstrate the various features of the DRRPM software package in an efficient manner. Figure 17[17] depicts the maintenance tree for the SLWT. Note that a dotted line surrounds the pump system. The freshwater, seawater, and hydraulic pumps are represented by nodes 27, 28, and 29, respectively.

The Side Loadable Warping Tug is described in Brammer (14). The SLWT is a part of the U.S. Navy's Container Offloading and Transfer System (COTS). The purpose of COTS is to provide logistics support to seaborne military personnel, and primarily involves the transfer to shore of bulk dry cargo and vehicles.

As a part of COTS, the SLWT can assist in the construction of the causeway on piers that connects ships to shore, in the mooring of vessels, craft salvage operations, or in the transport of shipping containers from ship to shore.

---

[16] Brammer, p. 157.

[17] Ibid., p. 163.

85 FT

5 FT

21 FT

SIDE—LOADABLE WARPING TUG
(WEIGHT= 191,900 lbs)
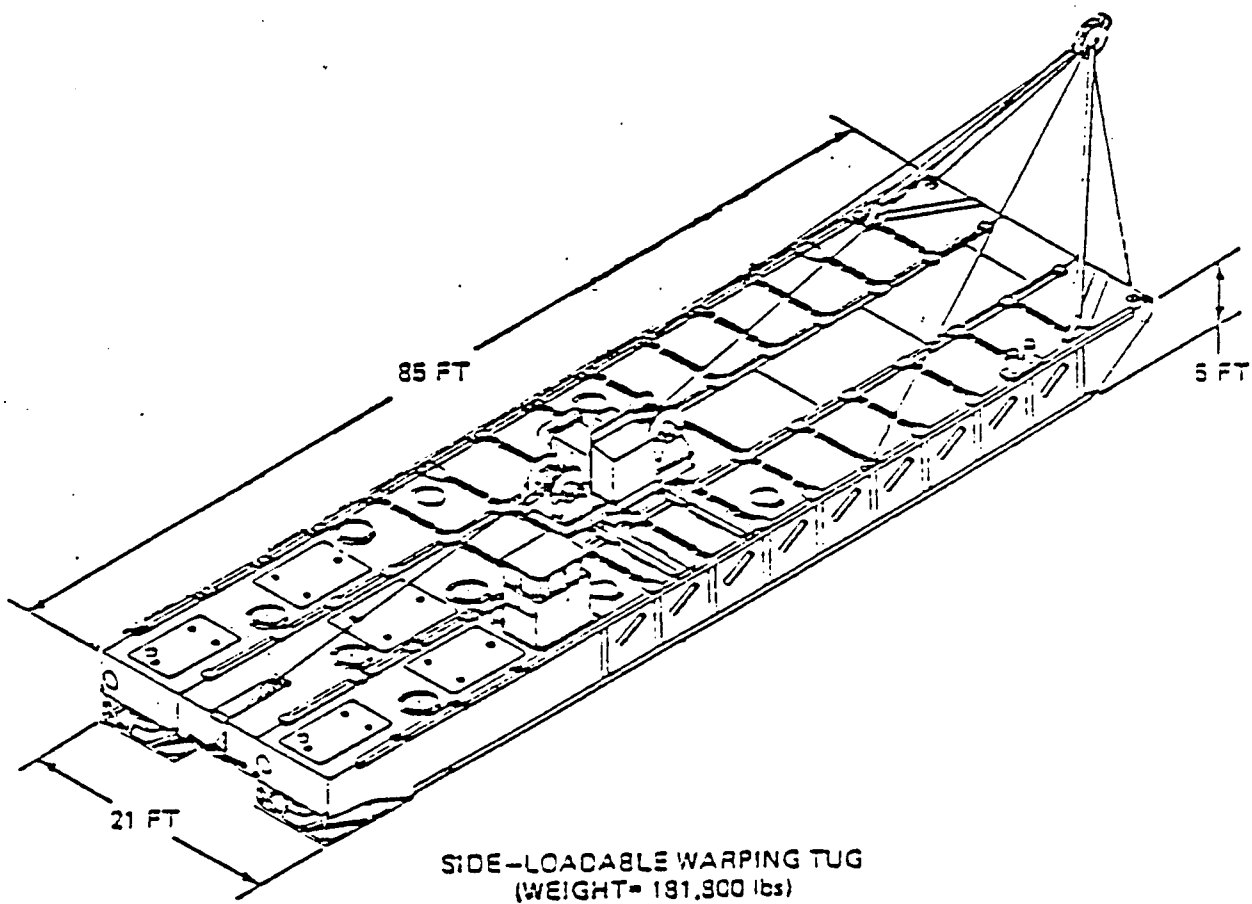
Figure 16.   Side Loadable Warping Tug (SLWT).
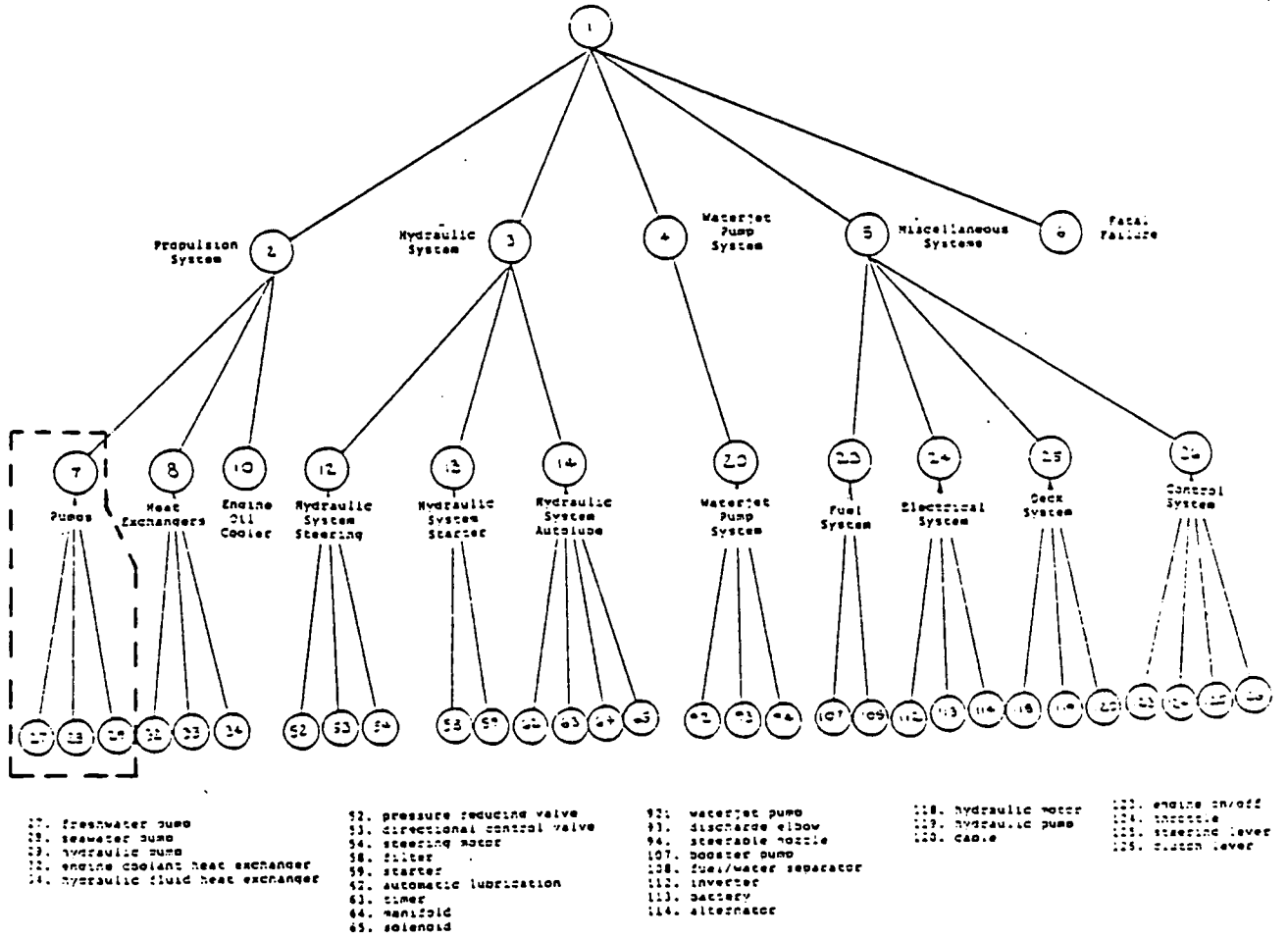
Figure 17. Maintenance Tree for SLWT.

The two operating environments that are analyzed are termed support and combat. The principal difference between the two environments is reflected in the Mean Time Between Failure or MTBF values. The SLWT works less hours in the support versus the combat environment, which translates to a higher MTBF value for the support versus the combat environment. Moreover, there is a lower probability of fatal failure in the support versus the combat environment.

Three levels of repair apply to the SLWT. A field repair or a level 1 repair can be performed aboard the SLWT, since the spare sparts for this repair type are carried on board. A level 2 repair is performed at an intermediate shore facility, since the required parts are carried in inventory at this facility. A level 3 repair requires that the SLWT be transported to a central repair facility. In the next section, the database requirements for the population base case are described.

5.3 Population Database

The input parameters for the population base case are presented in Table 12. The data for this base case on the Side Loadable Warping Tug (SLWT) has been collected by an independent agency and is presented in Brammer (14). Note that missing data has been fabricated, and data that is available may not reflect actual performance or cost characteristics of the SLWT currently in use by the U.S. Navy. For

example, data on transition probabilities were not available, and the approximations that are used in the base case are intended for illustrative purposes only.

As Table 12 indicates, there are 3 primary or main streams with 2 operating environments per stream. The operating environments are designated A for support and B for combat. The base case considers a planning horizon of three periods, where a period is defined to be one month. Note that the computerized model can accommodate three levels of repair - field, local facility, and central depot repair. The input parameters within each primary stream are essentially the same for each operating environment, with the principal exceptions of estimated rate of technological improvement, MTBF, demand, budget limit, repair capacity, and maintenance inventory carrying capacity values. Also, the hazard model may differ between operating environments within a primary stream. For example, stream 1a uses the linearly increasing hazard model, while stream 1b uses the piecewise linear bathtub hazard model. As explained in section 3.6, the computerized model does not work directly with the hazard model, but uses the corresponding reliability function to describe a "survivor probability" from period to period. In the next sections, the results of computer runs for the population base case are compared with eight single- and two multi-parametric pertubations.

TABLE 12. POPULATION BASE CASE INPUT PARAMETERS.

	1 A	1 B	2 A	2 B	3 A	3 B
Stream #:	1	1	2	2	3	3
Op. Environment:	A	B	A	B	A	B
Stream Name:	Freshwater Pumps	Freshwater Pumps	Seawater Pumps	Seawater Pumps	Hydraulic Pumps	Hydraulic Pumps
Pop. Age:	1	1	2	2	2	2
Pur. Price:	250	250	1965	1865	600	600
Sal. Value	10	10	30	30	25	25
Repair Cost:	28	28	88	88	40	40
Op. Cost ("Defender"):	25	25	65	65	32	32
Op. Cost ("Challenger"):	20	20	55	55	30	30
Carrying Cost:	5.00	5.00	15	15	5.00	5.00
Inspection Cost:	5	5	12	12	5	5
Rate of Tech. Improvement:	10	10	10	10	12	12
Level of Repair	2	2	2	2	1	1
P_{GG}^{P}	0.98	0.98	0.98	0.98	0.98	0.97
P_{GG}^{K}	0.95	0.92	0.96	0.95	0.95	0.91
P_{FG}^{P}	0.97	0.97	0.97	0.97	0.97	0.95
P_{FG}^{R}	0.93	0.91	0.94	0.91	0.93	0.90
Hazard Model:	2	3	5	5	2	2
MTBF	8.22	5.49	13.7	13.7	32.87	21.97
MTTR	0.0328	0.0328	0.04	0.04	0.0394	0.04

Period	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Demand	12	10	9	10	8	6	5	5	4	4	4	3	3	3	3	2	3	3
Budget Limit	2700	3000	2800	2700	2800	2800	9000	9200	9200	8900	9000	9100	2200	2300	2300	2200	2300	2300
Repair Capacity	2	3	3	3	3	2	2	2	2	1	2	2	1	1	1	1	1	1
Inventory Carrying Capacity	2	2	2	2	2	2	3	3	3	2	2	2	1	1	1	2	1	2

5.4 Population Base Case Results

As previously discussed, the input parameters for the population base case are presented in Table 12. The population under analysis is the pump system for the SLWT and consists of the freshwater, seawater, and hydraulic pumps. Computer printouts of base case results are included in Appendix II (Appendix A.1). However, concise summary tables are presented in this chapter for easy reference. The population summary in Table 13 reveals that the total expected future costs for the next three months are $9613.01 for the three primary streams of freshwater, seawater, and hydraulic pumps. With 3 periods to go (i.e. at the beginning of the planning horizon), the expected future costs total $4870.08. With 2 periods to go, the expected future costs total $3203.44, and with 1 period to go (i.e. at the end of the planning horizon), the expected future costs total $1539.49. In other words, 50.66% of the expected future costs for the planning horizon of three months are incurred at the beginning of the planning horizon.

The stream summary of Table 14 reveals that with 1 period to go (i.e. at the end of the planning horizon), the seawater pumps comprise 48.48% of the total expected future costs. With 2 periods to go, this percentage increases to 50.22%, and with 3 periods to go (i.e. at the beginning of the planning horizon), the percentage decreases to 48.45%. Thus, the seawater pumps have the most costly repair/replace policy,

TABLE 13.   CASE STUDY POPULATION SUMMARY.

1.   Total Number of Primary Streams   3

2.   Total Number of Periods   3

3.   Period definition . . . .   months

Period(s) to Go	Expected Future Costs
3	$4870.08
2	$3203.44
1	$1539.49

Total Population Cost $9613.01

Table 14. Case Study Stream Summary.

Stream Number	Stream Name	Expected Future Costs		
		Periods to go		
		3	2	1
1	Freshwater Pumps	$1736.90	$1074.27	$514.77
2	Seawater Pumps	2378.84	1608.84	746.42
3	Hydraulic Pumps	754.34	520.32	278.30

TABLE 15. STREAM 1A POLICY RECOMMENDATION (BASE CASE)

STREAM 1A - FRESHWATER PUMPS (SUPPORT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	K $1005.00		
2		K $630.00	
3			K $310.00
STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	R $1336.52		
2		R $896.47	
3			R $535.18

TABLE 16. STREAM 1B POLICY RECOMMENDATION (BASE CASE)

STREAM 1B - FRESHWATER PUMPS (COMBAT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	K $729.00		
2		K $442.00	
3			K $203.00

STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	R $994.81		
2		R $646.50	
3			R $250.25

TABLE 17.   STREAM 2A POLICY RECOMMENDATION (BASE CASE)

STREAM 2A - SEAWATER PUMPS (SUPPORT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	K $1333.00		
3		K $905.00	
4			K $426.00
STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	R $1764.72		
3		R $1335.87	
4			R $770.86

TABLE 18. STREAM 2B POLICY RECOMMENDATION (BASE CASE)

STREAM 2B - SEAWATER PUMPS (COMBAT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	K $1044.00		
3		K $702.00	
4			K $319.00

STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	R $1389.17		
3		R $1046.57	
4			R $577.72

TABLE 19. STREAM 3A POLICY RECOMMENDATION (BASE CASE)

STREAM 3A - HYDRAULIC PUMPS (SUPPORT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	K $377.00		
3		K $260.00	
4			K $139.00

STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	R $491.37		
3		R $367.47	
4			R $237.34

TABLE 20.   STREAM 3B POLICY RECOMMENDATION (BASE CASE)

STREAM 3B - HYDRAULIC PUMPS (COMBAT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	K $377.00		
3		K $260.00	
4			K $139.00
STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
2	R $491.14		
3		R $367.30	
4			R $237.23

followed in decreasing order by the freshwater and hydraulic pumps.

The policy recommendations for the population base case are presented in Tables 15 - 20. Note that the policy recommendations for states "good" and "failed" are the same for all streams per operating environment. The policy recommendation for state "good" follows the pattern of Keep-Keep-Keep with 3, 2, and 1 period(s) to go in the analysis. The policy recommendation for state "failed" follows the pattern of Repair-Repair-Repair with 3, 2, and 1 period(s) to go in the analysis. The policy cost for each period is listed under the policy recommendation.

Tables 21 and 22 present the reliability/unreliability and availability/unavailability values for each stream in the population base case. Reliability/unreliability and availability/unavailability are defined in section 3.6. To summarize, reliability is the probability that the system has not failed by time t, and availability is the probability that the system is operational at time t. Unreliability and unavailability are the respective complements of reliability and availability. For example, although a policy cost of $535.18 is associated with the policy recommendation of Repair for stream 1a, or "freshwater pumps (support)", with 1 period to go, the unreliability, or the probability that the pumps have failed by this time is only .106403. Moreover, the unavailability, or the probability that the pumps are not

operational at this time is only .003974. Thus, there is only a very small chance that the freshwater pumps will be in state "failed" and that the repair costs of $535.18 will be incurred. However, if the equipment is in state "failed", the repair policy costs are $535.18. Note that the availability/unavailability values are not time-dependent. As explained in section 3.6, the time-independent "inherent availability" is used in conjunction with a non-constant hazard model.

In the next sections, results of computer runs from single- and multi-parametric variations are presented. The single-parameter sensitivity analyses involve the following eight parameters: estimated rate of technological improvement, purchase price, operating expenses, repair costs, MTBF, hazard model, demand, and budget limit. There are two multi-parametric variations presented. One case involves perturbations of both purchase price and operating expenses of the "defender" asset. The other case examines the effect of variations on the parameters of population age, purchase price, and operating expenses of the "defender" asset. The primary intent of these case studies is to demonstrate the multi-faceted features of the computerized model, and to indicate how DRRPM can be used as a decision aid to assist logisticians with the determination of feasible repair/replace policies.

TABLE 21. RELIABILITY/UNRELIABILITY VALUES (BASE CASE).

STATE: GOOD   STATE: FAILED

STREAM	RELIABILITY			UNRELIABILITY		
	PERIOD(S) TO GO			PERIOD(S) TO GO		
	3	2	1	3	2	1
1A – FW(S)	.987578	.951229	.893597	.012422	.048771	.106403
1B – FW(C)	.994061	.913116	.878527	.046602	.086884	.121473
2A – SW(S)	.980849	.980369	.979877	.019151	.019631	.020123
2B – SW(C)	.980849	.980369	.979877	.019151	.019631	.021123
3A – H(S)	.951229	.893597	.818731	.048771	.106403	.181269
3B – H(C)	.951229	.893597	.818731	.048771	.106403	.181269

LEGEND: FW(S) – Freshwater Pumps (Support)
         FW(C) – Freshwater Pumps (Combat)
         SW(S) – Seawater Pumps (Support)
         SW(C) – Seawater Pumps (Combat)
         H(S) – Hydraulic Pumps (Support)
         H(C) – Hydraulic Pumps (Combat)

218

TABLE 22. AVAILABILITY/UNAVAILABILITY VALUES (BASE CASE).

<u>STATE:</u> GOOD   <u>STATE:</u> FAILED

STREAM	AVAILABILITY			UNAVAILABILITY		
	PERIOD(S) TO GO			PERIOD(S) TO GO		
	3	2	1	3	2	1
1A – FW(S)	.996026	.996026	.996026	.003974	.003974	.003974
1B – FW(C)	.994061	.994061	.994061	.005939	.005939	.005939
2A – SW(S)	.998053	.998053	.998053	.001947	.001947	.001947
2B – SW(C)	.997089	.997089	.997089	.002911	.002911	.002911
3A – H(S)	.998803	.998803	.998803	.001197	.001197	.001197
3B – H(C)	.998183	.998183	.998183	.001817	.001817	.001817

LEGEND: FW(S) – Freshwater Pumps (Support)
         FW(C) – Freshwater Pumps (Combat)
         SW(S) – Seawater Pumps (Support)
         SW(C) – Seawater Pumps (Combat)
         H(S) – Hydraulic Pumps (Support)
         H(C) – Hydraulic Pumps (Combat)

5.4.1 Scenario 1

In this scenario, the estimated rate of technological improvement is increased by 5% in all streams. The population cost for the 3 month planning horizon increases from $9613.01 to $10969.00 for an increase of 14.1%. The increase of $1355.99 can be interpreted by the logistician as a "penalty cost" associated with not using the most modern equipment. The policy recommendation for each stream per operating environment does not change, although the expected policy costs for each period increased. Computer output of population and stream summaries are presented in Appendix II (Appendix A.2). This scenario demonstrates how DRRPM can be utilized by the logistician to evaluate the effect of a change in the estimated rate of technological improvement on repair/replace policy recommendations and policy costs.

5.4.2 Scenario 2

In this scenario, the purchase price of freshwater pumps decreases by 40% in streams 1a and 1b. The price is reduced from $250 to $100 per pump. This price reduction has no effect on total population cost, and both policy recommendations and policy costs for streams 1a and 1b remain the same. In other words, although there is a substantial decrease in the purchase price of freshwater pumps, the Keep and Repair options still are more financially attractive than any of the available purchase options. Printouts of population and stream summaries are presented in Appendix II

(Appendix A.3). This scenario demonstrates how DRRPM can be utilized to evaluate the effect of either single- or multi-stream purchase price changes on repair/replace policy recommendations and policy costs.

5.4.3 Scenario 3

Operating expenses for the "defender" asset are increased by 40% in all streams in scenario 3. The total population cost increases from $9613.01 to $13000.00 for a 35.23% increase. However, although policy costs in each period increase for all streams, policy recommendations do not change from the base case. The costs for the seawater pumps still comprise the largest percentage of expected future costs in each period. Reliability/unreliability and availability/unavailability values also remain the same. Printouts of summary tables are presented in Appendix II (Appendix A.4). Scenario 3 demonstrates how DRRPM can be used to aid the logistician with the evaluation of feasible repair/replace policies as a result of either an increase or decrease in operating expenses for the "defender" asset.

5.4.4 Scenario 4

In scenario 4, the repair costs are increased by 40% in all streams. There is only a slight increase in total population cost. The population cost increases from $9613.01 to $9618.44 for a .056% increase. There is no change in policy recommendations from the base case for any of the streams. Thus, although repair costs increase significantly in all streams, the repair option remains more financially attractive than any of the purchase options for state "failed". Printouts of summary tables are presented in Appendix II

(Appendix A.5). This scenario demonstrates how DRRPM can be
utilized to evaluate the effect of changes in repair costs
due to the expansion or reduction of repair facilities or to
fluctuations in personnel and facility variable costs.

5.4.5 Scenario 5

In scenario 5, hazard models for the freshwater pumps in
the support and combat environments are changed from the
linearly increasing and the piecewise linear bathtub, re-
spectively, to the exponential hazard model for both streams.
The population cost increases from $9613.01 to $9889.35 for
a 2.87% increase. However, policy recommendations for
streams 1a and 1b do not change from the base case. The
reliability/unreliability values change for streams 1a and
1b and are presented in Table 23. Note that with the expo-
nential model, the reliability/unreliability values for
stream 1a remain relatively stable for the planning horizon
of three periods. However, with the base case linearly in-
creasing model for stream 1a, the reliability values decrease
and the unreliability increases with the progression of time.
With the base case piecewise linear bathtub hazard model, the
reliability and unreliability values decrease and increase,
respectively, with the progression of time, while the corre-
sponding values for the exponential model remain relatively
stable. Note also that the rate of change is most pronounced
when comparing the piecewise linear bathtub model values with

the exponential model values. Printouts of population and
stream summaries, as well as period by period output for
streams 1a and 1b are presented in Appendix II (Appendix
A.6). Scenario 5 demonstrates how DRRPM can accommodate
different hazard models to describe the failure dynamics of
a stream of end items.

5.4.6 Scenario 6

The Mean Time Between Failure (MTBF) value is shortened
for the seawater pumps in scenario 6. The MTBF value de-
creases from 20.5 to 14.5 months for stream 2a and from 13.7
to 7.7 months for stream 2b. There is a slight decrease in
the population cost from $9613.01 to $9610.10 or a .0303%
decrease. The change in MTBF value does not affect policy
recommendations for streams 2a or 2b. Also,
reliability/unreliability values are unaffected for streams
2a and 2b. However, the MTBF change does affect
availability/unavailability and the new values are presented
in Table 24. There is a slight decrease in availability and
a slight increase in unavailability for streams 2a and 2b
from the base case. This is logical, since a shortening of
the Mean Time Between Failure will decrease the probability
of the system being operational at time t, and increase the
probability of the system not being available or in repair
at time t. Printouts of population and stream summaries, as
well as period by period stream output are presented in Ap-

TABLE 23. SCENARIO 5 RELIABILITY/UNRELIABILITY
AND AVAILABILITY/UNAVAILABILITY VALUES.

STATE: GOOD   STATE: FAILED

STREAM	RELIABILITY			UNRELIABILITY		
	PERIOD(S) TO GO			PERIOD(S) TO GO		
	3	2	1	3	2	1
1A – FW(S)	.981317	.980849	.980369	.018683	.019151	.019631
1B – FW(C)	.981317	.980849	.980369	.018683	.019151	.019631
	AVAILABILITY			UNAVAILABILITY		
1A – FW(S)	.996026	.996026	.996026	.003974	.003974	.003974
1B – FW(C)	.994061	.994061	.994061	.005939	.005939	.005939

LEGEND: FW(S) – Freshwater Pumps (Support)

FW(C) – Freshwater Pumps (Combat)

225

pendix II (Appendix A.7). This scenario demonstrates how DRRPM can be used to evaluate the effect of changes in the design parameters of MTBF and MTTR on repair/replace policy recommendations and policy costs.

5.4.7 Scenario 7

In scenario 7, the demand for hydraulic pumps in each period is doubled. The demand increases from 3 to 6 pumps in streams 3a and 3b. As expected, the population cost increases from $9613.01 to $11169.75 for a 16.19% increase. However, policy recommendations for each stream do not change from the base case, although policy costs increase. Printouts of population and stream summaries, and stream output for period by period policy costs are included in Appendix II (Appendix A.8). Scenario 7 demonstrates how DRRPM can be used to evaluate the effect of a time varying demand on policy recommendations and costs.

5.4.8 Scenario 8

Scenario 8 represents the last of the single-parameter variations. In this scenario, the budget is reduced by 85% in each period for the freshwater pumps. This reduction does not change the overall population cost from the base case, and policy recommendations for streams 1a and 1b remain unaffected. However, there is a supplemental cost of exceeding the budget of $85.18 for stream 1a in state "failed" . Also,

TABLE 24. SCENARIO 6 RELIABILITY/UNRELIABILITY
AND AVAILABILITY/UNAVAILABILITY VALUES.

STATE: GOOD   STATE: FAILED

| STREAM | RELIABILITY | | | UNRELIABILITY | | |
| | PERIOD(S) TO GO | | | PERIOD(S) TO GO | | |
	3	2	1	3	2	1
2A – SW(S)	.980849	.980369	.979877	.019151	.019631	.020123
2B – SW(C)	.980849	.980369	.979877	.019151	.019631	.020123
	AVAILABILITY			UNAVAILABILITY		
2A – SW(S)	.997249	.997249	.997249	.002751	.002751	.002751
2B – SW(C)	.994832	.994832	.994832	.005168	.005168	.005168

LEGEND: SW(S) – Seawater Pumps (Support)

         SW(C) – Seawater Pumps (Combat)

there are a supplemental costs of exceeding the budget of $1005.00 and $31.52 for stream 1a with 3 periods to go for states "good" and "failed", respectively. Thus, in order to implement the policy recommendation of repair 9 units in stream 1a with 1 period to go, additional resources of $85.18 must be located. The 85% budget reduction for the freshwater pumps results in a total of $1121.70 in supplemental costs. Printouts of periods where the policy cost exceeds the budget limit are included in Appendix II (Appendix A.9). This scenario demonstrates how DRRPM can aid logisticians and fiscal planners with the determination of repair/replace policies that are financially feasible. Moreover, DRRPM computes the additional resources that are necessary for policy implementation if the budget allocation is exceeded.

5.4.9 Scenario 9

Scenario 9 involves variations of two parameters simultaneously. In this scenario, purchase price is decreased, and operating expenses of the "defender" asset are increased for the freshwater pumps. The purchase price decreases from $250 to $100 per pump and operating expenses of the "defender" pump increase from $25 per pump per month to $55 per pump per month. The overall population cost increases from $9613.01 to $13052.39 for a 35.78% increase. The freshwater pumps now comprise more than 50% of total expected costs in each period. The policy recommendation for state

"good" did not change from the base case, although policy costs are higher. However, there is a policy change for state "failed". The pattern for state "failed" is Repair-Purchase Option 1-Repair for both operating environments instead of Repair-Repair-Repair as in the base case. Policy recommendations and policy costs are presented in Tables 25 and 26. As these tables indicate, with the equipment in state "failed", the best decision is to repair the stream of 1 month old pumps with 3 periods to go in the analysis (i.e. at the beginning of the planning horizon). With 2 periods to go and with the equipment in state "failed", the best decision is Purchase Option 1 which is to purchase enough units (10) to meet the period demand. Note that upon replacement, the stream of new freshwater pumps ages by one month by the start of the next period (i.e. one month to go).

Reliability / unreliability and availability / unavailability values do not change from the base case. Printouts of population and stream summaries, as well as period by period output for streams 1a and 1b (i.e. freshwater pumps -support and combat environments, respectively) are presented in Appendix II (Appendix A.10). This scenario demonstrates how DRRPM can be used to evaluate the effect of multiparameteric variations on repair/replace policy recommendations and policy costs. In this case, the population dynamics of changes in purchase price and operating expenses

of the "defender" asset result in a policy change for the primary stream under evaluation.

5.4.10 Scenario 10

In scenario 10, three parameters are varied simultaneously. The parameters of population age, purchase price, and operating expenses of the "defender" asset are changed for the stream of hydraulic pumps. The initial population age is increased from 2 to 4 months, the purchase price is decreased from $600 to $300 per pump, and operating expenses of the "defender" asset are increased from $32 to $96 per pump per month for both the support and combat environments. The overall population cost increases from $9613.01 to $11555.82 for a 20.21% increase. Moreover, there are policy changes for both states "good" and "failed", along with an increase in policy costs.

Policy recommendations for scenario 10 are presented in Tables 27 and 28. Note that the policy recommendation for state "good" is now Keep-Keep-Purchase Option 1 for both operating environments instead of Keep-Keep-Keep as in the base case. Also, the policy recommendation for state "failed" is now Repair-Purchase Option 1-Repair for both operating environments instead of Repair-Repair-Repair as in the base case.

Note that the initial population age is now 4 months instead of 2 months old. With 2 periods to go and with the operational status of the hydraulic pumps in state "failed",

TABLE 25.   SCENARIO 9 (SUPPORT) POLICY RECOMMENDATION

STREAM 1A - FRESHWATER PUMPS (SUPPORT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	K $2043.00		
2		K $1286.00	
3			K $635.00

STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	R $2373.90		R $831.01
2		P1 $1512.58	
3			

TABLE 26. SCENARIO 9 (COMBAT) POLICY RECOMMENDATION

STREAM 1B - FRESHWATER PUMPS (COMBAT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	K $1479.00		
2		K $901.00	
3			K $415.00

STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1	R $1744.85		R $534.01
2		P1 $1076.22	
3			

TABLE 27. SCENARIO 10 (SUPPORT) POLICY RECOMMENDATION

STREAM 3A – HYDRAULIC PUMPS (SUPPORT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1			
2			
3			
4	K $879.00		
5		K $595.00	
6			P1 $274.50

STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1			R $453.59
2			
3			
4	R $977.83		
5		P1 $616.75	
6			

TABLE 28.   SCENARIO 10 (COMBAT) POLICY RECOMMENDATION

STREAM 3B - HYDRAULIC PUMPS (COMBAT)

STATE: GOOD	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1			
2			
3			
4	K $878.00		
5		K $594.00	
6			P1 $274.37

STATE: FAILED	PERIOD(S) TO GO		
POPULATION AGE	3	2	1
1			R $453.38
2			
3			
4	R $976.54		
5		P1 $616.37	
6			

TABLE 29. RELIABILITY/UNRELIABILITY AND AVAILABILITY/UNAVAILABILITY
VALUES FOR SCENARIO 10.

STREAM	RELIABILITY			UNRELIABILITY		
	PERIOD(S) TO GO			PERIOD(S) TO GO		
	3	2	1	3	2	1
3A - H(S)	.818731	.731616	.637628	.181269	.268384	.012422
3B - H(C)	.818731	.731616	.637628	.181269	.268384	.012422
	AVAILABILITY			UNAVAILABILITY		
3A - H(S)	.998803	.998803	.998803	.001197	.001197	.001197
3B - (HC)	.998183	.998183	.998183	.001817	.001817	.001817

LEGEND: H(S) - Hydraulic Pumps (Support)

H(C) - Hydraulic Pumps (Combat)

235

the stream of pumps is now 5 months old, and the best decision is Purchase Option 1. In other words, the recommended action is to purchase enough pumps to meet period demand (3). Upon replacement, the aging process regenerates, and the new stream of hydraulic pumps ages by one month by the start of the next period (i.e. one month to go).

Note also that reliability/unreliability values change for scenario 10, and are presented in Table 29. Since an older population is being evaluated, the reliability is lower and the unreliability is higher than the base case values for streams 3a and 3b. Note that since "inherent availability" is used for non-constant hazard models, availability/unavailability values do not change from the base case, because MTBF and MTTR values remain the same. Printouts of population and stream summaries, as well as period by period stream output, are presented in Appendix II (Appendix A.11). Scenario 10 also demonstrates how DRRPM can be utilized to evaluate the population dynamics of multi-parametric variations on repair/replace policy recommendations and costs. Although only one primary stream is analyzed, DRRPM is capable of aiding the decision maker with the evaluation of multi-stream parametric variations. In the next section, this chapter on population sensitivity analyses is summarized, and pertinent conclusions are presented.

5.5 Chapter Summary and Conclusions

The intent of this chapter is to demonstrate both single- and multi-parametric variations of a population base case that involves the pump system for the U.S. Navy's Side Loadable Warping Tug (SLWT). This pump system is comprised of freshwater, seawater, and hydraulic pumps, and is a part of the propulsion sub-system for the SLWT. The data that is used in the case studies is part of the database on the SLWT that is presented in Brammer (14). However, as Brammer mentions, missing data has been fabricated, and the data that is available may not reflect actual performance or cost characteristics of the SLWT currently in use by the U.S. Navy.

The ten scenarios that are developed involve eight single- and two multi-parametric variations of base case inputs to the computerized model "A Dynamic Repair/Replace Population Model" or DRRPM. The single- parametric variations allow the logistician to evaluate the isolated effect of input changes from the population base case. The multi-parameteric variations enable the decision maker to evaluate the complex interrelationships of the various inputs to the computerized model and to assist him or her in the determination of feasible repair/replace strategies.

The ten scenarios that are developed demonstrate how DRRPM can be utilized to evaluate how changes in estimated rate of technological improvement, purchase price, operating

expenses of the "defender" asset, repair costs, MTBF, hazard model, demand, budget limit, or any other input parameter affect repair/replace policy recommendations and costs, as well as reliability / unreliability and availability / unavailability. Moreover, DRRPM allows for the simultaneous evaluation of parametric changes, so that any combination of inputs can be analyzed. Note that for the scenarios evaluated, a policy change only occurs when multi-paramteric variations are considered, suggesting that policy recommendations are intricately woven with the interrelationships that exist among population model inputs. The computerized model is capable of evaluating parametric variations for either single- or multi-stream populations. Thus, the decision maker can evaluate an isolated primary stream or the interrelationships of numerous primary streams subject to system constraints. Again, at the present time, DRRPM is capable of analyzing 12 primary streams with 2 operating environments per stream for a maximum planning horizon of 12 periods.

As the ten scenarios demonstrate, DRRPM can be used at either the operational, tactical, or strategic levels within an organization. At the operational level, the repair/replace policy recommendation and policy costs serve as a planning tool for the operations manager in the scheduling of equipment procurements and repair facilities. The stream summary assists the logistician with the determination

of the most costly equipment in a population. The population summary assists top management with a concise recapitulation of overall policy costs and the effect of policy changes can be captured in this summary. Thus, DRRPM is seen as a multi-facted computerized model that has potential applications at all levels in the organization. It must be remembered that DRRPM is a software prototype, and that extensive testing in an actual operating environment is required prior to implementation. However, as the population sensitivity analyses demonstrate, DRRPM presents the logistician with a multi-faceted tool for the evaluation of a population of end items and can facilitate systematic resource allocation, while considering the trade-off between policy costs and end item availability. The source code for each module of DRRPM is listed in Appendix III (Appendices B.1 - B.5). In the next chapter, this dissertation is summarized, and research conclusions are presented in concise form. Also, suggestions for DRRPM program expansion are offered, and areas for future research are highlighted.

VI. FURTHER REMARKS

6.1 <u>Summary</u>

In this dissertation, a general modeling approach for the evaluation of feasible repair/replace strategies for a population of end item was developed. This general methodology accommodates both stochastic and deterministic demand; linear technology effects on purchase price; exponential technology effects on operating expenses; different hazard models; varying purchase options; a budget constraint; repair capacity constraint; and model implementation issues. The modeling approach uses the reliability function to describe a "survivor probability" from period to period. A two state dynamic program is developed where the state function is characterized by two parameters - item age and current operational status of the equipment. End items are grouped into "streams" according to similar failure characteristics. The modeling approach accommodates two operating environments per stream. The end item may be an entire system (e.g. a ship) or a sub-system (e.g. propulsion sub-system on a ship). However, the population data requirements are extremely sensitive to the level of model application.

In the first chapter, an overview of the basic replacement problem was presented. The unique features of the multi-stream replacement problem were then addressed. A

literature review of both durable and "sudden failure" equipment replacement/maintenance models was then presented. A taxonomy was developed that involves the following factors: states of the system, decision action(s), planning horizon, system knowledge, life pattern, system objective, solution method, and replacement model. Existing replacement/maintenance models were then analyzed according to the elements of the taxonomy.

A general solution methodology for the multi-stream replacement problem was presented in Chapter III. Modeling assumptions were grouped into four main categories: structural, descriptive, realistic, and simplifying (limiting) assumptions. A two period two stream numerical example is presented to demonstrate a simple application of the modeling approach. The software package "A Dynamic Repair/Replace Population Model", or DRRPM, was discussed in Chapter IV. This package supports the modeling approach and is capable of analyzing 12 primary or main streams with 2 operating environments per stream for a planning horizon of 12 periods. DRRPM is a mainframe package that is interactive in nature. A case study and pertubations of the base case on the U.S. Navy's Side Loadable Warping Tug (SLWT) were presented in Chapter V. Both single- and multi-parametric variations of base case inputs were evaluated in an attempt to demonstrate the multi-facetd features of DRRPM. The results of the population sensitivity analyses reveal that the prototype soft-

ware DRRPM can facilitate the determination of feasible repair/replace policies while considering the trade-off between policy costs and system availability.

Note that a point-by-point comparison can be made between the Dynamic Repair/Replace Population Model, or DRRPM, and the Repairable Equipment Population (REPS) Demonstrator by Fabrycky, et. al. (39). The REPS Demonstrator is used to compute estimated mean equivalent annual costs for the units of equipment, repair facilities, and shortages in a repairable equipment population system. DRRPM computes repair/replace/keep policy costs for a population of end items. REPS is used to model steady state behavior; DRRPM can capture non-steady state behavior in that the phase-in, operating, and phase-out periods of a population of end items can be analyzed in the dynamic programming calculations. REPS only considers a constant demand while DRRPM can accommodate both a deterministic and/or stochastic demand. REPS allows for the time value of money, while DRRPM does not consider either a constant or a variable interest rate. REPS refines the repair facility costs into initial costs and salvage values for the building, costs for small repair equipment, tool kits, test kits, and spare parts inventory located at the repair facility, and REPS also requires annual administrative, labor and operating costs of the repair facility as an input; DRRPM only considers an "average" repair cost that includes labor, transportation, and overhead. REPS

considers a "shortage cost", while DRRPM requires no such input. In REPS, the repair time is not affected by queue length and includes recovery and transportation of the item to the repair facility. In DRRPM, MTTR includes the entire amount of time that the system is down until it is returned to an operational status. REPS is only capable of evaluating one level of repair, while DRRPM can accommodate three levels of repair. Also, REPS computes the probability of a shortage, while DRRPM computes availability, or the probability that the system (end item) is operational at a specified time.

After the initial comparisons between REPS and DRRPM are made, it is seen that both REPS and DRRPM utilize a "population concept". REPS groups end items into age "cohorts" with similar MTTR and MTBF values. DRRPM groups end items into "streams" according to similar failure characteristics as described by a hazard function model, as well as MTTR and MTBF values. Both REPS and DRRPM utilize the concept of life cycle costing. However, the primary difference between REPS and DRRPM is that REPS is used to model steady state behavior, while DRRPM is capable of evaluating non-steady state behavior for a population of repairable units. Also, REPS is more concerned with the microscopic behavior of repair facilities than DRRPM, as evidenced by the refinement of repair facility cost and operational factors. DRRPM focuses

more on the determination of feasible repair/replace policies than on actual repair facility behavior.

In the next sections, research conclusions are presented in concise form. Recommendations for DRRPM program expansions and embellishments are then suggested. Finally, areas for future research are discussed.

6.2 Research Conclusions

The conclusions of this research on the multi-stream replacement problem are now presented in concise form:

(a) The multi-stream replacement can be analyzed using a two state dynamic program where the state function is characterized by two parameters -item age and current operational status of the equipment.

(b) The two state dynamic program facilitates the determination of feasible repair/replace policies, while considering the trade-off between policy costs and system availability. A dynamic programming solution methodology addresses the issue of life cycle costing as the phase-in, operational, and phase-out phases of system life can be captured in the dynamic program.

(c) Both constant and non-constant hazard models are capable of being analyzed, with Markovian and approximate Markovian deterioration occurring, respectively.

(d) Technology effects can be captured in a dynamic program for the multi-stream replacement problem.

(e) A stochastic demand can be incorporated in a multi-stream dynamic program.

(f) Several levels of repair and multiple operating environments can be included in a dynamic program for the multi-stream replacement problem.

(g) The data requirements for a population model are
extensive, but could be reduced by grouping or
"categorizing" data.

(h) An implementable software package can be developed
that incorporates the above modeling features
and facilitates the determination of feasible
repair/replace policies for the multi-stream
replacement problem.

6.3 Program Recommendations

Some recommendations for program expansions and
embellishments to "A Dynamic Repair/Replace Population
Model", or DRRPM, are listed below:

(1) The output from DRRPM could be linked to a
graphics package to facilitate period by period
evaluation of repair/replace policy costs,
system reliability, and system availability.

(2) A module could be attached to the MAIN program
that computes time-dependent availability for
non-constant hazard models. This module could
use Monte-Carlo simulation techniques to arrive
at availability estimates (see Messssinger (79)).
This would be more realistic than using
"inherent availability" for non-constant hazard
models.

(3) Model output could be linked to a statistical
analysis package in an attempt to provide the
decision maker with more insight into population
dynamics and the effect of sensitivity analyses.

(4) DRRPM system parameters could be expanded to
allow for the evaluation of more than 12 primary
or main streams and a planning horizon of more
than 12 periods. Also, the software could be
expanded to incorporate multiple operating
environments per stream, rather than the current
limit of two operating environments per stream.

(6) Lead time, inflationary effects, interest rate

and governmental regulations (e.g. Gramm-Rudman) could be incorporated into the computer program in an attempt to make the model more realistic.

(7) Different system configurations such as "parallel", "series", or combinations of these two types could be incorporated into DRRPM in order to increase model realism.

6.4 Areas for Future Research

The principal areas for future research are described below:

(1) The issue of "software reliability" needs to be examined. With the increasing technical sophistication of equipment, reliability problems are not so much hardware as software related.

(2) The application of replacement/maintenance models to the space arena presents exciting new possibilities for the field of logistics. Eventually, NASA will have have repair stations in space for the maintenance of satellites. Computer models like MRPM ("Maintenance Requirements Planning Model") and DRRPM ("Dynamic Repair/Replace Population Model") presently accommodate two operating environments per stream of end items. These models could be modified to consider the "environmental" factors of space so that decision makers can simultaneously analyze both earth and space environments. This area of space logistics requires further research and development.

(3) The application of MRPM and DRRPM to mission area analysis needs to be encouraged. The "bottom up" approach of these two models offers top management with a planning tool for the deployment of personnel and materials. Such tools enable management to evaluate the synergistic interrelationships among

hardware, organizational, management, and human elements of a technology, and the associated costs and operational effectiveness of the system. Both MRPM and DRRPM can facilitate study of the industrial mobilization process in the context of different war gaming scenarios. Moreover, perhaps these software technologies can advance increased coordination among the various branches of the military. Also, another area of study that is related to the industrial mobilization process is to determine the extent that the United States has becpome dependent on foreign markets for spare parts.

(4)   The MRPM and DRRPM software packages need to be combined so that the Logistics Decision Model (LDM) proposed by Frisch (41) can become a reality. MRPM evaluates the physical behavior of an acquired population of end items. Model outputs include spare parts inventory, warehousing, and manpower requirements and availability. MRPM outputs cost factors such as repair, shortage, inventory, and capital costs. These cost factors need to be linked to DRRPM so that cost trade-offs can be evaluated in the determination of feasible repair/replace strategies.

(5)   The application of goal programming to the multi-stream replacement problem could be attempted and model results compared with those of the dynamic programming solution methodology. Goal programming is a technique that is capable of accommodating decision problems with multiple goals or multiple sub-goals. Also, non-homogeneous units of measure, such as dollars and operational hours, may be included in the objective function of a goal programming model. Lee (70) gives an introduction to goal programming.

(6)   The issue of preventive maintenance in population models needs to be analyzed. Agee and Gallion (1) conclude that the incorporation of preventive maintenance into MRPM causes the model to lose its "population concept", since end items that had received preventive maintenance

would be allocated to new streams, and
eventually the number of streams would
approach the number of end items in the
population, thereby eliminating the
benefit of determining requirements for
"populations" of end items. Item by item
tracking would be necessary. Since DRRPM
utilizes ths same nested Markov chain
concept as MRPM, a similar argument applies
for the inclusion of preventive maintenance
in DRRPM. Agee and Gallion (1) suggest
that simulation techniques be employed to
examine the issue of preventive maintenance
for a population of end items. Both
MRPM and DRRPM results could then be
compared to simulation results with
regard to spares, system availability,
system reliability, repair/replace
policy recommendations and costs.

(7) The possibility of connecting both MRPM
and DRRPM to real-time data collection
systems such as the Computer Aided Reporting
System, or CARS (see Rosenthal (99)),
needs to be explored. Also, further research
is required on the use of voice activated
maintenance aids to assist in the collection
of repair/replace data.

(8) Finally, the economic impact of both
MRPM and DRRPM needs to be examined.
In other words, these software prototypes
need to undergo an extensive period of
evaluation in an operational environment
in order to assess the cost benefits
that may accrue from these new software
technologies. Performance criteria for
the models need to be established. One
possible framework is presented in Sink,
Tuttle, and DeVries (116) and involves
the performance criteria of effectiveness,
efficiency, quality, productivity, quality
of work life, innovation, and
profitability/budgetability. A possible
application area for both MRPM and DRRPM
is at one of the five Air Logistics
Centers (ALCs) for the Air Force. These

centers perform major maintenance, repair, replenishment, and renovation operations on Air Force weapons systems. Also, the issue of technology transfer between military and the private sector/industrial base needs to be addressed.

BIBLIOGRAPHY

1. Agee, M.H. and M.S. Gallion. "Draft: MRPM and Preventive Maintenance," Virginia Polytechnic Institute and State University, Feb. 1986.

2. Agee, M.H. and J.M.A. Tanchoco. "Cost Factors for Justifying Projects," Plant Engineering, Oct. 1980, pp. 145-147.

3. Ahmad, R.S. and A.N. Christakis. "A Policy Sensitive Model of Technology Assessment," IEEE Transactions of Systems, Man, and Cybernetics, Vol. SMC-9, No. 9, Sept. 1979, pp. 450-458.

4. Barlow, R. and L. Hunter. "Optimum Preventive Maintenance Policies," Operations Research, Vol. 8, 1960, pp. 90-100.

5. Barr, J.L. and K.E. Knight. "Technological Change and Learning in the Computer Industry," Management Science, Vol. 14, 1968, pp. 661-681.

6. Bell, D.E., R.L. Keeney, and H. Raiffa. (ed.) Conflicting Objectives in Decisions, New York: John Wiley and Sons, Inc., 1977.

7. Bellman, R.E. Dynamic Programming. Princeton, NJ: Princeton University Press, 1962.

8. Bellman, R.E. "Equipment Replacement Policy," Journal of the Society of Industrial and Applied Mathematics, Vol. 3, No. 3 (1955), pp. 133-136.

9. Bellman, R.E. and S.E. Dreyfus. Applied Dynamic Programming. Princeton, NJ: Princeton University Press, 1962.

10. Billinton, R. and R.N. Allan. Reliability Evaluation of Engineering Systems: Concepts and Techniques. New York: Plenum Press, 1983.

11. Blanchard, B.S. "Life Cycle Costing and Its Application to Logistics - An Overview," Proceedings of the 1981 International Logistics Congress/Society of Logistics Engineers, pp. II-1 - II-6.

12. Blanchard, B.S. <u>Logistics Engineering and Management,</u> <u>3rd edition</u>. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1986.

13. Blanchard, B.S. and E.E. Lowery. <u>Maintainability:</u> <u>Principles and Practices</u>. New York: McGraw-Hill Book Company, 1969.

14. Brammer, K.W. "A Transient State Maintenance Requirements Planning Model," M.S. Thesis, Virginia Polytechnic Institute and State University, (1985).

15. Bright, J.R. and Schoeman, M.E.F. (ed.) <u>A Guide to</u> <u>Practical Technological Forecasting</u>. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1973.

16. Bunn, D.W. <u>Analysis for Optimal Decisions</u>. New York: John Wiley and Sons, Ltd., 1982.

17. Calabro, S.R. <u>Reliability Principles and Practices</u>. New York: McGraw-Hill Book Company, 1962.

18. Carter, A.D.S. <u>Mechanical Reliability</u>. New York: The Macmillan Press, Ltd., 1972.

19. Cetron, M.J. and D.N. Dick. "Producing the First Navy Technological Forecast," in <u>A Guide to Practical Technological Forecasting</u>, by J.R. Bright and M.E.F. Schoeman (ed.). Englewood Cliffs, NJ: Prentice-Hall, Inc., 1973.

20. Chand, S. and S. Sethi. "Planning Horizon Procedures For Machine Replacement Models With Several Possible Replacement Alternatives," <u>Naval Research Logistics</u> <u>Quarterly</u>, Vol. 29, No. 3, Sept. 1982, pp. 483-493.

21. Chernoff, H. and L.E. Moses. <u>Elementary Decision Theory</u>. New York: John Wiley and Sons, Inc., 1959.

22. Churchman, C.W., R.L. Ackoff, and E.L. Arnoff. <u>Introduction to Operations Research</u>. New York: John Wiley and Sons, Inc., 1957.

23. Cinlar, E. <u>Introduction to Stochastic Processes</u>. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1975.

24. Clapham, J.C.R. "Economic Life of Equipment," <u>Operations Research Quarterly</u>, Vol. 8, 1957, pp. 181-190.

25. Cooper, L. and M.W. Cooper. <u>Introduction to Dynamic</u> <u>Programming</u>. New York: Pergamon Press, 1981.

26. Cox, D.R. <u>Renewal Theory</u>. New York: John Wiley and Sons, Inc., 1962.

27. Dean, J. <u>Capital Budgeting</u>. New York: Columbia University Press, 1951.

28. de la Mare, R.F. <u>Manufacturing Systems Economics</u>. New York: Holt, Rinehart, and Watson, 1982.

29. Derman, C. "Optimal Replacement and Maintenance Under Markovian Deterioration With Probability Bounds on Failure," <u>Management Science</u>, Vol. 9, 1963, pp. 478-481.

30. Derman, C. "On Sequential Decisions and Markov Chains," <u>Management Science</u>, Vol. 9, 1962, pp. 16-42.

31. Dernado, E.V. and B.L. Fox. "Multichain Markov Renewal Programs," <u>SIAM J. Appl. Math.</u>, Vol. 16, No. 3, May 1968, pp. 468-487.

32. Dobb, J.L. "Renewal Theory From The Point Of View Of The Theory Of Probability," <u>Transactions of the American Mathematical Society</u>, Vol. 63, 1948, pp. 422-438.

33. Dreyfus, S.E. "A Generalized Equipment Replacement Study," <u>Journal of the Society of Industrial and Applied Mathematics</u>, Vol. 8, No. 3 (1960), pp. 425-435.

34. Dreyfus, S.E. "A Note on an Industrial Replacement Process," <u>Operations Research Quarterly</u>, Vol. 7, 1956, pp. 190-193.

35. Dreyfus, S.E. and A.M. Law. <u>The Art and Theory of Dynamic Programming</u>. New York: Academic Press, 1977.

36. Elion, S., J.R. King, and D.E. Hutchinson. "A Study in Equipment Replacement," <u>Operational Research Quarterly</u>, Vol. 7, 1956, pp. 190-193.

37. Fabrycky, W.J. and J. Banks. <u>Procurement and Inventory Systems: Theory and Analysis</u>. New York: Reinhold Publishing Company, 1967.

38. Fabrycky, W.J., P.M. Ghare, and P.E. Torgerson. <u>Applied Operations Research and Management Science</u>. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1984.

39. Fabrycky, W.J., C.J. Malmborg, T.P. Moore, and K.W. Brammer. "Repairable Equipment Population Systems (REPS) Demonstrator," <u>User's Guide</u>. Department of In-

dustrial Engineering and Operations Research, Virginia Polytechnic Institute and State University, October, 1984.

40. Flehinger,B.J. "A Markovian Model For The Analysis Of The Effects Of Marginal Testing On System Reliability," Ann. Math. Stat., Vol. 33, 1962, pp. 754-766.

41. Frisch, F. "Mortality and Spareparts: A Conceptual Analysis," Proceedings of the 1983 Federal Acquisition Research Symposium , pp. 467-480.

42. Fusfeld, A.R. "The Technological Progress Function: A New Technique for Forecasting," in A Guide to Practical Technological Forecasting, by J.R. Bright and M.E.F. Schoeman (ed.). Englewood Cliffs, NJ: Prentice-Hall, Inc., 1973.

43. Gluss, B. "An Optimal Inventory Solution For Some Specific Demand Distributions," Naval Research Logistics Quarterly, Vol. 7, No. 1 (March 1960), pp. 45-48.

44. Goldman, A.S. and T.B. Slattery. Maintainability: A Major Element of System Effectiveness. New York: John Wiley and Sons, Inc., 1964.

45. Graves, S.C. and J. Keilson. "A Methodology For Studying The Dynamics Of Extended Logistics Systems," Naval Research Logistics Quarterly, Vol. 26, No. 2 (June 1979), pp. 169-197.

46. Gross, D. and C.M. Harris. Fundamentals of Queueing Theory, 2nd. ed.. New York: John Wiley and Sons, Inc., 1985.

47. Gross, D. and J.F. Ince. "Spares Provisioning for Repairable Items: Cyclic Queues in Light Traffic," AIIE Transactions, Vol. 10, No. 3 (Sept. 1978), pp. 307-314.

48. Gross, D., H.D. Kahn, and J.D. Marsh. "Queueing Models For Spares Provisioning," Naval Research Logistics Quarterly, Vol. 24, No. 4 (Dec. 1971), pp. 521-536.

49. Hadley, G. Nonlinear and Dynamic Programming. Reading, Mass.: Addison-Welsey Publishing Co., 1964.

50. Hadley, G. and T.M. Whitin. Analysis of Inventory Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1963.

51. Hadley, G. and T.M. Whitin. "A Family of Dynamic Inventory Models," *Management Science*, Vol. 8, No. 4 (1962), pp. 458-469.

52. Hastings, N.A.J. *Dynamic Programming With Management Applications*. London: Butterworth and Co., Ltd., 1973.

53. Hastings, N.A.J. "Some Notes on Dynamic Programming and Replacement," *Operational Research Quarterly*, Vol. 19, No. 4, pp. 453-464.

54. Howard, R.A. *Dynamic Programming and Markov Processes*. New York: John Wiley and Sons, Inc., 1960.

55. Hunter, L. and F. Proschan. "Replacement When Constant Failure Rate Precedes Wearout," *Naval Research Logistics Quarterly*, Vol. 8, 1961, pp. 127-136.

56. Jardine, A.K.S. *Maintenance, Replacement, and Reliability*. New York: John Wiley and Sons, Inc., 1973.

57. Jardine, A.K.S. (ed.) *Operational Research in Maintenance*. New York: Manchester University Press, 1970.

58. Jones, J.E. "Microcomputer Programming Package For The Assessment of Multiattribute Value Functions," M.S. Thesis, Virginia Polytechnic Institute and State University (1985).

59. Jones., M.S. "After-Tax Equipment Replacement Analysis With Technology Change," M.S. Thesis, Virginia Polytechnic Institute and State University (1985).

60. Jones, M.S. and J.M.A. Tanchoco. "Replacement Policy: The Impact of Technological Advances," *Engineering Costs and Production Economics*, (accepted for publication in 1985).

61. Jorgerson, D.W., J.J. McCall, and R. Radner. *Optimal Replacement Policy*. New York: American Elsevier Publishing Co., Inc., 1974.

62. Kapur, K.C. and L.R. Lamberson. *Reliability in Engineering Design*. New York: John Wiley and Sons, Inc., 1977.

63. Kaufmann, A. and R. Cruon. *Dynamic Programming*. New York: Academic Press, 1967.

64. Kemeny, J.G. and J.L. Snell. <u>Finite Markov Chains</u>. Princeton, NJ: D. Van Nostrand Co., Inc., 1969.

65. Klein, M. "Inspection-Maintenance-Replacement Schedules Under Markovian Deterioration," <u>Management Science</u>, Vol. 9 (1962), pp. 25-32.

66. Klein, M. amd L. Rosenberg. "Deterioration of Inventory and Equipment," <u>Naval Research Logistics Quarterly</u>, Vol. 7, 1960, pp. 49-62.

67. Kolesar, P. "Minimum Cost Replacement Under Markovian Deterioration," <u>Management Science</u>, Vol. 12, No. 9 (1966), pp. 694-706.

68. Larson, R.E. and J.L. Casti. <u>Principles of Dynamic Programming - Part 1</u>. New York: Marcel Drekker, Inc., 1982.

69. Larson, R.E. and J.L. Casti. <u>Principles of Dynamic Programming - Part 2</u>. New York: Marcel Drekker, Inc., 1982.

70. Lee, S.M. <u>Goal Programming For Decision Analysis</u>. Philadelphia, PA: Auerbach Publishers Inc., 1972.

71. Leung, L.C. "A Time-Dynamic Production Function Approach to Equipment Replacement Decisions," M.S. Thesis, Virginia Polytechnic Institute and State University (1980).

72. Lifson, M.W. <u>Decision and Risk Analysis for Practicing Engineers</u>. Boston, Mass.: Cahners Books, 1972.

73. Linstone, H.A. and D. Sahal. <u>Technological Substitution: Forecasting Techniques and Applications</u>. New York: American Elsevier Publishing Co., Inc., 1976.

74. Martin, K.A. "An Equipment Replacement Management Game," M.S. Thesis, Virginia Polytechnic Institute and State University (1967).

75. Martino, J.P. <u>Technological Forecasting for Decisionmaking</u>. New York: American Elsevier Publishing Co., Inc., 1972.

76. Mayer, R.R. "Problems in the Application of Replacement Theory," <u>Management Science</u>, Vol. 6, No. 3 (1960), pp. 750-758.

77. McCall, J.J. "Operating Characteristics of Opportunistic Replacement and Inspection Policies," Management Science, Vol. 10, No. 1 (1963), pp. 85-97.

78. McCall, J.J. "Maintenance Policies for Stochastically Failing Equipment: A Survey," Management Science, Vol. 11, No. 6 (1965), pp. 492-524.

79. Messinger, M. "Models, Analysis, and Approximations For System Reliability and Availability," Ph.D. Dissertation, Polytechnic Institute of Brooklyn (June, 1967).

80. Meyer, R.A. "Equipment Replacement Under Uncertainty," Management Science, Vol. 17, No. 11 (1971), pp. 750-758.

81. Mine, H. and S. Osaki. Markovian Decision Processes. New York: American Elsevier Publishing Company, Inc., 1970.

82. Morris, W.T. The Analysis of Management Decision. Homewood, Illinois: Richard D. Irvin, Inc., 1964.

83. Muckstadt, J.A. "A Model For A Multi-Item, Multi-Echelon, Multi-Indenture Inventory System," Management Science, Vol. 20, Dec., Part I, 1973, pp. 472-481.

84. Muckstadt, J.A. "A Three-Echelon, Multi-Item Model For Recoverable Items," Naval Research Logistics Quarterly, Vol. 26, No. 2 (June 1979), pp. 199-221.

85. Nahmias, S. "Managing Reparable Item Inventory Systems - A Review," in Multi-Level Production/Inventory Control Systems, edited by L.B. Schwarz, TIMS Studies in the Management Sciences, New York: North-Holland Publishing Co., 1981.

86. Nark, M.D. and K.P.K. Nair. "Multistage Replacement Strategies," Operations Research, Vol. 13 (1965a), pp. 279-290.

87. Osaki, S. and Y. Hatoyama (ed.) Stochastic Models in Reliability Theory. New York: Springer-Verlag, 1984.

88. Peterson, R. and E.A. Silver. Decision Systems For Inventory Management and Production Planning. New York: John Wiley and Sons, Inc., 1979.

89. Phillips, D.T., A. Rovindran, and J.J. Solberg. Operations Research: Principles and Applications. New York: John Wiley and Sons, Inc., 1976.

90. Pierskalla, W.P. and J.A. Voelker. "A Survey of Maintenance Models: The Control and Surveillance of Deteriorating Systems," Naval Research Logistics Quarterly, Vol. 23, No. 3 (1976), pp. 353-388.

91. Porteus, E.L. and Z.F. Lansdowne. "Optimal Design of a Multi-Item, Multi-Location, Multi-Repair Type and Supply System," Naval Research Logistics Quarterly, Vol. 21 (1974), pp. 353-388.

92. Preinreich, G.A.D. "The Economic Life of Industrial Equipment," Econometrica, Vol. 8, 1940, pp. 12-44.

93. Proschan, F. Pola Type Distributions in Renewal Theory With An Application To An Inventory Problem. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1960.

94. Radner, R. and D.W. Jorgenson. "Opportunistic Replacement of a Single Part in the Presence of Several Monitored Parts," Management Science, Vol. 10, No. 1 (1963), pp. 70-84.

95. Rapp, B. Models for Optimal Investment and Maintenance Decisions. New York: John Wiley and Sons, Inc., 1974.

96. Reisman, A. and E.S. Buffa. "A General Model for Investment Policy," Management Science, Vol. 8, No. 3 (1962), pp. 304-310.

97. Rosenfield, D. "Markovian Deterioration With Uncertain Information," Operations Research, Vol. 24, No. 1 (1976), pp. 141-155.

98. Rosenfield, D. "Markovian Deterioration With Uncertain Information - A More General Model," Naval Research Logistics Quarterly, Vol. 23, No. 3 (1976), pp. 389-405.

99. Rosenthal, D. "On the High-Tech Track," Roanoke Times and World News, Jan. 19, 1986, pp. EC1, EC12.

100. Ross, S.M. "Quality Control Under Markovian Deterioration," Management Science, Vol. 17, No. 9 (1971), pp. 587-596.

101. Ross, S.M. "A Markovian Replacement Model With a Generalization to Include Stocking," _Management Science_, Vol. 15, No. 11 (1960), pp. 702-715.

102. Sackrowitz, H. and E. Samuel-Cahn. "Inspection Procedures for Markov Chains," _Management Science_, Vol. 21, No. 3 (1974), pp. 261-270.

103. Salvendy, G. _Handbook of Industrial Engineering_. New York: John Wiley and Sons, Inc., 1982.

104. Sasieni, M.W. "A Markov Chain Process in Industrial Replacement," _Operations Research Quarterly_, Vol. 7, 1956, pp. 148-155.

105. Satia, J.K. and R.E. Lave. "Markovian Decision Processes With Uncertain Transition Probabilities," _Operations Research_, Vol. 21 (1973), pp. 728-740.

106. Scarf, H.E., D.M. Gilford, and M.W. Shelly (ed.) _Multistage Inventory Models and Techniques_. Stanford, CA: Stanford University press, 1963.

107. Schwartz, A.N., J.A. Scheler, and C.R. Cooper. "Dynamic Programming Approach to the Optimization of Naval Aircraft Rework and Replacement Policies," _Naval Research Logistics Quarterly_, Vol. 18 (1977), pp. 395-414.

108. Schwarz, L.B. (ed.) _Multi-Level Production/Inventory Control Systems_. TIMS Studies in the Management Sciences. New York: Norht-Holland Publishing Co., 1981.

109. Sethi, S. and S. Chand. "Planning Horizon Procedures for Machine Replacement Models," _Management Science_, Vol. 25, No. 2 (1979), pp. 140-151.

110. Sherbrooke, C.C. "METRIC: A Multi-Echelon Technique for Recoverable Item Control," _Operations Research_, Vol. 16 (1968), pp. 122-141.

111. Sherif, Y.S. and M.L. Smith. "Optimal Maintenance Models for Systems Subject to Failure - A Review," _Naval Research Logistics Quarterly_, March 1981, pp. 47-74.

112. Shooman, M.L. _Probabilistic Reliability: An Engineering Approach_. New York: McGraw-Hill Book Company, 1968.

113. Sinden, F.W. "The Replacement and Expansion of Durable Equipment," _Journal of the Society of Applied Mathematics,_ Vol. 8, No. 3 (1960), pp. 466-480.

114. Singh, C. and R. Billinton. _System Reliability Modelling and Evaluation._ London: Hutchinson & Co. (Publishers) Ltd., 1977.

115. Sink, D.S., L. Mallak, and J.T. Luxhoj. "The Illusory Nature of Management Decision Making," working paper, Virginia Polytechnic Institute and State University.

116. Sink, D.S., T.C. Tuttle, and S.J. DeVries. "Productivity Measurement and Evaluation: What is Available?" _National Productivity Review_, Summer 1984, pp. 265-287.

117. Smallwood, R.D. and E.J. Sondik. "The Optimal Control of Partially Observable Markov Processes Over A Finite Horizon," _Operations Research_, Vol. 21 (1973), pp. 1071-1088.

118. Smith, V.L. _Investment and Production._ Cambridge, Mass.: Harvard University Press, 1966.

119. Stapleton, R.C., D.B. Hemmings, and H.H. Scholefield. "Technical Change and the Optimal life of Assets," _Operational Research Quarterly_, Vol. 23, No. 1 (1972), pp. 45-59.

120. Starr, M.K. and D.W. Miller. _Inventory Control: Theory and Practice._ Englewood Cliffs, NJ: Prentice-Hall, Inc., 1962.

121. Taylor, J. and R.R.P. Jackson. "Applications of Birth and Death Processes to the Provision of Spare Machines," _Operational Research Quarterly_, Vol. 5 (1954), pp. 95-108.

122. Terborgh, G. _Business Investment Management._ Washington, D.C.: Machinery and Allied Products Institute, 1967.

123. Terborgh, G. _Business Investment Policy._ Washington, D.C.: Machinery and Allied Products Institute, 1958.

124. Terborgh, G. _Dynamic Equipment Policy._ New York: McGraw-Hill Book Co., Inc., 1949.

125. Thuesen, G.J. and W.J. Fabrycky. _Engineering Economy_, 6th ed., Englewood Cliffs, NJ: Prentice-Hall, 1984.

126. Thompson, R.G. and M.D. George. "Optimal Operations and Investments of the Firm," _Management Science_, Vol. 15, No. 1 (1968), pp. 49-56.

127. Truelove, A.J. "Strategic Reliability and Preventive Maintenance," _Operations Research_, Vol. 9, 1961, pp. 22-29.

128. Verheyen, P.A. "Economic Interpretation of Models for the Replacement of Machines," _European Journal of Operational Research_, Vol. 3, 1978, pp. 150-156.

129. Wagner, H.M. _Statistical Management of Inventory Systems_. New York: John Wiley and Sons, Inc., 1962.

130. Wagner, H.M. "A Postscript to 'Dynamic Problems in the Theory of the Firm'," _Naval Research Logistics Quarterly_, Vol. 17, No. 1 (1960), pp. 7-12.

131. Wagner, H.M. and T.M. Whitin. "Dynamic Version of the Economic Lot Size Model," _Management Science_, Vol. 5, No. 1 (1958), pp. 89-96.

132. Weiss, G.H. "A Problem in Equipment Maintenance," _Management Science_, Vol. 8, No. 3 (1962), pp. 266-277.

133. White, D.J. _Dynamic Programming_. San Francisco: Holden-Day, Inc., 1969.

134. White, J.A., M.H. Agee, and K.E. Case. _Principles of Engineering Economic Analysis_, 2nd ed.. New York: John Wiley and Sons, Inc., 1984.

135. Whitin, S. _The Theory of Inventory Management_. Princeton, NJ: Princeton University Press, 1957.

136. Zacks, S. "A Two-Echelon Multi-Station Inventory Model for Navy Applications," _Naval Research Logistics Quarterly_, Vol. 17, No. 1 (March 1970), pp. 79-85.

APPENDIX I

SYSTEM DOCUMENTATION

(DRRPM PROGRAM OPERATOR'S MANUAL)

PROGRAM OPERATOR'S MANUAL FOR

DRRPM

DYNAMIC REPAIR/REPLACE POPULATION MODEL

Developed by:

James T. Luxhoj

Graduate Research Assistant

Virginia Polytechnic Institute and State University

Blacksburg, VA 24060

(703)961-6656

TABLE OF CONTENTS

PROGRAM OPERATOR'S MANUAL FOR DRRPM

I. Introduction

"A Dynamic Repair/Replace Population Model" or DRRPM is the prototype software package that was created to support the modeling approach of the dissertation A Dynamic Programming Approach to the Multi-Stream Replacement Problem. This software package is capable of analyzing a population of end items, where the end item could be an entire system (e.g. a ship) or a sub-system (e.g. the propulsion system on a ship). Population data requirements are extremely sensitive to the level of application. The end items are grouped into "streams" depending on similar failure characteristics. DRRPM provides the logistician with a tool for analyzing 12 primary or main streams simultaneously for a maximum planning horizon of 12 periods. The user defines the period, which could be weeks, months, or years. The computer model accommodates two operating environments per stream and up to three levels of repair.

DRRPM involves the computerization of a two state dynamic program where the state function is characterized by two parameters - item age and current operational status of the equipment. The details of the modeling approach are explained in the chapter "Population Model Implementation" of the aforementioned dissertation. The intent of this Program

Operator's Manual is to familiarize the user with the workings of the software package. Consequently, this manual contains sections on system, equipment, and software requirements. Also, all introductory, input, and output screens are explained via actual screen printouts. DRRPM source code is listed in Appendix III.

1.1 System Requirements

DRRPM is a mainframe package that was developed at Virginia Tech using the facilities of the Virginia Tech Computing Center. The package runs on the VM2 system which is controlled by an IBM 3084 processor. This mainframe package is interactive in nature. IBM's Display Management System or DMS was used to create the "panels" or screens. DMS must be available in order for DRRPM screens to be displayed. A tape of all DRRPM files is available from Virginia Tech's Department of Industrial Engineering and Operations Research.

1.2 Equipment Requirements

Since DRRPM is a mainframe package, the user must be at a terminal that is connected to the VM2 system. Alternatively, a personal computer that is set up as a terminal will suffice. If printouts of either input or output screens are desired, then the personal computer needs to be connected to a small printer, such as an IBM Proprinter.

1.3 Software Requirements

If a personal computer is used as a terminal, then both DOS (Disk Operating System) and YTERM are required in order to connect to the mainframe. Copies of this software are available from the Virginia Tech Computing Center.

II. How To Use DRRPM

2.1 Begin the Program

If you are at a terminal that is connected to the mainframe computer, simply log on and type "PROGRAM" to initiate a session.   If you are using a personal computer, you must first set up the PC as a terminal.   The basic steps for connecting to the mainframe from a PC are outlined below:

(1)   Insert DOS 2.1 (for an IBM PC) or MS DOS (for an AT&T Model 6300 PC) into drive A.

(2)   When A> appears, remove DOS, and insert YTERM.

(3)   When A> reappears, type "X" (without quotation marks).

(4)   When A> reappears, type "t 9600" (without quotation marks) for 9600 baud. If using a 1200 baud modem, type "t 1200".

(5)   Now log on to mainframe. If you need assistance, contact a consultant. They are usually very friendly and willing to help.

(7)   Once you are logged on to the mainframe, type "PROGRAM" to initiate a session with DRRPM.

2.2 PF Keys

With the exception of INTRO SCREENS 2 and 3, the PF keys are used in DRRPM to control the display sequence of screens. To ADVANCE to the next screen, press "PF1". To go to the PREVIOUS screen, press "PF2". In order to end the program, simply press "PF3" for QUIT. For the data input screens,

"PF4" is used to REFRESH the screen in case any parameter changes are desired. After typing the new parameters, press "PF4" in order to redisplay the values to ensure that the new value has been properly recorded. Then press "ENTER" to file the new values.

2.3 Introductory Screens

Once the word "PROGRAM" has been typed, DRRPM will lead you through a series of introductory screens that provide a very brief overview of the software package. There are seven INTRO screens. The first INTRO screen is the title screen, and is labelled INTRO SCREEN 1. Simply press "PF1" to advance to the next screen. If you should happen to press another key, the error message "INVALID PF KEY, PLEASE USE VALID KEY." Will appear across the top of the screen. Simply press "PF1" to advance. The second INTRO screen is labelled INTRO SCREEN 2, and asks you for a data choice selection. There are essentially three data choices that are available with DRRPM. By pressing "PF1" a sample case study is initiated. Both input and parameters from the case study will be displayed on subsequent screens. If you change any of these values, they will not be filed or processed. The intent of the sample case study is to familiarize you with both sample inputs and outputs. If "PF2" is pressed, you will access existing stream data files. Any changes to these parameters will be filed and processed. By pressing "PF3" you may cre-

ate all new inputs for each stream, and "PF4" ends the program.

INTRO SCREEN 3 offers you three printer options. By pressing "PF1", a detailed listing of period by period multi-stream output is created. Stream summaries can be obtained by pressing "PF2", and an overall population summary can be acquired by pressing "PF3". If you desire printouts of more than one option, you will have the opportunity for multiple listings during viewing of the output panels or screens.

INTRO SCREEN 4 presents a graphical display of the multi-stream concept that is utilized in DRRPM to group end items according to similar failure characteristics. Simply press "PF1" to ADVANCE, "PF2" for PREVIOUS screen, or "PF3" to QUIT the program.

Introductory screens 5 and 6 also require input from the user. These screens request model or system parameters that define a framework for a model run. INTRO SCREEN 5 requests you to provide a PERIOD definition (i.e. weeks, months, or years). Simply type the appropriate word in the space provided. Use the TAB key to move between data fields. The length of the model run is also requested. Note that DRRPM has a maximum planning horizon of 12 periods. After the data has been typed, press "ENTER" to file the data. The PF key selection will then appear across the bottom. INTRO SCREEN 5 also contains operating environment information. INTRO

```
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
x                                                                         x
x                                                                         x
x                                                                         x
x                 +-----------------------------------------+             x
x                 | A DYNAMIC REPAIR/REPLACE POPULATION MODEL |           x
x                 +-----------------------------------------+             x
x                                                                         x
x                                                                         x
x                                  by                                     x
x                            James T. Luxhoj                              x
x                        Graduate Research Assistant                      x
x            Virginia Polytechnic Institute and State University          x
x                                                                         x
x                                                                         x
x                                                                         x
x          Press PF1 to advance to next screen.....                       x
x                                                                         x
x                                                                         x
x                                                                         x
x                                                                         x
x                                                                         x
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
```

INTRO SCREEN 1

```
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
x                                                                         x
x                                                                         x
x                                                                         x
x                                                                         x
x                              DATA CHOICE                                x
x                                                                         x
x                                                                         x
x            PF1 ... Sample Case Study                                    x
x                                                                         x
x            PF2 ... Use Existing Data Files                              x
x                                                                         x
x            PF3 ... All New Inputs                                       x
x                                                                         x
x            PF4 ... End Program                                          x
x                                                                         x
x                                                                         x
x            Enter PF1, PF2, PF3, or PF4 >                                x
x                                                                         x
x                                                                         x
x                                                                         x
x                                                                         x
x                                                                         x
x                                                                         x
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
```

INTRO SCREEN 2

270

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                         X
X                                                                         X
X                                                                         X
X                                                                         X
X                            PRINTER CHOICE                               X
X                                                                         X
X           PF1 ... Printer Listings of Stream by Stream Output           X
X                                                                         X
X                                                                         X
X           PF2 ... Printer Listings of Stream Summaries Only             X
X                                                                         X
X                                                                         X
X           PF3 ... Printer Listing of Population Summary Only            X
X                                                                         X
X                                                                         X
X                                                                         X
X                 Enter PF1, PF2, or PF3 >                                X
X                                                                         X
X                                                                         X
X                                                                         X
X                                                                         X
X                                                                         X
X                                                                         X
X                                                                         X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INTRO SCREEN 3

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                         X
X                                                                         X
X                         MULTI - STREAM CONCEPT                          X
X                                                                         X
X    +----------------------------------------------------------------+   X
X    |            T1       T2       T3       T4       T5              |   X
X    | AGE 3                       1a 1b    2a 2b    3a 3b            |   X
X    |                                                                |   X
X    | AGE 2              1a 1b    2a 2b    3a 3b    4a 4b            |   X
X    |                                                                |   X
X    | AGE 1     1a 1b    2a 2b    3a 3b    4a 4b    5a 5b            |   X
X    +----------------------------------------------------------------+   X
X                                                                         X
X    T1, T2,... = time period          AGE 1, AGE 2, ... = age of end items X
X                                                                         X
X    1a, 1b.... = end items of the same age, operating in failure environments a & b X
X                                                                         X
X    1a,1a,1a.. = a stream (A stream terminates when either all end items have X
X                 failed or all end items are retired.)                   X
X                                                                         X
X    ================================================================== X
X                 PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT             X
X    ================================================================== X
X                                                                         X
X                                                                         X
X                                                                         X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INTRO SCREEN 4

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                      X
X   +------------------------------------------------------------------+ X
X   | This model will produce period by period repair/replacement requirements | X
X   | for end items, and use a multi-stream concept to group end items with    | X
X   | similar attributes into unique "STREAMS".                                +
X   +------------------------------------------------------------------+
X                                                                      X
X              XXXUse the TAB key to move between data fieldsXXX        X
X                                                                      X
X      Will a PERIOD be defined in weeks, months, or years?.........   X
X                                                                      X
X      How many PERIODS should the model run?.......................   X
X         (There is a limit of 12 periods.)            Press ENTER to file data...   X
X                                                                      X
X      +------------------------------------+                          X
X      |OPERATING ENVIRONMENT INFORMATION  |                           X
X      +------------------------------------+                          X
X           It is possible for end items of the same age to have different failure   X
X           rates due to the respective environment in which the end items operate.  X
X           In this model, there is a limit of 2 different operating environments.   X
X                                                                      X
X      =============================================================== X
X                                                                      X
X      =============================================================== X
X                                                                      X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INTRO SCREEN 5

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                      X
X                        +--------------+                              X
X                        | STREAM DATA  |                              X
X                        +--------------+                              X
X                                                                      X
X              XXXUse the TAB key to move between data fieldsXXX        X
X                                                                      X
X      How many PRIMARY STREAMS of data input will there be?........      streams   X
X                                                                      X
X      (For example, with streams 1a,1b,2a,3a there are 3 primary      X
X      or main streams.  There is a LIMIT of 12 primary streams.)      X
X                                                                      X
X      What is the retirement age for the population of end items?...     periods   X
X      (Use the definition of PERIOD as previously defined.)           X
X                                                                      X
X                                        Press ENTER to file data...   X
X                                                                      X
X      =============================================================== X
X                                                                      X
X      =============================================================== X
X                                                                      X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INTRO SCREEN 6

SCREEN 6 requests some basic STREAM DATA such as the number of primary or main streams and the retirement age for a population of end items. Note that the definition of a primary stream is provided on the screen. Remember to be consistent with dimensions (weeks, months, or years) when inputting retirement age. After data has been typed, press "ENTER" to file the data, and follow the PF key selection across the bottom of the screen. INTRO SCREEN 7 contains introductory information about individual stream data. Certain stream parameters are requested once per stream, while others are requested on a period by period basis. The introductory screens have now been completed.

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                         X
X                                                                         X
X                          INDIVIDUAL STREAM DATA                         X
X     +-------------------------------------------------------------------+   X
X     | You will now be requested to input STREAM by STREAM data on demand, costs, |   X
X     | budget limits, repair capacity limits, transition probabilities, hazard    |   X
X     | function model, rate of technological improvement, and level of repair per  |   X
X     | operating environment.  Some data is requested only ONCE per stream, while  |   X
X     | data such as demand is requested on a period by period basis.               |   X
X     +-------------------------------------------------------------------+   X
X     For example, the following data is requested only ONCE per stream:        X
X     +-----------------+                                                       X
X     | LEVEL OF REPAIR |  (When requested, enter 1, 2, or 3.)                  X
X     +-----------------+                                                       X
X             There is a limit of 3 levels of repair:                          X
X                               1... field repair                              X
X                               2... local facility repair                     X
X                               3... central depot repair                      X
X     +-------------------------+                                              X
X     | OPERATING ENVIRONMENT |  (When requested, enter A or B.)               X
X     +-------------------------+                                              X
X             For example:      A... Support       B... Combat                 X
X     ===================================================================      X
X                 PF1  ADVANCE      PF2  PREVIOUS       PF3  QUIT               X
X     ===================================================================      X
X                                                                         X
X                                                                         X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INTRO SCREEN 7

III. Stream Input Screens

There are six INPUT screens that request stream data. INPUT SCREENS 1 - 5 request data once per stream, and INPUT SCREEN 6 requests stream data on a period by period basis. It is important to follow the instructions that are displayed on each INPUT SCREEN. For example, a stream name that has two words must be entered as "HYDRAULIC.PUMPS". Remember to include the period. Most of the input parameters can be entered in integer values; however, the inventory carrying cost must be entered using a real number. It is also extremely important to input all values in terms of the previously defined period to ensure a correct dimensional analysis. Also, if data is unavailable for any of the model parameters, it is important to input zeros in the appropriate field. INPUT SCREENS 1 and 2 request certain basic stream data as cost factors, level of repair, and estimated rate of technological improvement (expressed as a percentage).

INPUT SCREENS 3 and 4 request transition probabilities. It is important to use decimals when inputting these probabilities. These state transition probabilities can be estimated form past maintenance records. Remember to press "ENTER" to file the data. INPUT SCREEN 5 contains a "LIBRARY OF HAZARD FUNCTION MODELS". Type "1" for the "CONSTANT" hazard model, "2" for the "LINEARLY INCREASING" model, "3" for the "PIECEWISE LINEAR BATHTUB" model, "4" for the "WEIBULL (DECREASING)" model, and "5" for the "EXPONENTIAL" model. DRRPM does not work directly with the hazard func-

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                              X
X                                                                              X
X                         INDIVIDUAL STREAM DATA                               X
X      Number streams consecutively beginning with stream 1, and input values for  X
X      both operating environments (if data not available, input zeros(0)).  The   X
X      following data is requested only ONCE per STREAM per operating environment:  X
X                                                                              X
X         STREAM NUMBER:         OPERATING ENVIRONMENT (Enter either A or B):   X
X      1.  STREAM NAME (For example, HYDRAULIC.PUMPS)...........                X
X                      XXXUse Integer Values (e.g. #124)XXX                     X
X                                                                              X
X      2.  What is the current AGE of the units in this stream?..      period(s)  X
X          (There is a LIMIT of 12 periods, with PERIOD being previously defined.)  X
X                                                                              X
X      3.  Present Purchase Price of end item (First cost)....... $             X
X                                                                              X
X      4.  Salvage value of end item .......................... $              X
X                                                                              X
X      5.  Repair Cost per end item per period (labor, transportation, and     X
X          overhead costs, that are incurred, on the average, each time an      X
X          end item is serviced by a repair facility)........... $      /period  X
X                                        Press ENTER to file data...           X
X      ========================================================================  X
X                                                                              X
X      ========================================================================  X
X                                                                              X
X                                                                              X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INPUT SCREEN 1

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                              X
X                                                                              X
X                                                                              X
X                    INDIVIDUAL STREAM DATA (Continued)                        X
X                                                                              X
X      6.  Present Operating Cost per end item per period of the               X
X          existing asset or the "defender" end item............ $      /period  X
X                                                                              X
X      7.  Present Operating Cost per end item per period of the               X
X          replacement asset or the "challenger" end item....... $      /period  X
X                                                                              X
X      8.  Inventory Carrying Cost per end item per period....... $      /period  X
X          (Input a real number, e.g. $5.20)                                   X
X                                                                              X
X      9.  Inspection Cost per end item per period.............. $      /period  X
X                                                                              X
X      10. Estimated Rate of Technological Improvement..........      percent   X
X                                                                              X
X      11. Level of Repair (Enter 1, 2, or 3)...................               X
X                                                                              X
X                                    Press ENTER to file data...              X
X                                                                              X
X      ========================================================================  X
X                                                                              X
X      ========================================================================  X
X                                                                              X
X                                                                              X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INPUT SCREEN 2

276

```
**************************************************************************
*                                                                        *
*                                                                        *
*                         TRANSITION PROBABILITIES                       *
*                                                                        *
*   You are now requested to input the end item's state transition       *
*   probabilities.                                                       *
*   Use decimals when inputting the probabilities (e.g. .98).            *
*                                                                        *
*   ------------------------------------------------------------------   *
*      Condition at      |                |  Condition at End of Period   *
*     Start of Period    |   Decision     |           Good (G)            *
*   ------------------------------------------------------------------   *
*                        |                |        P                      *
*                        | Purchase (P)   |       P    =                  *
*                        |                |        GG                     *
*      Good (G)          |                |                               *
*                        |                |        K                      *
*                        | Keep (K)       |       P    =                  *
*                        |                |        GG                     *
*   ------------------------------------------------------------------   *
*                                                                        *
*                                    Press ENTER to file data...          *
*                                                                        *
*   ==================================================================   *
*                                                                        *
*   ==================================================================   *
*                                                                        *
*                                                                        *
**************************************************************************
```

$$P^{P}_{GG} =$$

$$P^{K}_{GG} =$$

INPUT SCREEN 3

```
**************************************************************************
*                                                                        *
*                                                                        *
*                    +-------------------------------------+             *
*                    | TRANSITION PROBABILITIES (Continued) |            *
*                    +-------------------------------------+             *
*                                                                        *
*   ------------------------------------------------------------------   *
*      Condition at      |                |  Condition at End of Period   *
*     Start of Period    |   Decision     |           Good (G)            *
*   ------------------------------------------------------------------   *
*                        |                |        P                      *
*                        | Purchase (P)   |       P    =                  *
*                        |                |        FG                     *
*      Failed (F)        |                |                               *
*                        |                |        R                      *
*                        | Repair (R)     |       P    =                  *
*                        |                |        FG                     *
*   ------------------------------------------------------------------   *
*                                                                        *
*                                    Press ENTER to file data...          *
*                                                                        *
*   ==================================================================   *
*                                                                        *
*   ==================================================================   *
*                                                                        *
*                                                                        *
**************************************************************************
```

$$P^{P}_{FG} =$$

$$P^{R}_{FG} =$$

INPUT SCREEN 4

277

tion, but uses the corresponding reliability function to describe a "survivor probability" from period to period. The use of the reliability function in the modeling approach is explained in section 3.6 of the dissertation A Dynamic Programming Approach to the Multi-Stream Replacement Problem. You are also requested to input Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) for the stream of end items. Remember to use the definition of a period as previously defined.

INPUT SCREEN 6 requests period by period stream data. Note that demand, budget limit, repair capacity, and inventory capacity are all requested. Demand, repair capacity, and maintenance inventory capacity must be inputted in number of units, and the budget limit in dollars. If data is unavailable for any period, it is important to input zeros in each of the columns for that period. INPUT SCREEN 6 is the last of the stream input screens. This set of six input screens is used for each stream in an iterative procedure. Once all stream data has been inputted, simply press "PF3" to quit the input module. Allow several moments for the computer to process the input data. Once processing is complete, DRRPM will go directly to the display sequence for stream output.

```
*********************************************************************************
*                                                                               *
*                                                                               *
*                                                                               *
*                         +------------------------------------+                *
*                         | LIBRARY OF HAZARD FUNCTION MODELS |                 *
*                         +------------------------------------+                *
*      You are now requested to select one hazard function model from the list  *
*      below to describe the instantaneous failure rate of the STREAM of end    *
*      items under evaluation.                                                   *
*                         1... CONSTANT                                         *
*                         2... LINEARLY INCREASING                              *
*                         3... PIECEWISE LINEAR BATHTUB                         *
*                         4... WEIBULL (DECREASING)                             *
*                         5... EXPONENTIAL                                      *
*                                                                               *
*                         Enter 1, 2, 3, 4, or 5 >                              *
*                                                                               *
*      Now input, in terms of the period previously defined, the Mean Time Between *
*      Failure (MTBF) and the Mean Time To Repair (MTTR) for the STREAM of end items. *
*      (Use real numbers, e.g. 8.2).                                            *
*                         MTBF (no. of periods)....                            *
*                         MTTR (no. of periods)....                            *
*                                               Press ENTER to file data...     *
*      ===================================================================      *
*                                                                               *
*      ===================================================================      *
*                                                                               *
*********************************************************************************
```

INPUT SCREEN 5

```
*********************************************************************************
*                                                                               *
*                                                                               *
*                                                                               *
*                    INDIVIDUAL STREAM DATA (Continued)                         *
*                                                                               *
*         The following end item data per STREAM is requested PERIOD by PERIOD: *
*      NOTES:  (1)   DEMAND is the number of end items required for mission success. *
*              (2)   Input DEMAND, REPAIR and INVENTORY CAPACITIES in NUMBER of units. *
*                                                                               *
*      PERIOD  FORECASTED DEMAND  BUDGET LIMIT($)  REPAIR CAPACITY  INVENTORY CAPACITY *
*         1                                                                     *
*         2                                                                     *
*         3                                                                     *
*         4                                                                     *
*         5                                                                     *
*         6                                                                     *
*         7                                                                     *
*         8                                                                     *
*         9                                                                     *
*        10                                                                     *
*        11                                                                     *
*        12                                                                     *
*                                               Press ENTER to file data...     *
*      ===================================================================      *
*                                                                               *
*      ===================================================================      *
*                                                                               *
*********************************************************************************
```

INPUT SCREEN 6

IV. Stream Output Screens

There are essentially four stream output screens that are repeatedly used to display information. OUTPUT SCREEN 1 basically outputs selected stream inputs in an attempt to identify the stream and its important attributes. OUTPUT SCREEN 2 is used in an iterative fashion to display period by period stream data for states "good" and "failed". Both a Repair/Replace Policy recommendation and Policy Cost can be ascertained by viewing these screens. The different purchase options are explained in the legend. Note if the budget is exceeded, DRRPM computes a supplemental cost of exceeding the budget. If there is no output available for a period, the words "NO OUTPUT" will appear in row 8. If "PF2" is pressed for "REVIEW", the display sequence returns to OUTPUT SCREEN 1, and the period by period information can be viewed again. Note that DRRPM uses the terminology "Period(s) to go", since backward recursion is used in the solution methodology. Thus, the first period to be displayed is labeled "1 period to go" and is actually the end of the model planning horizon.

OUTPUT SCREEN 3 is used to display a STREAM SUMMARY. This screen is also used in an iterative fashion to display period by period stream data. Each stream and its corresponding expected future cost can be analyzed. The logistician at this level can assess what is the contribution of each stream of end items to overall population cost on a period by period basis. If "PF2" is pressed, the immediate

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                                                        X
X                                                                        X
X                       +------------------+                             X
X                       |  STREAM OUTPUT   |                             X
X                       +------------------+                             X
X                                                                        X
X   STREAM NUMBER:              OPERATING ENVIRONMENT:                   X
X                                                                        X
X      1.   STREAM NAME..................................                X
X                                                                        X
X      2.   Hazard Model.................................                X
X                                                                        X
X      3.   Level of Repair..............................                X
X                                                                        X
X      4.   Initial Age of Population....................       Period(s) X
X                                                                        X
X      5.   Mean Time Between Failure (MTBF).............       Period(s) X
X                                                                        X
X      6.   Mean Time To Repair (MTTR)...................       Period(s) X
X                                                                        X
X      7.   Estimated Rate of Technological Improvement....     Percent  X
X                                                                        X
X   ------------------------------------------------------------------   X
X              PF1 = ADVANCE              PF3 = QUIT                      X
X   ------------------------------------------------------------------   X
X                                                                        X
X                                                                        X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

OUTPUT SCREEN 1

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X                                           .                            X
X                                                                        X
X                     STREAM OUTPUT(Continued)                           X
X                                                                        X
X     STREAM NUMBER:              OPERATING ENVIRONMENT:                 X
X         8.    Period(s) To Go...............................          X
X         9.    Operational State of the Equipment.........             X
X        10.    Population Age..............................   period(s)  X
X        11.    Policy Recommendation.......................            X
X        12.    Forecasted Demand...........................   units     X
X        13.    Policy Requirements.........................   units     X
X        14.    Policy Cost................................. $           X
X        15.    Supplemental Cost of Exceeding Budget...... $            X
X        16.    Reliability  (Unreliability for state F)...             X
X        17.    Availability (Unavailability for state F)..             X
X   ------------------------------------------------------------------   X
X   Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)        X
X             P2 = Purchase Option 2 (Purchase 2 period's supply and carry next X
X                  period's supply in inventory)                         X
X             P3 = Purchase Option 3 (Purchase 3 period's supply and carry next X
X                  2 period's supply in inventory)                       X
X             K  = Keep ("Do nothing" alternative)      R = Repair       X
X   ------------------------------------------------------------------   X
X              PF1 = ADVANCE        PF2 = REVIEW        PF3 = QUIT        X
X   ------------------------------------------------------------------   X
X                                                                        X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

OUTPUT SCREEN 2

predecessor screen is redisplayed. The final output screen is OUTPUT SCREEN 4 and provides the logistician with an overall population summary. The total number of primary streams, total number of periods, and period definition are all outputted. The expected future costs for that defined population is displayed on a period by period basis. Remember that the term "Period(s) to go" is used, so that "1 period to go" is actually the end of the model planning horizon. Note that when you are in the stream output display sequence and "PF3" is pressed for "QUIT", you are given the option of viewing alternative output displays other than the one just viewed, or you can end the DRRPM program at this point.

```
*******************************************************************************
*                                                                             *
*                                                                             *
*                             +-----------------+                             *
*                             | STREAM SUMMARY  |                             *
*                             +-----------------+                             *
*                                                                             *
*     PERIOD(S) TO GO:                                                        *
*                                                                             *
*     STREAM NUMBER            STREAM NAME          EXPECTED FUTURE COSTS      *
*                                                                             *
*          1                                            $                     *
*          2                                            $                     *
*          3                                            $                     *
*          4                                            $                     *
*          5                                            $                     *
*          6                                            $                     *
*          7                                            $                     *
*          8                                            $                     *
*          9                                            $                     *
*         10                                            $                     *
*         11                                            $                     *
*         12                                            $                     *
*     -------------------------------------------------------------------     *
*           PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT             *
*     -------------------------------------------------------------------     *
*                                                                             *
*                                                                             *
*******************************************************************************
```

OUTPUT SCREEN 3

```
*******************************************************************************
*                                                                             *
*                                                                             *
*                          POPULATION SUMMARY                                 *
*                                                                             *
*     1.  Total Number of Primary Streams......................               *
*     2.  Total Number of Periods..............................               *
*     3.  Period definition....................................               *
*                                                                             *
*              PERIOD(S) TO GO              EXPECTED FUTURE COSTS              *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                 $                           *
*                                                                             *
*     Total Population Cost..........  $                                      *
*                                                                             *
*                                  Press PF3 to Quit...                       *
*                                                                             *
*******************************************************************************
```

OUTPUT SCREEN 4
```

# V. Acessing the Printer

If a small printer, such as the IBM Proprinter, is connected on-line to your personal computer, then printouts of all INTRO, INPUT, and OUTPUT SCREENS can be obtained by simply pressing "SHIFT PrtSc".

## VI. Recommendations

DRRPM or "A Dynamic Repair/Replace Population Model" is relatively user friendly. Be extremely careful when selecting a data option, since it is possible to erase all stream input files if "PF3" is pressed unintentionally. DRRPM can be used by the logistician for the evaluation of feasible repair/replace strategies for a population of end items, and considers the trade-offs between policy costs and system availability. Note that DRRPM allows the logistician to perform either single- or multi-parameter sensitivity analyses. Moreover, either single- or multi-stream populations can be evaluated. See the dissertation, A Dynamic Programming Approach to the Multi-Stream Replacement Problem, for a systematic treatment of population model sensitivity analyses. It must be remembered that DRRPM is a software prototype that must undergo an extensive period of evaluation in an operational environment in order to properly assess the economic impact of this new software technology.

**APPENDIX II**

**CASE STUDIES**

# APPENDIX A.1

# POPULATION BASE CASE

## POPULATION SUMMARY

1. Total Number of Primary Streams...................... 3
2. Total Number of Periods............................. 3
3. Period definition................................... MONTHS

|        PERIOD(S) TO GO        |        EXPECTED FUTURE COSTS        |
|-------------------------------|-------------------------------------|
| 12                            | $ 0.00                              |
| 11                            | $ 0.00                              |
| 10                            | $ 0.00                              |
| 9                             | $ 0.00                              |
| 8                             | $ 0.00                              |
| 7                             | $ 0.00                              |
| 6                             | $ 0.00                              |
| 5                             | $ 0.00                              |
| 4                             | $ 0.00                              |
| 3                             | $ 4870.08                           |
| 2                             | $ 3203.44                           |
| 1                             | $ 1539.49                           |

Total Population Cost.......... $ 9613.01

Press PF3 to Quit...

```
                    +-----------------+
                    | STREAM SUMMARY  |
                    +-----------------+

PERIOD(S) TO GO: 1

STREAM NUMBER            STREAM NAME              EXPECTED FUTURE COSTS

     1            FRESHWATER.PUMPS                  514.77
     2            SEAWATER.PUMPS                    746.42
     3            HYDRAULIC.PUMPS                   278.30
     4                                                0.00
     5                                                0.00
     6                                                0.00
     7                                                0.00
     8                                                0.00
     9                                                0.00
    10                                                0.00
    11                                                0.00
    12                                                0.00
----------------------------------------------------------------------------
        PF1 = ADVANCE        PF2 = PREVIOUS       PF3 = QUIT
----------------------------------------------------------------------------
```

```
                    +-----------------+
                    ¦ STREAM SUMMARY  ¦
                    +-----------------+

PERIOD(S) TO GO: 2

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

     1            FRESHWATER.PUMPS                      1074.27
     2            SEAWATER.PUMPS                        1608.84
     3            HYDRAULIC.PUMPS                        520.32
     4                                                    0.00
     5                                                    0.00
     6                                                    0.00
     7                                                    0.00
     8                                                    0.00
     9                                                    0.00
    10                                                    0.00
    11                                                    0.00
    12                                                    0.00
------------------------------------------------------------------------
     PF1 = ADVANCE          PF2 = PREVIOUS          PF3 = QUIT
------------------------------------------------------------------------
```

```
          +------------------+
          ¦ STREAM SUMMARY  ¦
          +------------------+


PERIOD(S) TO GO: 3

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

       1            FRESHWATER.PUMPS                    1736.90
       2            SEAWATER.PUMPS                    ·2378.84
       3            HYDRAULIC.PUMPS                     754.34
       4                                                 0.00
       5                                                 0.00
       6                                                 0.00
       7                                                 0.00
       8                                                 0.00
       9                                                 0.00
      10                                                 0.00
      11                                                 0.00
      12                                                 0.00
-----------------------------------------------------------------------

     PF1 = ADVANCE          PF2 = PREVIOUS          PF3 = QUIT
-----------------------------------------------------------------------
```

```
                    +------------------+
                    :   STREAM OUTPUT  :
                    +------------------+

STREAM NUMBER: 1                OPERATING ENVIRONMENT: A

  1.  STREAM NAME...................................  FRESHWATER.PUMPS

  2.  Hazard Model.................................  LINEARLY INCREASING

  3.  Level of Repair..............................  2

  4.  Initial Age of Population.....................  1         Period(s)

  5.  Mean Time Between Failure (MTBF)..............  8.22      Period(s)

  6.  Mean Time To Repair (MTTR)....................  0.0328    Period(s)

  7.  Estimated Rate of Technological Improvement....  10        Percent
-----------------------------------------------------------------------------
            PF1 = ADVANCE                 PF3 - QUIT
-----------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
 8.   Period(s) To Go............................   1
 9.   Operational State of the Equipment........   GOOD
10.   Population Age............................   3   period(s)
11.   Policy Recommendation.....................   K
12.   Forecasted Demand.........................   9   units
13.   Policy Requirements.......................   9   ·   units
14.   Policy Cost............................... $ 310.00
15.   Supplemental Cost of Exceeding Budget...... $ 0.00
16.   Reliability (Unreliability for state F)...   0.893597
17.   Availability (Unavailability for state F)..   0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
 8.   Period(s) To Go............................   1
 9.   Operational State of the Equipment........   FAILED
10.   Population Age............................   3   period(s)
11.   Policy Recommendation.....................   R
12.   Forecasted Demand.........................   9   units
13.   Policy Requirements.......................   9   units
14.   Policy Cost............................... $ 535.18
15.   Supplemental Cost of Exceeding Budget...... $ 0.00
16.   Reliability (Unreliability for state F)...   0.106403
17.   Availability (Unavailability for state F)..   0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

293

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go........................   2
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age...........................   2   period(s)
    11.   Policy Recommendation....................   K
    12.   Forecasted Demand........................   10   units
    13.   Policy Requirements......................   10   units
    14.   Policy Cost.............................. $ 630.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.951229
    17.   Availability (Unavailability for state F)..   0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go........................   2
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age...........................   2   period(s)
    11.   Policy Recommendation....................   R
    12.   Forecasted Demand........................   10   units
    13.   Policy Requirements......................   10   units
    14.   Policy Cost.............................. $ 896.47
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.043771
    17.   Availability (Unavailability for state F)..   0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go............................ 3
    9.   Operational State of the Equipment........ GOOD
    10. Population Age............................. 1   period(s)
    11. Policy Recommendation..................... K
    12. Forecasted Demand......................... 12   units
    13. Policy Requirements....................... 12   units
    14. Policy Cost............................... $ 1005.00
    15. Supplemental Cost of Exceeding Budget..... $ 0.00
    16. Reliability (Unreliability for state F)... 0.987578
    17. Availability (Unavailability for state F).. 0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go............................ 3
    9.   Operational State of the Equipment........ FAILED
    10. Population Age............................. 1   period(s)
    11. Policy Recommendation..................... R
    12. Forecasted Demand......................... 12   units
    13. Policy Requirements....................... 12   units
    14. Policy Cost............................... $ 1336.52
    15. Supplemental Cost of Exceeding Budget..... $ 0.00
    16. Reliability (Unreliability for state F)... 0.012422
    17. Availability (Unavailability for state F).. 0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

```
                    +------------------+
                    :  STREAM OUTPUT   :
                    +------------------+

STREAM NUMBER: 1              OPERATING ENVIRONMENT: B

   1.   STREAM NAME.................................   FRESHWATER.PUMPS

   2.   Hazard Model...............................   PIECE. LIN. BATH.

   3.   Level of Repair............................   2

   4.   Initial Age of Population..................   1          Period(s)

   5.   Mean Time Between Failure (MTBF)...........   5.49       Period(s)

   6.   Mean Time To Repair (MTTR).................   0.0328     Period(s)

   7.   Estimated Rate of Technological Improvement....  10      Percent
_____

              PF1 = ADVANCE            PF3 = QUIT
_____
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 1                OPERATING ENVIRONMENT: B
    8.    Period(s) To Go............................   1
    9.    Operational State of the Equipment........   GOOD
   10.    Population Age.............................   3        period(s)
   11.    Policy Recommendation.....................   K
   12.    Forecasted Demand.........................   6        units
   13.    Policy Requirements.......................   6        units
   14.    Policy Cost............................... $ 203.00
   15.    Supplemental Cost of Exceeding Budget...... $ 0.00
   16.    Reliability  (Unreliability for state F)...   0.878527
   17.    Availability (Unavailability for state F)..   0.994061
```

```
egend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K  = Keep ("Do nothing" alternative)      R = Repair
```

```
         PF1 = ADVANCE          PF2 = REVIEW          PF3 = QUIT
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 1                OPERATING ENVIRONMENT: B
    8.    Period(s) To Go............................   1
    9.    Operational State of the Equipment........   FAILED
   10.    Population Age.............................   3        period(s)
   11.    Policy Recommendation.....................   R
   12.    Forecasted Demand.........................   6        units
   13.    Policy Requirements.......................   6        units
   14.    Policy Cost............................... $ 350.25
   15.    Supplemental Cost of Exceeding Budget...... $ 0.00
   16.    Reliability  (Unreliability for state F)...   0.121473
   17.    Availability (Unavailability for state F)..   0.005939
```

```
egend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K  = Keep ("Do nothing" alternative)      R = Repair
```

```
         PF1 = ADVANCE          PF2 = REVIEW          PF3 = QUIT
```

297

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B

8. Period(s) To Go............................ 2
9. Operational State of the Equipment........ GOOD
10. Population Age............................. 2   period(s)
11. Policy Recommendation...................... K
12. Forecasted Demand......................... 8   units
13. Policy Requirements....................... 8   units
14. Policy Cost............................... $ 442.00
15. Supplemental Cost of Exceeding Budget...... $ 0.00
16. Reliability (Unreliability for state F)... 0.913116
17. Availability (Unavailability for state F).. 0.994061

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
   P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
     period's supply in inventory)
   P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
     2 period's supply in inventory)
   K = Keep ("Do nothing" alternative) R = Repair

   PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B

8. Period(s) To Go............................ 2
9. Operational State of the Equipment........ FAILED
10. Population Age............................. 2   period(s)
11. Policy Recommendation...................... R
12. Forecasted Demand......................... 8   units
13. Policy Requirements....................... 8   units
14. Policy Cost............................... $ 646.50
15. Supplemental Cost of Exceeding Budget...... $ 0.00
16. Reliability (Unreliability for state F)... 0.086884
17. Availability (Unavailability for state F).. 0.005939

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
   P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
     period's supply in inventory)
   P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
     2 period's supply in inventory)
   K = Keep ("Do nothing" alternative) R = Repair

   PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment.........   GOOD
    10.   Population Age..............................   1   period(s)
    11.   Policy Recommendation.......................   K
    12.   Forecasted Demand...........................   10   units
    13.   Policy Requirements.........................   10   units
    14.   Policy Cost................................. $ 729.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.953398
    17.   Availability (Unavailability for state F)..   0.994061

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                 period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                 2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment.........   FAILED
    10.   Population Age..............................   1   period(s)
    11.   Policy Recommendation.......................   R
    12.   Forecasted Demand...........................   10   units
    13.   Policy Requirements.........................   10   units
    14.   Policy Cost................................. $ 994.81
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.046602
    17.   Availability (Unavailability for state F)..   0.005939

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                 period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                 2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

```
            +------------------+
            |  STREAM OUTPUT   |
            +------------------+

STREAM NUMBER: 2                OPERATING ENVIRONMENT: A

   1.   STREAM NAME.....................................   SEAWATER.PUMPS

   2.   Hazard Model....................................   EXPONENTIAL

   3.   Level of Repair.................................   2

   4.   Initial Age of Population.......................   2          Period(s)

   5.   Mean Time Between Failure (MTBF)................   20.50      Period(s)

   6.   Mean Time To Repair (MTTR)......................   0.0400     Period(s)

   7.   Estimated Rate of Technological Improvement....   10         Percent
--------------------------------------------------------------------------------
            PF1 = ADVANCE                    PF3 = QUIT
--------------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   1
    9.   Operational State of the Equipment.........   GOOD
    10.   Population Age..............................   4   period(s)
    11.   Policy Recommendation......................   K
    12.   Forecasted Demand..........................   4   units
    13.   Policy Requirements........................   4   units
    14.   Policy Cost................................ $ 426.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.979877
    17.   Availability (Unavailability for state F)..   0.998053

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   1
    9.   Operational State of the Equipment.........   FAILED
    10.   Population Age..............................   4   period(s)
    11.   Policy Recommendation......................   R
    12.   Forecasted Demand..........................   4   units
    13.   Policy Requirements........................   4   units
    14.   Policy Cost................................ $ 770.86
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.020123
    17.   Availability (Unavailability for state F)..   0.001947

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go........................   2
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age...........................   3   period(s)
    11.   Policy Recommendation....................   K
    12.   Forecasted Demand........................   5   units
    13.   Policy Requirements......................   5   units
    14.   Policy Cost.............................. $ 905.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.980369
    17.   Availability (Unavailability for state F)..   0.998053

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go..........................   2
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age...........................   3   period(s)
    11.   Policy Recommendation....................   R
    12.   Forecasted Demand........................   5   units
    13.   Policy Requirements......................   5   units
    14.   Policy Cost.............................. $ 1335.87
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.019631
    17.   Availability (Unavailability for state F)..   0.001947

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
  8.   Period(s) To Go............................   3
  9.   Operational State of the Equipment........   GOOD
 10.   Population Age.............................   2   period(s)
 11.   Policy Recommendation.....................   K
 12.   Forecasted Demand.........................   5   units
 13.   Policy Requirements.......................   5   units
 14.   Policy Cost............................... $ 1333.00
 15.   Supplemental Cost of Exceeding Budget..... $ 0.00
 16.   Reliability (Unreliability for state F)...   0.980849
 17.   Availability (Unavailability for state F)..   0.998053
_____
Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair
_____
          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT
_____

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
  8.   Period(s) To Go............................   3
  9.   Operational State of the Equipment........   FAILED
 10.   Population Age.............................   2   period(s)
 11.   Policy Recommendation.....................   R
 12.   Forecasted Demand.........................   5   units
 13.   Policy Requirements.......................   5   units
 14.   Policy Cost............................... $ 1764.72
 15.   Supplemental Cost of Exceeding Budget..... $ 0.00
 16.   Reliability (Unreliability for state F)...   0.019151
 17.   Availability (Unavailability for state F)..   0.001947
_____
Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair
_____
          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT
_____

```
                    +-----------------+
                    !  STREAM OUTPUT  !
                    +-----------------+

STREAM NUMBER: 2                OPERATING ENVIRONMENT: B

   1.   STREAM NAME...................................  SEAWATER.PUMPS

   2.   Hazard Model..................................  EXPONENTIAL

   3.   Level of Repair...............................  2

   4.   Initial Age of Population.....................  2        Period(s)

   5.   Mean Time Between Failure (MTBF)..............  13.70    Period(s)

   6.   Mean Time To Repair (MTTR)....................  0.0400   Period(s)

   7.   Estimated Rate of Technological Improvement....  10       Percent
```

```
            PF1 = ADVANCE               PF3 = QUIT
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation.....................   K
    12.   Forecasted Demand.........................   3   units
    13.   Policy Requirements.......................   3   units
    14.   Policy Cost............................... $ 319.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.979877
    17.   Availability (Unavailability for state F)..   0.997089

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation.....................   R
    12.   Forecasted Demand.........................   3   units
    13.   Policy Requirements.......................   3   units
    14.   Policy Cost............................... $ 577.72
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.020123
    17.   Availability (Unavailability for state F)..   0.002911

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 2              OPERATING ENVIRONMENT: B
    8.    Period(s) To Go..............................  2
    9.    Operational State of the Equipment........  GOOD
   10.    Population Age...............................  3          period(s)
   11.    Policy Recommendation.......................  K
   12.    Forecasted Demand...........................  4          units
   13.    Policy Requirements.........................  4          units
   14.    Policy Cost................................. $ 702.00
   15.    Supplemental Cost of Exceeding Budget...... $ 0.00
   16.    Reliability  (Unreliability for state F)...  0.980369
   17.    Availability (Unavailability for state F)..  0.997089
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)       R = Repair
```

```
          PF1 = ADVANCE          PF2 = REVIEW          PF3 = QUIT
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 2              OPERATING ENVIRONMENT: B
    8.    Period(s) To Go..............................  2
    9.    Operational State of the Equipment........  FAILED
   10.    Population Age...............................  3          period(s)
   11.    Policy Recommendation.......................  R
   12.    Forecasted Demand...........................  4          units
   13.    Policy Requirements.........................  4          units
   14.    Policy Cost................................. $ 1046.57
   15.    Supplemental Cost of Exceeding Budget...... $ 0.00
   16.    Reliability  (Unreliability for state F)...  0.019631
   17.    Availability (Unavailability for state F)..  0.002911
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)       R = Repair
```

```
          PF1 = ADVANCE          PF2 = REVIEW          PF3 = QUIT
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................ 3
    9.   Operational State of the Equipment........ GOOD
   10.   Population Age............................. 2   period(s)
   11.   Policy Recommendation...................... K
   12.   Forecasted Demand.......................... 4   units
   13.   Policy Requirements........................ 4   units
   14.   Policy Cost................................ $ 1044.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)... 0.980849
   17.   Availability (Unavailability for state F).. 0.997089

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................ 3
    9.   Operational State of the Equipment........ FAILED
   10.   Population Age............................. 2   period(s)
   11.   Policy Recommendation...................... R
   12.   Forecasted Demand.......................... 4   units
   13.   Policy Requirements........................ 4   units
   14.   Policy Cost................................ $ 1389.17
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)... 0.019151
   17.   Availability (Unavailability for state F).. 0.002911

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

```
                    +-------------------+
                    :  STREAM OUTPUT    :
                    +-------------------+

STREAM NUMBER: 3                OPERATING ENVIRONMENT: A

   1.   STREAM NAME....................................  HYDRAULIC.PUMPS

   2.   Hazard Model...................................  LINEARLY INCREASING

   3.   Level of Repair................................  1

   4.   Initial Age of Population......................  2        Period(s)

   5.   Mean Time Between Failure (MTBF)...............  32.87    Period(s)

   6.   'Mean Time To Repair (MTTR).....................  0.0394   Period(s)

   7.   Estimated Rate of Technological Improvement....  12       Percent
----------------------------------------------------------------------------
           PF1 = ADVANCE                 PF3 = QUIT
----------------------------------------------------------------------------
```

303

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   1
    9.   Operational State of the Equipment.........   GOOD
    10.   Population Age..............................   4   period(s)
    11.   Policy Recommendation.......................   K
    12.   Forecasted Demand...........................   3   units
    13.   Policy Requirements.........................   3   units
    14.   Policy Cost................................. $ 139.00
    15.   Supplemental Cost of Exceeding Budget....... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.818731
    17.   Availability (Unavailability for state F)..   0.998803
----
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   1
    9.   Operational State of the Equipment.........   FAILED
    10.   Population Age..............................   4   period(s)
    11.   Policy Recommendation.......................   R
    12.   Forecasted Demand...........................   3   units
    13.   Policy Requirements.........................   3   units
    14.   Policy Cost................................. $ 237.34
    15.   Supplemental Cost of Exceeding Budget....... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.181269
    17.   Availability (Unavailability for state F)..   0.001197
----
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3                OPERATING ENVIRONMENT: A
   8.   Period(s) To Go.............................   2
   9.   Operational State of the Equipment.........   GOOD
  10.   Population Age..............................   3         period(s)
  11.   Policy Recommendation.......................  K
  12.   Forecasted Demand...........................  3         units
  13.   Policy Requirements.........................  3         units
  14.   Policy Cost.................................  $ 260.00
  15.   Supplemental Cost of Exceeding Budget......  $ 0.00
  16.   Reliability  (Unreliability for state F)...  0.893597
  17.   Availability (Unavailability for state F)..  0.998803
```
----
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K = Keep ("Do nothing" alternative)   R = Repair

         PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3                OPERATING ENVIRONMENT: A
   8.   Period(s) To Go.............................   2
   9.   Operational State of the Equipment.........   FAILED
  10.   Population Age..............................   3         period(s)
  11.   Policy Recommendation.......................  R
  12.   Forecasted Demand...........................  3         units
  13.   Policy Requirements.........................  3         units
  14.   Policy Cost.................................  $ 367.47
  15.   Supplemental Cost of Exceeding Budget......  $ 0.00
  16.   Reliability  (Unreliability for state F)...  0.106403
  17.   Availability (Unavailability for state F)..  0.001197
```
----
egend: .P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K = Keep ("Do nothing" alternative)   R = Repair

         PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

```

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment........   GOOD
   10.   Population Age.............................   2   period(s)
   11.   Policy Recommendation.....................   K
   12.   Forecasted Demand.........................   3   units
   13.   Policy Requirements.......................   3   units
   14.   Policy Cost............................... $ 377.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.951229
   17.   Availability (Unavailability for state F)..   0.998803
----
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment........   FAILED
   10.   Population Age.............................   2   period(s)
   11.   Policy Recommendation.....................   R
   12.   Forecasted Demand.........................   3   units
   13.   Policy Requirements.......................   3   units
   14.   Policy Cost............................... $ 491.37
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.048771
   17.   Availability (Unavailability for state F)..   0.001197
----
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

311

```
                +-------------------+
                :   STREAM OUTPUT   :
                +-------------------+

STREAM NUMBER: 3                OPERATING ENVIRONMENT: B

  1.   STREAM NAME.................................  HYDRAULIC.PUMPS

  2.   Hazard Model................................  LINEARLY INCREASING

  3.   Level of Repair.............................  1

  4.   Initial Age of Population...................  2         Period(s)

  5.   Mean Time Between Failure (MTBF)............  21.97     Period(s)

  6.   Mean Time To Repair (MTTR)..................  0.0400    Period(s)

  7.   Estimated Rate of Technological Improvement....  12     Percent
---------------------------------------------------------------------------
              PF1 = ADVANCE               PF3 = QUIT
---------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3                    OPERATING ENVIRONMENT: B
    8.     Period(s) To Go...........................  1
    9.     Operational State of the Equipment........  GOOD
   10.     Population Age............................  4         period(s)
   11.     Policy Recommendation.....................  K
   12.     Forecasted Demand.........................  3         units
   13.     Policy Requirements.......................  3         units
   14.     Policy Cost...............................  $ 139.00
   15.     Supplemental Cost of Exceeding Budget.....  $ 0.00
   16.     Reliability  (Unreliability for state F)...  0.819731
   17.     Availability (Unavailability for state F)..  0.998183
```
_____
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K = Keep ("Do nothing" alternative)   R = Repair
_____
         PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT
_____

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3                    OPERATING ENVIRONMENT: B
    8.     Period(s) To Go...........................  1
    9.     Operational State of the Equipment........  FAILED
   10.     Population Age............................  4         period(s)
   11.     Policy Recommendation.....................  R
   12.     Forecasted Demand.........................  3         units
   13.     Policy Requirements.......................  3         units
   14.     Policy Cost...............................  $ 237.23
   15.     Supplemental Cost of Exceeding Budget.....  $ 0.00
   16.     Reliability  (Unreliability for state F)...  0.181269
   17.     Availability (Unavailability for state F)..  0.001817
```
_____
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K = Keep ("Do nothing" alternative)   R = Repair
_____
         PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT
_____
```

313

STREAM OUTPUT(Continued)

STREAM NUMBER: 3                    OPERATING ENVIRONMENT: B
     8.    Period(s) To Go............................    2
     9.    Operational State of the Equipment........    GOOD
    10.    Population Age.............................    3         period(s)
    11.    Policy Recommendation......................    K
    12.    Forecasted Demand..........................    3         units
    13.    Policy Requirements........................    3         units
    14.    Policy Cost................................  $ 260.00
    15.    Supplemental Cost of Exceeding Budget......  $ 0.00
    16.    Reliability  (Unreliability for state F)...    0.893597
    17.    Availability (Unavailability for state F)..    0.998183
-------------------------------------------------------------------------------
egend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K  = Keep ("Do nothing" alternative)      R = Repair
-------------------------------------------------------------------------------
             PF1 = ADVANCE        PF2 = REVIEW          PF3 = QUIT
-------------------------------------------------------------------------------


STREAM OUTPUT(Continued)

STREAM NUMBER: 3                    OPERATING ENVIRONMENT: B
     8.    Period(s) To Go............................    2
     9.    Operational State of the Equipment........    FAILED
    10.    Population Age.............................    3         period(s)
    11.    Policy Recommendation......................    R
    12.    Forecasted Demand..........................    3         units
    13.    Policy Requirements........................    3         units
    14.    Policy Cost................................  $ 367.30
    15.    Supplemental Cost of Exceeding Budget......  $ 0.00
    16.    Reliability  (Unreliability for state F)...    0.106403
    17.    Availability (Unavailability for state F)..    0.001817
-------------------------------------------------------------------------------
egend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
         P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
         P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
         K  = Keep ("Do nothing" alternative)      R = Repair
-------------------------------------------------------------------------------
             PF1 = ADVANCE        PF2 = REVIEW          PF3 = QUIT
-------------------------------------------------------------------------------

314

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3               OPERATING ENVIRONMENT: B
   8.   Period(s) To Go..............................  3
   9.   Operational State of the Equipment.........  GOOD
  10.   Population Age...............................  2        period(s)
  11.   Policy Recommendation........................  K
  12.   Forecasted Demand............................  3        units
  13.   Policy Requirements..........................  3        units
  14.   Policy Cost..................................  $ 377.00
  15.   Supplemental Cost of Exceeding Budget......  $ 0.00
  16.   Reliability   (Unreliability for state F)...  0.951229
  17.   Availability (Unavailability for state F)..  0.998183
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)        R = Repair
```

```
          PF1 = ADVANCE          PF2 = REVIEW          PF3 = QUIT
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3               OPERATING ENVIRONMENT: B
   8.   Period(s) To Go..............................  3
   9.   Operational State of the Equipment.........  FAILED
  10.   Population Age...............................  2        period(s)
  11.   Policy Recommendation........................  R
  12.   Forecasted Demand............................  3        units
  13.   Policy Requirements..........................  3        units
  14.   Policy Cost..................................  $ 491.14
  15.   Supplemental Cost of Exceeding Budget......  $ 0.00
  16.   Reliability   (Unreliability for state F)...  0.048771
  17.   Availability (Unavailability for state F)..  0.001817
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)        R = Repair
```

```
          PF1 = ADVANCE          PF2 = REVIEW          PF3 = QUIT
```

APPENDIX A.2

SCENARIO 1 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams..................... 3
2. Total Number of Periods........................... 3
3. Period definition................................. MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 4870.08
2	$ 3203.44
1	$ 1539.49

Total Population Cost.......... $ 9613.01

Press PF3 to Quit...


```
              +------------------+
              ! STREAM SUMMARY  !
              +------------------+
```

PERIOD(S) TO GO: 1

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	514.77
2	SEAWATER.PUMPS	746.42
3	HYDRAULIC.PUMPS	278.30
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

```
-------------------------------------------------------------------------------
        PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
-------------------------------------------------------------------------------
```

```
                    +------------------+
                    : STREAM SUMMARY :
                    +------------------+

PERIOD(S) TO GO: 2

STREAM NUMBER               STREAM NAME              EXPECTED FUTURE COSTS

     1               FRESHWATER.PUMPS                    1074.27
     2               SEAWATER.PUMPS                      1608.84
     3               HYDRAULIC.PUMPS                      520.32
     4                                                     0.00
     5                                                     0.00
     6                                                     0.00
     7                                                     0.00
     8                                                     0.00
     9                                                     0.00
    10                                                     0.00
    11                                                     0.00
    12                                                     0.00
----------------------------------------------------------------------------------
        PF1 = ADVANCE          PF2 = PREVIOUS          PF3 = QUIT
----------------------------------------------------------------------------------



                    +------------------+
                    : STREAM SUMMARY :
                    +------------------+

PERIOD(S) TO GO: 3

STREAM NUMBER               STREAM NAME              EXPECTED FUTURE COSTS

     1               FRESHWATER.PUMPS                    1736.90
     2               SEAWATER.PUMPS                      2378.84
     3               HYDRAULIC.PUMPS                      754.34
     4                                                     0.00
     5                                                     0.00
     6                                                     0.00
     7                                                     0.00
     8                                                     0.00
     9                                                     0.00
    10                                                     0.00
    11                                                     0.00
    12                                                     0.00
----------------------------------------------------------------------------------
        PF1 = ADVANCE          PF2 = PREVIOUS          PF3 = QUIT
----------------------------------------------------------------------------------
```

APPENDIX A.3

SCENARIO 2 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams...................... 3
2. Total Number of Periods............................ 3
3. Period definition.................................. MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 5468.08
2	$ 3685.44
1	$ 1815.49

Total Population Cost.......... $ 10969.00

Press PF3 to Quit...

```
+-----------------+
: STREAM SUMMARY :
+-----------------+
```

PERIOD(S) TO GO: 1

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	587.77
2	SEAWATER.PUMPS	873.42
3	HYDRAULIC.PUMPS	334.30
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
            +-----------------+
            : STREAM SUMMARY :
            +-----------------+
```

PERIOD(S) TO GO: 2

STREAM NUMBER   STREAM NAME   EXPECTED FUTURE COSTS

    1   FRESHWATER.PUMPS   1197.27
    2   SEAWATER.PUMPS   1877.84
    3   HYDRAULIC.PUMPS   610.32
    4   0.00
    5   0.00
    6   0.00
    7   0.00
    8   0.00
    9   0.00
   10   0.00
   11   0.00
   12   0.00

        PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
            +-----------------+
            : STREAM SUMMARY :
            +-----------------+
```

PERIOD(S) TO GO: 3

STREAM NUMBER   STREAM NAME   EXPECTED FUTURE COSTS

    1   FRESHWATER.PUMPS   1886.90
    2   SEAWATER.PUMPS   2716.84
    3   HYDRAULIC.PUMPS   864.04
    4   0.00
    5   0.00
    6   0.00
    7   0.00
    8   0.00
    9   0.00
   10   0.00
   11   0.00
   12   0.00

        PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

321

APPENDIX A.4

SCENARIO 3 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams..................... 3
2. Total Number of Periods............................. 3
3. Period definition................................... MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 4872.09
2	$ 3205.19
1	$ 1540.87

Total Population Cost.......... $ 9418.14

Press PF3 to Quit...

```
+------------------+
! STREAM SUMMARY !
+------------------+
```

PERIOD(S) TO GO: 1

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	515.46
2	SEAWATER.PUMPS	746.99
3	HYDRAULIC.PUMPS	278.41
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
            +-----------------+
            | STREAM SUMMARY  |
            +-----------------+
```

PERIOD(S) TO GO: 2

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	1075.16
2	SEAWATER.PUMPS	1609.57
3	HYDRAULIC.PUMPS	520.45
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
            +-----------------+
            | STREAM SUMMARY  |
            +-----------------+
```

PERIOD(S) TO GO: 3

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	1738.03
2	SEAWATER.PUMPS	2379.58
3	HYDRAULIC.PUMPS	754.48
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

324

APPENDIX A.5

SCENARIO 4 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams................... 3
2. Total Number of Periods........................... 3
3. Period definition................................. MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 6578.08
2	$ 4335.43
1	$ 2086.49

Total Population Cost......... $ 13000.00

Press PF3 to Quit...

```
+-------------------+
! STREAM SUMMARY !
+-------------------+
```

PERIOD(S) TO GO: 1

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	693.77
2	SEAWATER.PUMPS	1012.42
3	HYDRAULIC.PUMPS	380.30
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

    PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
                    +-----------------+
                    | STREAM SUMMARY  |
                    +-----------------+


PERIOD(S) TO GO: 2

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

      1              FRESHWATER.PUMPS                    1447.27
      2              SEAWATER.PUMPS                      2177.84
      3              HYDRAULIC.PUMPS                      710.32
      4                                                    0.00
      5                                                    0.00
      6                                                    0.00
      7                                                    0.00
      8                                                    0.00
      9                                                    0.00
     10                                                    0.00
     11                                                    0.00
     12                                                    0.00
-----------------------------------------------------------------------------
        PF1 = ADVANCE       PF2 = PREVIOUS        PF3 = QUIT
-----------------------------------------------------------------------------



                    +-----------------+
                    | STREAM SUMMARY  |
                    +-----------------+


PERIOD(S) TO GO: 3

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

      1              FRESHWATER.PUMPS                    2333.90
      2              SEAWATER.PUMPS                      3215.84
      3              HYDRAULIC.PUMPS                     1028.34
      4                                                    0.00
      5                                                    0.00
      6                                                    0.00
      7                                                    0.00
      8                                                    0.00
      9                                                    0.00
     10                                                    0.00
     11                                                    0.00
     12                                                    0.00
-----------------------------------------------------------------------------
        PF1 = ADVANCE       PF2 = PREVIOUS        PF3 = QUIT
-----------------------------------------------------------------------------
```

APPENDIX A.6

SCENARIO 5 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams..................... 3
2. Total Number of Periods........................... 3
3. Period definition................................. MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 4988.12
2	$ 3308.56
1	$ 1592.68

Total Population Cost.......... $ 9889.35

Press PF3 to Quit...

329

```
                    +-----------------+
                    ¦ STREAM SUMMARY  ¦
                    +-----------------+

PERIOD(S) TO GO: 1

STREAM NUMBER            STREAM NAME            EXPECTED FUTURE COSTS

      1             FRESHWATER.PUMPS                 567.96
      2             SEAWATER.PUMPS                   746.42
      3             HYDRAULIC.PUMPS                  278.30
      4                                                0.00
      5                                                0.00
      6                                                0.00
      7                                                0.00
      8                                                0.00
      9                                                0.00
     10                                                0.00
     11                                                0.00
     12                                                0.00
----------------------------------------------------------------------
       PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
----------------------------------------------------------------------
```

```
                    +------------------+
                    | STREAM SUMMARY   |
                    +------------------+

PERIOD(S) TO GO: 2

STREAM NUMBER            STREAM NAME            EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                1179.39
     2              SEAWATER.PUMPS                  1608.84
     3              HYDRAULIC.PUMPS                  520.32
     4                                                0.00
     5                                                0.00
     6                                                0.00
     7                                                0.00
     8                                                0.00
     9                                                0.00
    10                                                0.00
    11                                                0.00
    12                                                0.00
---------------------------------------------------------------------
       PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
---------------------------------------------------------------------
```

```
        +-----------------+
        | STREAM SUMMARY  |
        +-----------------+

PERIOD(S) TO GO: 3

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

      1             FRESHWATER.PUMPS          .       1854.93
      2             SEAWATER.PUMPS                    2378.34
      3             HYDRAULIC.PUMPS                    754.34
      4                                                  0.00
      5                                                  0.00
      6                                                  0.00
      7                                                  0.00
      8                                                  0.00
      9                                                  0.00
     10                                                  0.00
     11                                                  0.00
     12                                                  0.00
---------------------------------------------------------------------------
      PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
---------------------------------------------------------------------------
```

```
                    +------------------+
                    :   STREAM OUTPUT  :
                    +------------------+
                        .

STREAM NUMBER: 1              OPERATING ENVIRONMENT: A

   1.   STREAM NAME.................................. FRESHWATER.PUMPS

   2.   Hazard Model................................. EXPONENTIAL

   3.   Level of Repair.............................. 2

   4.   Initial Age of Population.................... 1          Period(s)

   5.   Mean Time Between Failure (MTBF)............. 8.22       Period(s)

   6.   Mean Time To Repair (MTTR)................... 0.0328     Period(s)

   7.   Estimated Rate of Technological Improvement.... 10       Percent
```

```
              PF1 = ADVANCE              PF3 = QUIT
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 1                    OPERATING ENVIRONMENT: A
    8.    Period(s) To Go............................    1
    9.    Operational State of the Equipment........    GOOD
   10.    Population Age.............................    3          period(s)
   11.    Policy Recommendation......................    K
   12.    Forecasted Demand..........................    9          units
   13.    Policy Requirements........................    9          units
   14.    Policy Cost................................  $ 340.00
   15.    Supplemental Cost of Exceeding Budget......  $ 0.00
   16.    Reliability  (Unreliability for state F)...    0.980369
   17.    Availability (Unavailability for state F)..    0.996026
-------------------------------------------------------------------------------
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)        R = Repair
-------------------------------------------------------------------------------
          PF1 = ADVANCE         PF2 = REVIEW         PF3 = QUIT
-------------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 1                    OPERATING ENVIRONMENT: A
    8.    Period(s) To Go............................    1
    9.    Operational State of the Equipment........    FAILED
   10.    Population Age.............................    3          period(s)
   11.    Policy Recommendation......................    R
   12.    Forecasted Demand..........................    9          units
   13.    Policy Requirements........................    9          units
   14.    Policy Cost................................  $ 587.15
   15.    Supplemental Cost of Exceeding Budget......  $ 0.00
   16.    Reliability  (Unreliability for state F)...    0.019631
   17.    Availability (Unavailability for state F)..    0.003974
-------------------------------------------------------------------------------
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)        R = Repair
-------------------------------------------------------------------------------
          PF1 = ADVANCE         PF2 = REVIEW         PF3 = QUIT
-------------------------------------------------------------------------------
```

334

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 1                OPERATING ENVIRONMENT: A
   8.    Period(s) To Go.............................   2
   9.    Operational State of the Equipment........   GOOD
  10.    Population Age.............................   2          period(s)
  11.    Policy Recommendation.....................   K
  12.    Forecasted Demand.........................   10         units
  13.    Policy Requirements.......................   10         units
  14.    Policy Cost...............................  $ 679.00
  15.    Supplemental Cost of Exceeding Budget.....  $ 0.00
  16.    Reliability  (Unreliability for state F)...   0.980849
  17.    Availability (Unavailability for state F)..   0.996026
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                  period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                  2 period's supplK9 inventory)
          K  = Keep ("Do nothing" alternative)      R = Repair
```

```
          PF1 = ADVANCE         PF2 = REVIEW           PF3 = QUIT
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 1                OPERATING ENVIRONMENT: A
   8.    Period(s) To Go.............................   2
   9.    Operational State of the Equipment........   FAILED
  10.    Population Age.............................   2          period(s)
  11.    Policy Recommendation.....................   R
  12.    Forecasted Demand.........................   10         units
  13.    Policy Requirements.......................   10         units
  14.    Policy Cost...............................  $ 953.72
  15.    Supplemental Cost of Exceeding Budget.....  $ 0.00
  16.    Reliability  (Unreliability for state F)...   0.019151
  17.    Availability (Unavailability for state F)..   0.003974
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                  period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                  2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)      R = Repair
```

```
          PF1 = ADVANCE         PF2 = REVIEW           PF3 = QUIT
```

335

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   3
   9.   Operational State of the Equipment........   GOOD
  10.   Population Age............................   1   period(s)
  11.   Policy Recommendation.....................   K
  12.   Forecasted Demand.........................   12   units
  13.   Policy Requirements.......................   12   units
  14.   Policy Cost............................... $ 1047.00
  15.   Supplemental Cost of Exceeding Budget..... $ 0.00
  16.   Reliability (Unreliability for state F)...   0.981317
  17.   Availability (Unavailability for state F)..   0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   3
   9.   Operational State of the Equipment........   FAILED
  10.   Population Age............................   1   period(s)
  11.   Policy Recommendation.....................   R
  12.   Forecasted Demand.........................   12   units
  13.   Policy Requirements.......................   12   units
  14.   Policy Cost............................... $ 1375.97
  15.   Supplemental Cost of Exceeding Budget..... $ 0.00
  16.   Reliability (Unreliability for state F)...   0.019683
  17.   Availability (Unavailability for state F)..   0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

336

```
                    +-------------------+
                    :   STREAM OUTPUT   :
                    +-------------------+

STREAM NUMBER: 1                OPERATING ENVIRONMENT: B

   1.  STREAM NAME.....................................  FRESHWATER.PUMPS

   2.  Hazard Model...................................  EXPONENTIAL

   3.  Level of Repair................................  2

   4.  Initial Age of Population......................  1         Period(s)

   5.  Mean Time Between Failure (MTBF)...............  5.49      Period(s)

   6.  Mean Time To Repair (MTTR).....................  0.0328    Period(s)

   7.  Estimated Rate of Technological Improvement....  10        Percent
_____

            PF1 = ADVANCE                  PF3 = QUIT
_____
```

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B

No.	Item	Value	
8.	Period(s) To Go	1	
9.	Operational State of the Equipment	GOOD	
10.	Population Age	3	period(s)
11.	Policy Recommendation	K	
12.	Forecasted Demand	6	units
13.	Policy Requirements	6	units
14.	Policy Cost	$ 226.00	
15.	Supplemental Cost of Exceeding Budget	$ 0.00	
16.	Reliability (Unreliability for state F)	0.980369	
17.	Availability (Unavailability for state F)	0.994061	

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B

No.	Item	Value	
8.	Period(s) To Go	1	
9.	Operational State of the Equipment	FAILED	
10.	Population Age	3	period(s)
11.	Policy Recommendation	R	
12.	Forecasted Demand	6	units
13.	Policy Requirements	6	units
14.	Policy Cost	$ 390.85	
15.	Supplemental Cost of Exceeding Budget	$ 0.00	
16.	Reliability (Unreliability for state F)	0.019631	
17.	Availability (Unavailability for state F)	0.005939	

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................ 3
    9.   Operational State of the Equipment......... GOOD
   10.   Population Age............................. 1   period(s)
   11.   Policy Recommendation...................... K
   12.   Forecasted Demand.......................... 10   units
   13.   Policy Requirements........................ 10   units
   14.   Policy Cost................................ $ 805.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)... 0.981317
   17.   Availability (Unavailability for state F).. 0.994061

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................ 3
    9.   Operational State of the Equipment......... FAILED
   10.   Population Age............................. 1   period(s)
   11.   Policy Recommendation...................... R
   12.   Forecasted Demand.......................... 10   units
   13.   Policy Requirements........................ 10   units
   14.   Policy Cost................................ $ 1078.63
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)... 0.018683
   17.   Availability (Unavailability for state F).. 0.005939

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

339

APPENDIX A.7

SCENARIO 6 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams..................... 3
2. Total Number of Periods............................. 3
3. Period definition................................... MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 4867.20
2	$ 3202.56
1	$ 1540.34

Total Population Cost.......... $ 9610.10

Press PF3 to Quit...

```
+-------------------+
| STREAM SUMMARY |
+-------------------+
```

PERIOD(S) TO GO: 1

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	514.77
2	SEAWATER.PUMPS	747.29
3	HYDRAULIC.PUMPS	278.30
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
            +-----------------+
            ! STREAM SUMMARY  !
            +-----------------+

PERIOD(S) TO GO: 2

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                    1074.27
     2              SEAWATER.PUMPS                      1607.96
     3              HYDRAULIC.PUMPS                      520.32
     4                                                    0.00
     5                                                    0.00
     6                                                    0.00
     7                                                    0.00
     8                                                    0.00
     9                                                    0.00
    10                                                    0.00
    11                                                    0.00
    12                                                    0.00
------------------------------------------------------------------------
      PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
------------------------------------------------------------------------
```

```
            +-----------------+
            ! STREAM SUMMARY  !
            +-----------------+

PERIOD(S) TO GO: 3

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                    1736.90
     2              SEAWATER.PUMPS                      2375.97
     3              HYDRAULIC.PUMPS·                     754.34
     4                                                    0.00
     5                                                    0.00
     6                                                    0.00
     7                                                    0.00
     8                                                    0.00
     9                                                    0.00
    10                                                    0.00
    11                                                    0.00
    12                                                    0.00
------------------------------------------------------------------------
      PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
------------------------------------------------------------------------
```

342

```
                    +-----------------+
                    !  STREAM OUTPUT  !
                    +-----------------+

STREAM NUMBER: 2                 OPERATING ENVIRONMENT: A

   1.   STREAM NAME...................................   SEAWATER.PUMPS

   2.   Hazard Model..................................   EXPONENTIAL

   3.   Level of Repair...............................   2

   4.   Initial Age of Population.....................   2         Period(s)

   5.   Mean Time Between Failure (MTBF)..............   14.50     Period(s)

   6.   Mean Time To Repair (MTTR)....................   0.0400    Period(s)

   7.   Estimated Rate of Technological Improvement....  10        Percent
----------------------------------------------------------------------------
                 PF1 = ADVANCE              PF3 = QUIT
----------------------------------------------------------------------------
```

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go...........................   1
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age............................   4   period(s)
    11.   Policy Recommendation.....................   K
    12.   Forecasted Demand.........................   4   units
    13.   Policy Requirements.......................   4   units
    14.   Policy Cost............................... $ 426.00
    15.   Supplemental Cost of Exceeding Budget..... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.979877
    17.   Availability (Unavailability for state F)..   0.997249

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go...........................   1
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age............................   4   period(s)
    11.   Policy Recommendation.....................   R
    12.   Forecasted Demand.........................   4   units
    13.   Policy Requirements.......................   4   units
    14.   Policy Cost............................... $ 770.39
    15.   Supplemental Cost of Exceeding Budget..... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.020123
    17.   Availability (Unavailability for state F)..   0.002751

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age............................   3   period(s)
    11.   Policy Recommendation.....................   K
    12.   Forecasted Demand.........................   5   units
    13.   Policy Requirements.......................   5   units
    14.   Policy Cost............................... $ 904.00
    15.   Supplemental Cost of Exceeding Budget..... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.980369
    17.   Availability (Unavailability for state F)..   0.997249

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age............................   3   period(s)
    11.   Policy Recommendation.....................   R
    12.   Forecasted Demand.........................   5   units
    13.   Policy Requirements.......................   5   units
    14.   Policy Cost............................... $ 1335.03
    15.   Supplemental Cost of Exceeding Budget..... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.019631
    17.   Availability (Unavailability for state F)..   0.002751

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go............................   3
    9.   Operational State of the Equipment.........   GOOD
    10.   Population Age.............................   2   period(s)
    11.   Policy Recommendation......................   K
    12.   Forecasted Demand..........................   5   units
    13.   Policy Requirements........................   5   units
    14.   Policy Cost................................ $ 1332.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.980849
    17.   Availability (Unavailability for state F)..   0.997249

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

               PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go............................   3
    9.   Operational State of the Equipment.........   FAILED
    10.   Population Age.............................   2   period(s)
    11.   Policy Recommendation......................   R
    12.   Forecasted Demand..........................   5   units
    13.   Policy Requirements........................   5   units
    14.   Policy Cost................................ $ 1762.62
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.019151
    17.   Availability (Unavailability for state F)..   0.002751

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

               PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

346

```
                    +------------------+
                    :  STREAM OUTPUT   :
                    +------------------+

STREAM NUMBER: 2              OPERATING ENVIRONMENT: B

  1.   STREAM NAME...................................  SEAWATER.PUMPS

  2.   Hazard Model..................................  EXPONENTIAL

  3.   Level of Repair...............................  2

  4.   Initial Age of Population.....................  2         Period(s)

  5.   Mean Time Between Failure (MTBF)..............  7.70      Period(s)

  6.   Mean Time To Repair (MTTR)....................  0.0400    Period(s)

  7.   Estimated Rate of Technological Improvement....  10        Percent
-----------------------------------------------------------------------------
              PF1 = ADVANCE              PF3 = QUIT
-----------------------------------------------------------------------------
```

347

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation.....................   K
    12.   Forecasted Demand.........................   3   units
    13.   Policy Requirements.......................   3   units
    14.   Policy Cost............................... $ 319.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.979877
    17.   Availability (Unavailability for state F)..   0.994832

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation.....................   R
    12.   Forecasted Demand.........................   3   units
    13.   Policy Requirements.......................   3   units
    14.   Policy Cost............................... $ 576.71
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.020123
    17.   Availability (Unavailability for state F)..   0.005168

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 2              OPERATING ENVIRONMENT: B
    8.    Period(s) To Go...........................    2
    9.    Operational State of the Equipment........   GOOD
   10.    Population Age............................    3        period(s)
   11.    Policy Recommendation.....................    K
   12.    Forecasted Demand.........................    4        units
   13.    Policy Requirements.......................    4        units
   14.    Policy Cost...............................  $ 701.00
   15.    Supplemental Cost of Exceeding Budget.....  $ 0.00
   16.    Reliability  (Unreliability for state F)...   0.980369
   17.    Availability (Unavailability for state F)..   0.994832
```

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carrsext
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 2              OPERATING ENVIRONMENT: B
    8.    Period(s) To Go...........................    2
    9.    Operational State of the Equipment........   FAILED
   10.    Population Age............................    3        period(s)
   11.    Policy Recommendation.....................    R
   12.    Forecasted Demand.........................    4        units
   13.    Policy Requirements.......................    4        units
   14.    Policy Cost...............................  $ 1044.72
   15.    Supplemental Cost of Exceeding Budget.....  $ 0.00
   16.    Reliability  (Unreliability for state F)...   0.019631
   17.    Availability (Unavailability for state F)..   0.005168
```

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment......... GOOD
    10.   Population Age..............................   2   period(s)
    11.   Policy Recommendation......................   K
    12.   Forecasted Demand..........................   4   units
    13.   Policy Requirements........................   4   units
    14.   Policy Cost................................ $ 1041.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.980849
    17.   Availability (Unavailability for state F)..   0.994832
----
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 2   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment......... FAILED
    10.   Population Age..............................   2   period(s)
    11.   Policy Recommendation......................   R
    12.   Forecasted Demand..........................   4   units
    13.   Policy Requirements........................   4   units
    14.   Policy Cost................................ $ 1385.71
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.019151
    17.   Availability (Unavailability for state F)..   0.005168
----
egend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

APPENDIX A.8

SCENARIO 7 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams.................. 3
2. Total Number of Periods.......................... 3
3. Period definition................................ MONTHS

         PERIOD(S) TO GO   EXPECTED FUTURE COSTS
              12                           $ 0.00
              11                           $ 0.00
              10                           $ 0.00
               9                           $ 0.00
               8                           $ 0.00
               7                           $ 0.00
               6                           $ 0.00
               5                           $ 0.00
               4                           $ 0.00
               3                           $ 5624.43
               2                           $ 3723.76
               1                           $ 1821.57

Total Population Cost......... $ 11169.75

                                    Press PF3 to Quit...

                   +------------------+
                   : STREAM SUMMARY :
                   +------------------+

PERIOD(S) TO GO: 1

STREAM NUMBER   STREAM NAME   EXPECTED FUTURE COSTS

      1   FRESHWATER.PUMPS   514.77
      2   SEAWATER.PUMPS   746.42
      3   HYDRAULIC.PUMPS   560.37
      4   0.00
      5   0.00
      6   0.00
      7   0.00
      8   0.00
      9   0.00
     10   0.00
     11   0.00
     12   0.00

      PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
                    +----------------+
                    : STREAM SUMMARY :
                    +----------------+

PERIOD(S) TO GO: 2

STREAM NUMBER              STREAM NAME            EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                  1074.27
     2              SEAWATER.PUMPS                    1608.84
     3              HYDRAULIC.PUMPS                   1040.65
     4                                                   0.00
     5                                                   0.00
     6                                                   0.00
     7                                                   0.00
     8                                                   0.00
     9                                                   0.00
    10                                                   0.00
    11                                                   0.00
    12                                                   0.00
--------------------------------------------------------------------------
        PF1 = ADVANCE        PF2 = PREVIOUS       PF3 = QUIT
--------------------------------------------------------------------------



                    +----------------+
                    : STREAM SUMMARY :
                    +----------------+

PERIOD(S) TO GO: 3

STREAM NUMBER              STREAM NAME            EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                  1736.90
     2              SEAWATER.PUMPS                    2378.84
     3              HYDRAULIC.PUMPS                   1508.69
     4                                                   0.00
     5                                                   0.00
     6                                                   0.00
     7                                                   0.00
     8                                                   0.00
     9                                                   0.00
    10                                                   0.00
    11                                                   0.00
    12                                                   0.00
--------------------------------------------------------------------------
        PF1 = ADVANCE        PF2 = PREVIOUS       PF3 = QUIT
--------------------------------------------------------------------------
```

353

```
                    +------------------+
                    |  STREAM OUTPUT   |
                    +------------------+

STREAM NUMBER: 3              OPERATING ENVIRONMENT: A

   1.   STREAM NAME...................................   HYDRAULIC.PUMPS

   2.   Hazard Model..................................   LINEARLY INCREASING

   3.   Level of Repair...............................   1

   4.   Initial Age of Population.....................   2         Period(s)

   5.   Mean Time Between Failure (MTBF)..............   32.87     Period(s)

   6.   Mean Time To Repair (MTTR)....................   0.0394    Period(s)

   7.   Estimated Rate of Technological Improvement....  12        Percent
------------------------------------------------------------------------------------
              PF1 = ADVANCE                 PF3 = QUIT
------------------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   1
   9.   Operational State of the Equipment......... GOOD
  10.   Population Age.............................   4   period(s)
  11.   Policy Recommendation......................   K
  12.   Forecasted Demand..........................   6   units
  13.   Policy Requirements........................   6   units
  14.   Policy Cost................................ $ 278.00
  15.   Supplemental Cost of Exceeding Budget...... $ 0.00
  16.   Reliability (Unreliability for state F)... 0.818731
  17.   Availability (Unavailability for state F).. 0.998803

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   1
   9.   Operational State of the Equipment......... FAILED
  10.   Population Age.............................   4   period(s)
  11.   Policy Recommendation......................   P1
  12.   Forecasted Demand..........................   6   units
  13.   Policy Requirements........................   6   units
  14.   Policy Cost................................ $ 1729.48
  15.   Supplemental Cost of Exceeding Budget...... $ 0.00
  16.   Reliability (Unreliability for state F)... 0.181269
  17.   Availability (Unavailability for state F).. 0.001197

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go.............................   2
   9.   Operational State of the Equipment........   GOOD
  10.   Population Age..............................   3   period(s)
  11.   Policy Recommendation......................   K
  12.   Forecasted Demand..........................   6   units
  13.   Policy Requirements........................   6   units
  14.   Policy Cost................................ $ 520.00
  15.   Supplemental Cost of Exceeding Budget...... $ 0.00
  16.   Reliability (Unreliability for state F)...   0.893597
  17.   Availability (Unavailability for state F)..   0.998803

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go.............................   2
   9.   Operational State of the Equipment........   FAILED
  10.   Population Age..............................   3   period(s)
  11.   Policy Recommendation......................   R
  12.   Forecasted Demand..........................   6   units
  13.   Policy Requirements........................   6   units
  14.   Policy Cost................................ $ 734.94
  15.   Supplemental Cost of Exceeding Budget...... $ 0.00
  16.   Reliability (Unreliability for state F)...   0.106403
  17.   Availability (Unavailability for state F)..   0.001197

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

356

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A

```
 8.    Period(s) To Go.............................    3
 9.    Operational State of the Equipment........    GOOD
10.    Population Age..............................    2          period(s)
11.    Policy Recommendation......................    K
12.    Forecasted Demand..........................    6          units
13.    Policy Requirements........................    6          units
14.    Policy Cost................................    $ 754.00
15.    Supplemental Cost of Exceeding Budget......    $ 0.00
16.    Reliability  (Unreliability for state F)...    0.951229
17.    Availability (Unavailability for state F)..    0.998303
```

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

        PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A

```
 8.    Period(s) To Go.............................    3
 9.    Operational State of the Equipment........    FAILED
10.    Population Age..............................    2          period(s)
11.    Policy Recommendation......................    R
12.    Forecasted Demand..........................    6          units
13.    Policy Requirements........................    6          units
14.    Policy Cost................................    $ 982.75
15.    Supplemental Cost of Exceeding Budget......    $ 0.00
16.    Reliability  (Unreliability for state F)...    0.048771
17.    Availability (Unavailability for state F)..    0.001197
```

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

        PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

```
               +-----------------+
               :  STREAM OUTPUT  :
               +-----------------+

STREAM NUMBER: 3              OPERATING ENVIRONMENT: B

   1.   STREAM NAME..................................  HYDRAULIC.PUMPS

   2.   Hazard Model.................................  LINEARLY INCREASING

   3.   Level of Repair..............................  1

   4.   Initial Age of Population....................  2        Period(s)

   5.   Mean Time Between Failure (MTBF).............  21.97    Period(s)

   6.   Mean Time To Repair (MTTR)...................  0.0400   Period(s)

   7.   Estimated Rate of Technological Improvement....  12     Percent
-------------------------------------------------------------------------
              PF1 = ADVANCE              PF3 = QUIT
-------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
     8.   Period(s) To Go............................   1
     9.   Operational State of the Equipment........   GOOD
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation......................   K
    12.   Forecasted Demand..........................   6   units
    13.   Policy Requirements........................   6   units
    14.   Policy Cost................................ $ 278.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.818731
    17.   Availability (Unavailability for state F)..   0.998183

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
     8.   Period(s) To Go............................   1
     9.   Operational State of the Equipment........   FAILED
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation......................   P1
    12.   Forecasted Demand..........................   6   units
    13.   Policy Requirements........................   6   units
    14.   Policy Cost................................ $ 1728.43
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.181269
    17.   Availability (Unavailability for state F)..   0.001817

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment.........   GOOD
   10.   Population Age.............................   3   period(s)
   11.   Policy Recommendation......................   K
   12.   Forecasted Demand..........................   6   units
   13.   Policy Requirements........................   6   units
   14.   Policy Cost................................ $ 520.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.893597
   17.   Availability (Unavailability for state F)..   0.998183

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment.........   FAILED
   10.   Population Age.............................   3   period(s)
   11.   Policy Recommendation......................   R
   12.   Forecasted Demand..........................   6   units
   13.   Policy Requirements........................   6   units
   14.   Policy Cost................................ $ 734.60
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.106403
   17.   Availability (Unavailability for state F)..   0.001317

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment........   GOOD
   10.   Population Age..............................   2   period(s)
   11.   Policy Recommendation......................   K
   12.   Forecasted Demand..........................   6   units
   13.   Policy Requirements........................   6   units
   14.   Policy Cost................................ $ 754.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability   (Unreliability for state F)...   0.951229
   17.   Availability (Unavailability for state F)..   0.998183

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

APPENDIX A.9

SCENARIO 8 SELECTED OUTPUT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   1
   9.   Operational State of the Equipment........   FAILED
   10. Population Age............................   3   period(s)
   11. Policy Recommendation.....................   R
   12. Forecasted Demand.........................   9   units
   13. Policy Requirements.......................   9   units
   14. Policy Cost............................... $ 535.18
   15. Supplemental Cost of Exceeding Budget..... $ 85.18
   16. Reliability (Unreliability for state F)...   0.106403
   17. Availability (Unavailability for state F)..   0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   3
   9.   Operational State of the Equipment........   GOOD
   10. Population Age............................   1   period(s)
   11. Policy Recommendation.....................   K
   12. Forecasted Demand.........................   12   units
   13. Policy Requirements.......................   12   units
   14. Policy Cost............................... $ 1005.00
   15. Supplemental Cost of Exceeding Budget..... $ 0.00
   16. Reliability (Unreliability for state F)...   0.987578
   17. Availability (Unavailability for state F)..   0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 1                    OPERATING ENVIRONMENT: A
    8.    Period(s) To Go............................    3
    9.    Operational State of the Equipment........    FAILED
   10.    Population Age............................    1         period(s)
   11.    Policy Recommendation.....................    R
   12.    Forecasted Demand.........................    12        units
   13.    Policy Requirements.......................    12        units
   14.    Policy Cost...............................  $ 1336.52
   15.    Supplemental Cost of Exceeding Budget.....  $ 31.52
   16.    Reliability  (Unreliability for state F)...   0.012422
   17.    Availability (Unavailability for state F)..   0.003974
```

```
Legend:    P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                   period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                   2 period's supply in inventory)
           K  = Keep ("Do nothing" alternative)      R = Repair
```

```
           PF1 = ADVANCE         PF2 = REVIEW         PF3 = QUIT
```

APPENDIX A.10

SCENARIO 9 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams.................... 3
2. Total Number of Periods........................... 3
3. Period definition................................ MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 6658.08
2	$ 4318.11
1	$ 2076.21

Total Population Cost.......... $ 13052.39

Press PF3 to Quit...


```
                    +-----------------+
                    ! STREAM SUMMARY  !
                    +-----------------+
```

PERIOD(S) TO GO: 1

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	1051.49
2	SEAWATER.PUMPS	746.42
3	HYDRAULIC.PUMPS	278.30
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

```
------------------------------------------------------------------
     PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
------------------------------------------------------------------
```

```
                    +-----------------+
                    : STREAM SUMMARY :
                    +-----------------+

PERIOD(S) TO GO: 2

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                    2188.94
     2              SEAWATER.PUMPS                      1608.84
     3              HYDRAULIC.PUMPS                      520.32
     4                                                    0.00
     5                                                    0.00
     6                                                    0.00
     7                                                    0.00
     8                                                    0.00
     9                                                    0.00
    10                                                    0.00
    11                                                    0.00
    12                                                    0.00
_____
        PF1 = ADVANCE         PF2 = PREVIOUS        PF3 = QUIT
_____




                    +-----------------+
                    : STREAM SUMMARY :
                    +-----------------+

PERIOD(S) TO GO: 3

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                    3524.89
     2              SEAWATER.PUMPS                      2378.84
     3              HYDRAULIC.PUMPS                      754.34
     4                                                    0.00
     5                                                    0.00
     6                                                    0.00
     7                                                    0.00
     8                                                    0.00
     9                                                    0.00
    10                                                    0.00
    11                                                    0.00
    12                                                    0.00
_____
        PF1 = ADVANCE         PF2 = PREVIOUS        PF3 = QUIT
_____
```

```
                    +-----------------+
                    :   STREAM OUTPUT  :
                    +-----------------+

STREAM NUMBER: 1                 OPERATING ENVIRONMENT: A

   1.   STREAM NAME....................................  FRESHWATER.PUMPS

   2.   Hazard Model..................................  LINEARLY INCREASING

   3.   Level of Repair...............................  2

   4.   Initial Age of Population.....................  1        Period(s)

   5.   Mean Time Between Failure (MTBF)..............  8.22     Period(s)

   6.   Mean Time To Repair (MTTR)....................  0.0328   Period(s)

   7.   Estimated Rate of Technological Improvement...  10       Percent
_____

              PF1 = ADVANCE                  PF3 = QUIT
_____
```

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go...............................   1
   9.   Operational State of the Equipment.........   GOOD
  10.   Population Age.............................   3   period(s)
  11.   Policy Recommendation......................   K
  12.   Forecasted Demand..........................   9   units
  13.   Policy Requirements........................   9   units
  14.   Policy Cost................................ $ 635.00
  15.   Supplemental Cost of Exceeding Budget...... $ 0.00
  16.   Reliability (Unreliability for state F)...   0.893597
  17.   Availability (Unavailability for state F)..   0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go...............................   1
   9.   Operational State of the Equipment.........   FAILED
  10.   Population Age.............................   1   period(s)
  11.   Policy Recommendation......................   R
  12.   Forecasted Demand..........................   9   units
  13.   Policy Requirements........................   9   units
  14.   Policy Cost................................ $ 831.01
  15.   Supplemental Cost of Exceeding Budget...... $ 0.00
  16.   Reliability (Unreliability for state F)...   0.012422
  17.   Availability (Unavailability for state F)..   0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go........................   2
    9.   Operational State of the Equipment.......   GOOD
   10.   Population Age...........................   2   period(s)
   11.   Policy Recommendation....................   K
   12.   Forecasted Demand........................   10   units
   13.   Policy Requirements......................   10   units
   14.   Policy Cost.............................. $ 1286.00
   15.   Supplemental Cost of Exceeding Budget..... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.951229
   17.   Availability (Unavailability for state F)..   0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go..........................   2
    9.   Operational State of the Equipment.......   FAILED
   10.   Population Age...........................   2   period(s)
   11.   Policy Recommendation....................   P1
   12.   Forecasted Demand........................   10   units
   13.   Policy Requirements......................   10   units
   14.   Policy Cost.............................. $ 1512.58
   15.   Supplemental Cost of Exceeding Budget..... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.048771
   17.   Availability (Unavailability for state F)..   0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

370

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment........   GOOD
   10.   Population Age..............................   1   period(s)
   11.   Policy Recommendation......................   K
   12.   Forecasted Demand..........................   12   units
   13.   Policy Requirements........................   12   units
   14.   Policy Cost................................ $ 2043.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.987578
   17.   Availability (Unavailability for state F)..   0.996026

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   FF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: A
    8.   Period(s) To Go.............................   3
    9.   Operational State of the Equipment........   FAILED
   10.   Population Age..............................   1   period(s)
   11.   Policy Recommendation......................   R
   12.   Forecasted Demand..........................   12   units
   13.   Policy Requirements........................   12   units
   14.   Policy Cost................................ $ 2373.90
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.012422
   17.   Availability (Unavailability for state F)..   0.003974

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

```
                    +-----------------+
                    |  STREAM OUTPUT  |
                    +-----------------+

STREAM NUMBER: 1              OPERATING ENVIRONMENT: B

  1.   STREAM NAME.................................... FRESHWATER.PUMPS

  2.   Hazard Model.................................. PIECE. LIN. BATH.

  3.   Level of Repair............................... 2

  4.   Initial Age of Population..................... 1          Period(s)

  5.   Mean Time Between Failure (MTBF).............. 5.49       Period(s)

  6.   Mean Time To Repair (MTTR).................... 0.0328     Period(s)

  7.   Estimated Rate of Technological Improvement.... 10        Percent
------------------------------------------------------------------------------
              PF1 = ADVANCE              FF3 = QUIT
------------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment........   GOOD
   10.   Population Age.............................   3   period(s)
   11.   Policy Recommendation......................   K
   12.   Forecasted Demand..........................   6   units
   13.   Policy Requirements........................   6   units
   14.   Policy Cost................................ $ 415.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.878527
   17.   Availability (Unavailability for state F)..   0.994061

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment........   FAILED
   10.   Population Age.............................   1   period(s)
   11.   Policy Recommendation......................   R
   12.   Forecasted Demand..........................   6   units
   13.   Policy Requirements........................   6   units
   14.   Policy Cost................................ $ 524.01
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.046602
   17.   Availability (Unavailability for state F)..   0.005939

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age.............................   2   period(s)
    11.   Policy Recommendation.....................   K
    12.   Forecasted Demand.........................   8   units
    13.   Policy Requirements.......................   8   units
    14.   Policy Cost............................... $ 901.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.913116
    17.   Availability (Unavailability for state F)..   0.994061

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age.............................   2   period(s)
    11.   Policy Recommendation.....................   P1
    12.   Forecasted Demand.........................   8   units
    13.   Policy Requirements.......................   8   units
    14.   Policy Cost............................... $ 1076.22
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.086884
    17.   Availability (Unavailability for state F)..   0.005939

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

374

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   3
    9.   Operational State of the Equipment........   GOOD
   10.   Population Age.............................   1   period(s)
   11.   Policy Recommendation......................   K
   12.   Forecasted Demand.........................   10   units
   13.   Policy Requirements.......................   10   units
   14.   Policy Cost............................... $ 1479.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.953398
   17.   Availability (Unavailability for state F)..   0.994061

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM NUMBER: 1   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   3
    9.   Operational State of the Equipment........   FAILED
   10.   Population Age.............................   1   period(s)
   11.   Policy Recommendation......................   R
   12.   Forecasted Demand.........................   10   units
   13.   Policy Requirements.......................   10   units
   14.   Policy Cost............................... $ 1744.85
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.046602
   17.   Availability (Unavailability for state F)..   0.005939

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
              period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
              2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

APPENDIX A.11

SCENARIO 10 SELECTED OUTPUT

POPULATION SUMMARY

1. Total Number of Primary Streams...................... 3
2. Total Number of Periods............................. 3
3. Period definition................................... MONTHS

PERIOD(S) TO GO	EXPECTED FUTURE COSTS
12	$ 0.00
11	$ 0.00
10	$ 0.00
9	$ 0.00
8	$ 0.00
7	$ 0.00
6	$ 0.00
5	$ 0.00
4	$ 0.00
3	$ 5873.04
2	$ 3872.18
1	$ 1810.61

Total Population Cost.......... $ 11555.82

Press PF3 to Quit...

```
+------------------+
: STREAM SUMMARY :
+------------------+
```

PERIOD(S) TO GO: 1

STREAM NUMBER	STREAM NAME	EXPECTED FUTURE COSTS
1	FRESHWATER.PUMPS	514.77
2	SEAWATER.PUMPS	746.42
3	HYDRAULIC.PUMPS	549.42
4		0.00
5		0.00
6		0.00
7		0.00
8		0.00
9		0.00
10		0.00
11		0.00
12		0.00

PF1 = ADVANCE   PF2 = PREVIOUS   PF3 = QUIT

```
                    +----------------+
                    | STREAM SUMMARY |
                    +----------------+

PERIOD(S) TO GO: 2

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                      1074.27
     2              SEAWATER.PUMPS                        1608.84
     3              HYDRAULIC.PUMPS                       1189.07
     4                                                       0.00
     5                                                       0.00
     6                                                       0.00
     7                                                       0.00
     8                                                       0.00
     9                                                       0.00
    10                                                       0.00
    11                                                       0.00
    12                                                       0.00
--------------------------------------------------------------------------
     PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
--------------------------------------------------------------------------
```

```
                    +----------------+
                    | STREAM SUMMARY |
                    +----------------+

PERIOD(S) TO GO: 3

STREAM NUMBER              STREAM NAME              EXPECTED FUTURE COSTS

     1              FRESHWATER.PUMPS                      1736.90
     2              SEAWATER.PUMPS                        2378.84
     3              HYDRAULIC.PUMPS                       1757.30
     4                                                       0.00
     5                                                       0.00
     6                                                       0.00
     7                                                       0.00
     8                                                       0.00
     9                                                       0.00
    10                                                       0.00
    11                                                       0.00
    12                                                       0.00
--------------------------------------------------------------------------
     PF1 = ADVANCE        PF2 = PREVIOUS        PF3 = QUIT
--------------------------------------------------------------------------
```

378

```
                        +------------------+
                        :  STREAM OUTPUT   :
                        +------------------+

STREAM NUMBER: 3                 OPERATING ENVIRONMENT: A

    1.   STREAM NAME................................  HYDRAULIC.PUMPS

    2.   Hazard Model...............................  LINEARLY INCREASING

    3.   Level of Repair............................  1

    4.   Initial Age of Population..................  4        Period(s)

    5.   Mean Time Between Failure (MTBF)...........  32.87    Period(s)

    6.   Mean Time To Repair (MTTR).................  0.0394   Period(s)

    7.   Estimated Rate of Technological Improvement....  12   Percent

---------------------------------------------------------------------------
                 PF1 = ADVANCE              PF3 = QUIT
---------------------------------------------------------------------------
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3              OPERATING ENVIRONMENT: A
    8.    Period(s) To Go..............................   1
    9.    Operational State of the Equipment........   GOOD
   10.    Population Age................................   6         period(s)
   11.    Policy Recommendation.......................   P1
   12.    Forecasted Demand...........................   3         units
   13.    Policy Requirements.........................   3         units
   14.    Policy Cost..................................   $ 274.50
   15.    Supplemental Cost of Exceeding Budget......   $ 0.00
   16.    Reliability  (Unreliability for state F)...   0.637628
   17.    Availability (Unavailability for state F)..   0.998203
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)      R = Repair
```

```
          PF1 = ADVANCE         PF2 = REVIEW           PF3 = QUIT
```

STREAM OUTPUT(Continued)

```
STREAM NUMBER: 3              OPERATING ENVIRONMENT: A
    8.    Period(s) To Go..............................   1
    9.    Operational State of the Equipment........   FAILED
   10.    Population Age................................   1         period(s)
   11.    Policy Recommendation.......................   R
   12.    Forecasted Demand...........................   3         units
   13.    Policy Requirements.........................   3         units
   14.    Policy Cost..................................   $ 453.59
   15.    Supplemental Cost of Exceeding Budget......   $ 0.00
   16.    Reliability  (Unreliability for state F)...   0.012422
   17.    Availability (Unavailability for state F)..   0.001197
```

```
Legend:   P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K  = Keep ("Do nothing" alternative)      R = Repair
```

```
          PF1 = ADVANCE         PF2 = REVIEW           PF3 = QUIT
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   2
   9.   Operational State of the Equipment........   GOOD
   10.   Population Age.............................   5 .   period(s)
   11.   Policy Recommendation......................   K
   12.   Forecasted Demand.........................   3   units
   13.   Policy Requirements........................   3   units
   14.   Policy Cost............................... $ 595.00
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.731616
   17.   Availability (Unavailability for state F)..   0.998803

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
   8.   Period(s) To Go............................   2
   9.   Operational State of the Equipment........   FAILED
   10.   Population Age.............................   5   period(s)
   11.   Policy Recommendation......................   P1
   12.   Forecasted Demand.........................   3   units
   13.   Policy Requirements........................   3   units
   14.   Policy Cost............................... $ 616.75
   15.   Supplemental Cost of Exceeding Budget...... $ 0.00
   16.   Reliability (Unreliability for state F)...   0.268384
   17.   Availability (Unavailability for state F)..   0.001197

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

331

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
     8.   Period(s) To Go.............................   3
     9.   Operational State of the Equipment........   GOOD
    10.   Population Age..............................   4   period(s)
    11.   Policy Recommendation......................   K
    12.   Forecasted Demand..........................   3   units
    13.   Policy Requirements........................   3   units
    14.   Policy Cost................................ $ 879.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.818731
    17.   Availability (Unavailability for state F)..   0.998803

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: A
     8.   Period(s) To Go.............................   3
     9.   Operational State of the Equipment........   FAILED
    10.   Population Age..............................   4   period(s)
    11.   Policy Recommendation......................   R
    12.   Forecasted Demand..........................   3   units
    13.   Policy Requirements........................   3   units
    14.   Policy Cost................................ $ 977.83
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.181269
    17.   Availability (Unavailability for state F)..   0.001197

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

```
                    +------------------+
                    |  STREAM OUTPUT   |
                    +------------------+

STREAM NUMBER: 3 .              OPERATING ENVIRONMENT: B

   1.   STREAM NAME..................................   HYDRAULIC.PUMPS

   2.   Hazard Model.................................   LINEARLY INCREASING

   3.   Level of Repair..............................   1

   4.   Initial Age of Population....................   4          Period(s)

   5.   Mean Time Between Failure (MTBF).............   21.97      Period(s)

   6.   Mean Time To Repair (MTTR)...................   0.0400     Period(s)

   7.   Estimated Rate of Technological Improvement....   12        Percent
```

```
              PF1 = ADVANCE                 PF3 = QUIT
```

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment.........   GOOD
    10.   Population Age.............................   6   period(s)
    11.   Policy Recommendation......................   P1
    12.   Forecasted Demand..........................   3   units
    13.   Policy Requirements........................   3   units
    14.   Policy Cost................................ $ 274.37
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.637628
    17.   Availability (Unavailability for state F)..   0.998183

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                 period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                 2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   1
    9.   Operational State of the Equipment.........   FAILED
    10.   Population Age.............................   1   period(s)
    11.   Policy Recommendation......................   R
    12.   Forecasted Demand..........................   3   units
    13.   Policy Requirements........................   3   units
    14.   Policy Cost................................ $ 453.38
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.012422
    17.   Availability (Unavailability for state F)..   0.001817

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
           P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
                 period's supply in inventory)
           P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
                 2 period's supply in inventory)
           K = Keep ("Do nothing" alternative)   R = Repair

           PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment.........   GOOD
    10.   Population Age.............................   5   period(s)
    11.   Policy Recommendation......................   K
    12.   Forecasted Demand..........................   3   units
    13.   Policy Requirements........................   3   units
    14.   Policy Cost................................ $ 594.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.731616
    17.   Availability (Unavailability for state F)..   0.998183

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   2
    9.   Operational State of the Equipment.........   FAILED
    10.   Population Age.............................   5   period(s)
    11.   Policy Recommendation......................   P1
    12.   Forecasted Demand..........................   3   units
    13.   Policy Requirements........................   3   units
    14.   Policy Cost................................ $ 616.37
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.268384
    17.   Availability (Unavailability for state F)..   0.001817

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

385

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   3
    9.   Operational State of the Equipment........   GOOD
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation.....................   K
    12.   Forecasted Demand.........................   3   units
    13.   Policy Requirements.......................   3   units
    14.   Policy Cost............................... $ 878.00
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.818731
    17.   Availability (Unavailability for state F)..   0.998183

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

STREAM OUTPUT(Continued)

STREAM NUMBER: 3   OPERATING ENVIRONMENT: B
    8.   Period(s) To Go............................   3
    9.   Operational State of the Equipment........   FAILED
    10.   Population Age.............................   4   period(s)
    11.   Policy Recommendation.....................   R
    12.   Forecasted Demand.........................   3   units
    13.   Policy Requirements.......................   3   units
    14.   Policy Cost............................... $ 976.54
    15.   Supplemental Cost of Exceeding Budget...... $ 0.00
    16.   Reliability (Unreliability for state F)...   0.181269
    17.   Availability (Unavailability for state F)..   0.001817

Legend: P1 = Purchase Option 1 (Purchase 1 period's supply)
          P2 = Purchase Option 2 (Purchase 2 period's supply and carry next
               period's supply in inventory)
          P3 = Purchase Option 3 (Purchase 3 period's supply and carry next
               2 period's supply in inventory)
          K = Keep ("Do nothing" alternative)   R = Repair

          PF1 = ADVANCE   PF2 = REVIEW   PF3 = QUIT

APPENDIX III

DRRPM SOURCE CODE

APPENDIX B.1

PROGRAM EXEC

```
&TRACE OFF
EUDEXEC2       ·
SET CMSTYPE HT
EXEC INPUT        ·
EXEC NAVY
EXEC OUTPUT
EXEC PRINTER
SET CMSTYPE RT
```

APPENDIX B.2
INPUT EXEC

```
&TRACE OFF
EUDEXEC2
*********************************************************************
*  NOTE:  DMS RUNS IN THE USER AREA.  OTHER USER AREA CMS COMMANDS
*         CANNOT BE ISSUED UNTIL DMS HAS BEEN TERMINATED.
*********************************************************************
&PRESUME &SUBCOMMAND DISPLAY
&I = 1
&LOOP 1 24
     &CALL -DISPLAY
&CALL -CLEANUP
&EXIT
*********************************************************************
*         DISPLAY
*********************************************************************
-DISPLAY
&CALL -CLEAR
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY
&D1 =
&IF &I = 2 &CALL -INTRO2
&IF &I = 3 &CALL -INTRO3
&IF &I = 4 &CALL -INTRO4
&IF &I = 5 &CALL -INTRO5
&IF &I = 6 &CALL -INTRO6
&IF &I = 8 &CALL -INTRO8
&IF &I = 9 &CALL -INTRO9
&IF &I = 10 &CALL -INTRO10
&IF &I = 11 &CALL -INTRO11
&IF &I = 12 &CALL -INTRO12
&IF &I = 13 &CALL -INTRO13
&SUBCOMMAND DISPLAY USE PANEL INTRO&I
&SUBCOMMAND DISPLAY CURSOR &RCURSOR &RCURSOROFFSET
-REDISPLAY
&D1 =
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &I = 4 &IF &RSTATUS = PF4 &GOTO -INTRO4
&IF &I = 5 &IF &RSTATUS = PF4 &GOTO -INTRO5
&IF &I = 6 &IF &RSTATUS = PF4 &GOTO -INTRO6
&IF &I = 8 &IF &RSTATUS = PF4 &GOTO -INTRO8
&IF &I = 9 &IF &RSTATUS = PF4 &GOTO -INTRO9
&IF &I = 10 &IF &RSTATUS = PF4 &GOTO -INTRO10
&IF &I = 11 &IF &RSTATUS = PF4 &GOTO -INTRO11
&IF &I = 12 &IF &RSTATUS = PF4 &GOTO -INTRO12
&IF &I = 13 &IF &RSTATUS = PF4 &GOTO -INTRO13
&IF &RSTATUS = ENTER &GOTO -REDISPLAY
&IF &RSTATUS = PF1  &I = &I + 1
&IF &I = 1 &IF &RSTATUS NE PF1 &GOTO -PF4
&IF &RSTATUS = PF2  &I = &I - 1
&IF &RSTATUS EQ PF3 &IF &I NE 2 &IF &I NE 3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &GOTC
&GOTO -DISPLAY
&RETURN
*********************************************************************
```

```
*   PF4
****************************************************************
-PF4
    &D1 = &STRING OF INVALID PF KEY, PLEASE USE VALID KEY.
    &GOTO -REDISPLAY
****************************************************************
*    INTRO2
****************************************************************
-INTRO2
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY  USE PANEL INTRO2
&SUBCOMMAND DISPLAY DISPLAY
&WPOS=&POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = ENTER &GOTO -REDISPLAY
&IF &RSTATUS = PF1  &GOTO -INPUT1
&IF &RSTATUS = PF2  &GOTO -INPUT2
&IF &RSTATUS = PF3  &GOTO -INPUT3
&IF &RSTATUS = PF4  &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &IF &
&D1 =
&RETURN
****************************************************************
*       INTRO3
****************************************************************
-INTRO3
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY USE PANEL INTRO3
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&WPOS=&POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = ENTER &GOTO -REDISPLAY
    DESBUF
    &STACK &E
    EXECIO 1 DISKW DATA OPTION A1 1 F 10 (FINIS
    DROPBUF
&IF &RSTATUS = PF1 &GOTO -INPUT6
&IF &RSTATUS = PF2 &GOTO -INPUT7
&IF &RSTATUS = PF3 &GOTO -INPUT8
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -INTRO3
&D1 =
&RETURN
****************************************************************
*    INPUT1
****************************************************************
-INPUT1
*  USE SAMPLE CASE STUDY
&E = 2
&S = 1
&I = &I + 1
&RETURN
****************************************************************
*    INPUT2
****************************************************************
-INPUT2
*  USE EXISTING DATA FILES
```

```
&E = 1
&S = 1
&I = &I + 1
&RETURN
*********************************************************************
*   INPUT3
*********************************************************************
-INPUT3
&PRESUME &COMMAND
ERASE MODEL DATA A1
&S = 0
&LOOP -END 24
&S = &S + 1
ERASE STREAM&S INPUT A1
-END
&I = &I + 1
&S = 1
&E = 0
&RETURN
*********************************************************************
*   INPUT6
*********************************************************************
-INPUT6
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&P = 1
&I = &I + 1
&RETURN
*********************************************************************
*   INPUT7
*********************************************************************
-INPUT7
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&P = 2
&I = &I + 1
&RETURN
*********************************************************************
*   INPUT8
*********************************************************************
-INPUT8
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&P = 3
&I = &I + 1
&RETURN
*********************************************************************
*   INTRO4
*********************************************************************
-INTRO4
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO4
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
```

```
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
    DESBUF
    &STACK &P
    EXECIO 1 DISKW PRINT OPTION A1 1 F 10 (FINIS
    DROPBUF
&IF &RSTATUS = PF1 &I = &I + 1
&IF &RSTATUS = PF2 &I = &I - 1
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -INTRO4
&RETURN
*********************************************************************
*       INTRO5
*********************************************************************
-INTRO5
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO5
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF &RSTATUS EQ PF4 &SKIP 16
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 10
    &IF &E NE 2 &SKIP 1
    EXECIO 2 DISKR CASE DATA A1 1 (FINIS
    &IF &E EQ 2 &SKIP 1
    EXECIO 2 DISKR MODEL DATA A1 1 (FINIS
    STACKTAG CONSOLE FIFO
    &READ VAR &A1
    &READ VAR &A2
    &D2 = &A1
    &D3 = &A2
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 6
    DESBUF
    &STACK &D2
    &STACK &D3
&IF &E = 2 &SKIP 1
    EXECIO 2 DISKW MODEL DATA A1 1 (FINIS
    DROPBUF
&CALL -KEYS
&CALL -CLEAR
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &GOTC
&D1 =
&RETURN
*********************************************************************
*   INTRO6
*********************************************************************
-INTRO6
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
```

```
&SUBCOMMAND DISPLAY USE PANEL INTRO6
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF &RSTATUS = PF4 &SKIP 16
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 10
&IF &E NE 2 &SKIP 1
EXECIO 2 DISKR CASE DATA A1 3 (FINIS
&IF &E EQ 2 &SKIP 1
EXECIO 2 DISKR MODEL DATA A1 3 (FINIS
     STACKTAG CONSOLE FIFO
     &READ VAR &A1
     &READ VAR &A2
     &D2 = &A1
     &D3 = &A2
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 7
     DESBUF
     &STACK &D2
     &STACK &D3
&IF &E = 2 &SKIP 1
     EXECIO 2 DISKW MODEL DATA A1 3 (FINIS
     &N = &D2
     DROPBUF
&CALL -KEYS
&CALL -CLEAR
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF3 &GOTC
&D1 =
&RETURN
*********************************************************************
*   INTRO8
*********************************************************************
-INTRO8
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO8
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF &RSTATUS = PF4 &SKIP 28
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 22
&IF &E NE 2 &SKIP 2
&IF &E = 2 &IF &S = 7 &EXIT
     EXECIO 7 DISKR CASE&S INPUT A1 1 (FINIS
&IF &E = 2 &SKIP 1
     EXECIO 7 DISKR STREAM&S INPUT A1 1 (FINIS
     STACKTAG CONSOLE FIFO
     &READ VAR &A1
     &READ VAR &A2
```

```
      &OE = &A2
      &READ VAR &A3
      &READ VAR &A4
      &READ VAR &A5
      &READ VAR &A6
      &READ VAR &A7
      &D2 = &A1
      &D3 = &A2
      &D4 = &A3
      &D5 = &A4
      &D6 = &A5
      &D7 = &A6
      &D8 = &A7
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 11
      DESBUF
      &STACK &D2
      &STACK &D3
      &STACK &D4
      &STACK &D5
      &STACK &D6
      &STACK &D7
      &STACK &D8
&IF &E = 2 &SKIP 1
      EXECIO 7 DISKW STREAM&S INPUT Al 1 F 80 (FINIS
      DROPBUF
&CALL -KEYS
&CALL -CLEAR
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &IF &
&D1 =
&RETURN
**************************************************************************
*    INTRO9
**************************************************************************
-INTRO9
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO9
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF &RSTATUS = PF4 &SKIP 25
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 18
&IF &E NE 2 &SKIP 1
EXECIO 6 DISKR CASE&S INPUT Al 8 (FINIS
&IF &E = 2 &SKIP 1
EXECIO 6 DISKR STREAM&S INPUT Al 8 (FINIS
      STACKTAG CONSOLE FIFO
      &READ VAR &A1
      &READ VAR &A2
```

```
        &READ VAR &A3
        &READ VAR &A4
        &READ VAR &A5
        &READ VAR &A6
        &D2 = &A1
        &D3 = &A2
        &D4 = &A3
        &D5 = &A4
        &D6 = &A5
        &D7 = &A6
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 10
        DESBUF
        &STACK &D2
        &STACK &D3
        &STACK &D4
        &STACK &D5
        &STACK &D6
        &STACK &D7
&IF &E = 2 &SKIP 1
        EXECIO 6 DISKW STREAM&S INPUT A1 8 F 80 (FINIS
        DROPBUF
&CALL -KEYS
&CALL -CLEAR
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &GOTC
&D1 =
&RETURN
*********************************************************************
*   INTRO10
*********************************************************************
-INTRO10
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO10
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF &RSTATUS = PF4 &SKIP 15
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 10
&IF &E NE 2 &SKIP 1
EXECIO 2 DISKR CASE&S INPUT A1 14 (FINIS
&IF &E = 2 &SKIP 1
EXECIO 2 DISKR STREAM&S INPUT A1 14 (FINIS
    .   STACKTAG CONSOLE FIFO
        &READ VAR &A1
        &READ VAR &A2
        &D2 = &A1
        &D3 = &A2
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
```

```
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 6
&IF &E = 2 &SKIP 7
    DESBUF
    &STACK &D2
    &STACK &D3
    EXECIO 2 DISKW STREAM&S INPUT A1 14 F 80 (FINIS
    DROPBUF
&CALL -KEYS
&CALL -CLEAR
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &GOTC
&D1 =
&RETURN
*********************************************************************
*    INTRO11
*********************************************************************
-INTRO11
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO11
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF ·&RSTATUS = PF4 &SKIP 16
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 10
&IF &E NE 2 &SKIP 1
    EXECIO 2 DISKR CASE&S INPUT A1 16 (FINIS
&IF &E = 2 &SKIP1
    EXECIO 2 DISKR STREAM&S INPUT A1 16 (FINIS
    STACKTAG CONSOLE FIFO
    &READ VAR &A1
    &READ VAR &A2
    &D2 = &A1
    &D3 = &A2
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 6
    DESBUF
    &STACK &D2
    &STACK &D3
&IF &E = 2 &SKIP 1
    EXECIO 2 DISKW STREAM&S INPUT A1 16 F 80 (FINIS
    DROPBUF
&CALL -KEYS
&CALL -CLEAR
&D1 =
&RETURN
*********************************************************************
*    INTRO12
```

398

```
*******************************************************************
-INTRO12
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO12
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF &RSTATUS = PF4 &SKIP 18
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 12
&IF &E NE 2 &SKIP 1
      EXECIO 3 DISKR CASE&S INPUT A1 18 (FINIS
&IF &E = 2 &SKIP 1
      EXECIO 3 DISKR STREAM&S INPUT A1 18 (FINIS
      STACKTAG CONSOLE FIFO
      &READ VAR &A1
      &READ VAR &A2
      &READ VAR &A3
      &D2 = &A1
      &D3 = &A2
      &D4 = &A3
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 7
      DESBUF
      &STACK &D2
      &STACK &D3
      &STACK &D4
&IF &E = 2 &SKIP 1
      EXECIO 3 DISKW STREAM&S INPUT A1 18 F 80 (FINIS
      DROPBUF
&CALL -KEYS
&CALL -CLEAR
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &GOTO
&D1 =
&RETURN
*******************************************************************
*  INTRO13
*******************************************************************
-INTRO13
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY CASE M
&SUBCOMMAND DISPLAY USE PANEL INTRO13
&IF &E NE 0 &SKIP 1
&SUBCOMMAND DISPLAY DISPLAY
&PRESUME &COMMAND
&IF &RSTATUS = PF4 &SKIP 29
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &E EQ 0 &SKIP 23
&IF &E NE 2 &SKIP 1
      EXECIO 12 DISKR CASE&S INPUT A1 21 (FINIS
```

```
&IF &E = 2 &SKIP 1
      EXECIO 12 DISKR STREAM&S INPUT A1 21 (FINIS
      STACKTAG CONSOLE FIFO
      &READ VAR &A2 &A3 &A4 &A5
      &READ VAR &A6 &A7 &A8 &A9
      &READ VAR &A10 &A11 &A12 &A13
      &READ VAR &A14 &A15 &A16 &A17
      &READ VAR &A18 &A19 &A20 &A21
      &READ VAR &A22 &A23 &A24 &A25
      &READ VAR &A26 &A27 &A28 &A29
      &READ VAR &A30 &A31 &A32 &A33
      &READ VAR &A34 &A35 &A36 &A37
      &READ VAR &A38 &A39 &A40 &A41
      &READ VAR &A42 &A43 &A44 &A45
      &READ VAR &A46 &A47 &A48 &A49
&G = 1
&LOOP -MOM 48
&G = &G + 1
&D&G = &A&G
-MOM
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS EQ ENTER &SKIP 3
&IF &RSTATUS NE ENTER &D1 = &STRING OF PLEASE PRESS ENTER KEY!
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&SUBCOMMAND DISPLAY DISPLAY
&IF &RSTATUS ¬= ENTER &SKIP 16
      DESBUF
      &STACK &D2   &D3    &D4 &D5
      &STACK &D6   &D7    &D8 &D9
      &STACK &D10 &D11 &D12 &D13
      &STACK &D14 &D15 &D16 &D17
      &STACK &D18 &D19 &D20 &D21
      &STACK &D22 &D23 &D24 &D25
      &STACK &D26 &D27 &D28 &D29
      &STACK &D30 &D31 &D32 &D33
      &STACK &D34 &D35 &D36 &D37
      &STACK &D38 &D39 &D40 &D41
      &STACK &D42 &D43 &D44 &D45
      &STACK &D46 &D47 &D48 &D49
&IF &E = 2 &SKIP 1
      EXECIO 12 DISKW STREAM&S INPUT A1 21 F 80 (FINIS
      DROPBUF
&S = &S + 1
&J = &MULTIPLICATION OF &N 2
&LOOP 1 &J
    &CALL -CLEAR
    &I = 8
    &CALL -INTRO8
    &I = 9
    &CALL -INTRO9
    &I = 10
    &CALL -INTRO10
    &I = 11
    &CALL -INTRO11
    &I = 12
```

```
      &CALL -INTRO12
      &I = 13
      &CALL -INTRO13
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &IF &RSTATUS NE PF4 &GOTC
&D1 =
&EXIT
*********************************************************************
*    KEYS
*********************************************************************
-KEYS
   &IF &I = 5 &J = 4
   &IF &I = 6 &J = 4
   &IF &I = 8 &J = 9
   &IF &I = 9 &J = 8
   &IF &I = 10 &J = 4
   &IF &I = 11 &J = 4
   &IF &I = 12 &J = 5
   &IF &I = 13 &J = 50
&D&J = &STRING OF            PF1 = ADVANCE  PF2 = PREVIOUS  PF3 = QUIT  PF4 = REFRESH
&GOTO -REDISPLAY
&RETURN
*********************************************************************
*    TERMINATE --- RESTORE ENVIRONMENT
*********************************************************************
-CLEANUP
CLEAR NEXT
&RETURN
*********************************************************************
*    CLEAR VARIABLES
*********************************************************************
-CLEAR
&C = 1
&LOOP -VAR 60
&C = &C + 1
&D&C =
-VAR
&RETURN
*********************************************************************
```

401

APPENDIX B.3

NAVY EXEC

```
&TRACE OFF
FORTVS MAIN (SOURCE
GLOBAL TXTLIB VFORTLIB CMSLIB VPIUTIL
GLOBAL LOADLIB VFLODLIB
FILEDEF 01 DISK MODEL DATA A1 (PERM
FILEDEF 02 DISK PRINT OPTION A1 (PERM
FILEDEF 03 DISK DATA OPTION A1 (PERM
FILEDEF 04 DISK CASE DATA A1 (PERM
FILEDEF 10 DISK STREAM1 INPUT A1 (PERM
FILEDEF 11 DISK STREAM2 INPUT A1 (PERM
FILEDEF 12 DISK STREAM3 INPUT A1 (PERM
FILEDEF 13 DISK STREAM4 INPUT A1 (PERM
FILEDEF 14 DISK STREAM5 INPUT A1 (PERM
FILEDEF 15 DISK STREAM6 INPUT A1 (PERM
FILEDEF 16 DISK STREAM7 INPUT A1 (PERM
FILEDEF 17 DISK STREAM8 INPUT A1 (PERM
FILEDEF 18 DISK STREAM9 INPUT A1 (PERM
FILEDEF 19 DISK STREAM10 INPUT A1 (PERM
FILEDEF 20 DISK STREAM11 INPUT A1 (PERM
FILEDEF 21 DISK STREAM12 INPUT A1 (PERM
FILEDEF 22 DISK STREAM13 INPUT A1 (PERM
FILEDEF 23 DISK STREAM14 INPUT A1 (PERM
FILEDEF 24 DISK STREAM15 INPUT A1 (PERM
FILEDEF 25 DISK STREAM16 INPUT A1 (PERM
FILEDEF 26 DISK STREAM17 INPUT A1 (PERM
FILEDEF 27 DISK STREAM18 INPUT A1 (PERM
FILEDEF 28 DISK STREAM19 INPUT A1 (PERM
FILEDEF 29 DISK STREAM20 INPUT A1 (PERM
FILEDEF 30 DISK STREAM21 INPUT A1 (PERM
FILEDEF 31 DISK STREAM22 INPUT A1 (PERM
FILEDEF 32 DISK STREAM23 INPUT A1 (PERM
FILEDEF 33 DISK STREAM24 INPUT A1 (PERM
FILEDEF 34 DISK STREAM1 OUTPUT A1 (PERM
FILEDEF 35 DISK STREAM2 OUTPUT A1 (PERM
FILEDEF 36 DISK STREAM3 OUTPUT A1 (PERM
FILEDEF 37 DISK STREAM4 OUTPUT A1 (PERM
FILEDEF 38 DISK STREAM5 OUTPUT A1 (PERM
FILEDEF 39 DISK STREAM6 OUTPUT A1 (PERM
FILEDEF 40 DISK STREAM7 OUTPUT A1 (PERM
FILEDEF 41 DISK STREAM8 OUTPUT A1 (PERM
FILEDEF 42 DISK STREAM9 OUTPUT A1 (PERM
FILEDEF 43 DISK STREAM10 OUTPUT A1 (PERM
FILEDEF 44 DISK STREAM11 OUTPUT A1 (PERM
FILEDEF 45 DISK STREAM12 OUTPUT A1 (PERM
FILEDEF 46 DISK STREAM13 OUTPUT A1 (PERM
FILEDEF 47 DISK STREAM14 OUTPUT A1 (PERM
FILEDEF 48 DISK STREAM15 OUTPUT A1 (PERM
FILEDEF 49 DISK STREAM16 OUTPUT A1 (PERM
FILEDEF 50 DISK STREAM17 OUTPUT A1 (PERM
FILEDEF 51 DISK STREAM18 OUTPUT A1 (PERM
FILEDEF 52 DISK STREAM19 OUTPUT A1 (PERM
FILEDEF 53 DISK STREAM20 OUTPUT A1 (PERM
FILEDEF 54 DISK STREAM21 OUTPUT A1 (PERM
FILEDEF 55 DISK STREAM22 OUTPUT A1 (PERM
FILEDEF 56 DISK STREAM23 OUTPUT A1 (PERM
```

NAVY   EXEC   A1 04/15/86 20:24 SRSR14   V 40   74 RECS   VA TECH   PRIN

```
FILEDEF 57 DISK STREAM24 OUTPUT A1 (PERM
FILEDEF 58 DISK STREAM SUMMARY A1 (PERM
FILEDEF 59 DISK POP SUMMARY A1 (PERM
FILEDEF 60 DISK CASE1 INPUT A1 (PERM
FILEDEF 61 DISK CASE2 INPUT A1 (PERM
FILEDEF 62 DISK CASE3 INPUT A1 (PERM
FILEDEF 63 DISK CASE4 INPUT A1 (PERM
FILEDEF 64 DISK CASE5 OUTPUT A1 (PERM
FILEDEF 65 DISK CASE6 OUTPUT A1 (PERM
FILEDEF 66 DISK CASE1 OUTPUT A1 (PERM
FILEDEF 67 DISK CASE2 OUTPUT A1 (PERM
FILEDEF 68 DISK CASE3 OUTPUT A1 (PERM
FILEDEF 69 DISK CASE4 OUTPUT A1 (PERM
FILEDEF 70 DISK CASE5 OUTPUT A1 (PERM
FILEDEF 71 DISK CASE6 OUTPUT A1 (PERM
FILEDEF 72 DISK CASE SUMMARY A1 (PERM
FILEDEF 73 DISK DEMO SUMMARY A1 (PERM
FILEDEF 74 DISK DUMMY BLANK A1 (PERM
LOAD MAIN (START
```

APPENDIX B.4

MAIN FORTRAN

```
C**********************************************************************
C          A DYNAMIC REPAIR/REPLACE POPULATION MODEL
C**********************************************************************
C THIS MODEL DETERMINES THE NUMBER OF UNITS TO REPAIR, REPLACE, OR KEEP
C (DO NOTHING) FOR A POPULATION OF END ITEMS ON A PERIOD BY PERIOD BASIS
C**********************************************************************
C          DEFINE VARIABLES
C**********************************************************************
C          PERIOD = PERIOD DEFINITION
C          N      = TOTAL NUMBER OF PERIODS
C          NUMSTR = NUMBER OF STREAMS
C          RETAGE = RETIREMENT AGE FOR STREAM OF END ITEMS
C          PUR    = PRESENT PURCHASE PRICE
C          SV     = SALVAGE VALUE
C          P      = PURCHASE PRICE LESS SALVAGE VALUE
C          CC     = INVENTORY CARRYING COST
C          RC     = REPAIR COST
C          OD     = OPERATING COST OF THE "DEFENDER" ASSET
C          OC     = OPERATING COST OF THE "CHALLENGER" ASSET
C          ISP    = INSPECTION COST
C          LAMDA  = ESTIMATED RATE OF TECHNOLOGICAL IMPROVEMENT
C          V      = LEVEL OF REPAIR
C          HM     = HAZARD FUNCTION MODEL
C          MTBF   = MEAN TIME BETWEEN FAILURE
C          MTTR   = MEAN TIME TO REPAIR
C          PGGP   = PROB. (GOOD - GOOD) FOR PURCHASE ALTERNATIVE
C          PGGK   = PROB. (GOOD - GOOD) FOR KEEP ALTERNATIVE
C          PFGP   = PROB. (FAILED - GOOD) FOR PURCHASE ALTERNATIVE
C          PFGR   = PROB. (FAILED - GOOD) FOR REPAIR ALTERNATIVE
C          PDATA( )  = ARRAY THAT CONTAINS PERIOD BY PERIOD DATA
C          BUD( )    = ARRAY THAT HOLDS PERIOD BUDGET LIMITS
C          CBUD( )   = ARRAY THAT HOLDS CUMULATIVE BUDGET LIMITS
C          A      = AGE OF THE END ITEMS
C          T      = PERIODS TO GO IN THE ANALYSIS
C          G      = CURRENT AGE OF THE END ITEMS
C          PER    = BEGINNING PERIOD
C          PU#G( ) = ARRAY THAT HOLDS PURCHASE OPTION # COSTS FOR STATE G
C          PU#F( ) = ARRAY THAT HOLDS PURCHASE OPTION # COSTS FOR STATE F
C          KE( ) = ARRAY THAT HOLDS KEEP OPTION COSTS
C          D( )  = ARRAY THAT HOLDS DEMAND DATA
C          IL( ) = ARRAY THAT HOLDS INVENTORY LIMITS
C          RL( ) = ARRAY THAT HOLDS REPAIR LIMITS
C          IC( ) = ARRAY THAT HOLDS "INVENTORY CARRIED" REQUIREMENTS
C          HORIZ  = PLANNING HORIZON
C          HAZ    = HAZARD FUNCTION VALUE
C          REL    = RELIABILITY FUNCTION VALUE
C          AVAIL  = AVAILABILITY FUNCTION VALUE
C          STATE  = INITIAL STATE OF EQUIPMENT CONDITION
C          AGE    = AGE OF END ITEM FOR THE MINIMUM COST ALTERNATIVE
C          PC     = "PENALTY COST" OF FOLLOWING SUB-OPTIMAL PATH
C**********************************************************************
          INTEGER PDATA(12,4),D(12),IL(12),RL(12),BUD(12),CBUD(12),ABUD(12)
          INTEGER DE0(12,24),DE1(12,24),DE2(12,24),DE3(12,24),DE4(12,24)
          REAL POL12G(24),POL12F(24),POL11G(24),POL11F(24)
          REAL POL10G(24),POL10F(24),POL9G(24),POL9F(24)
```

```
      REAL POL8G(24),POL8F(24),POL7G(24),POL7F(24)
      REAL POL6G(24),POL6F(24),POL5G(24),POL5F(24)
      REAL POL4G(24),POL4F(24),POL3G(24),POL3F(24)
      REAL POL2G(24),POL2F(24),POL1G(24),POL1F(24)
      REAL IC(12),KE(12,24),RE(12,24),RF(12,24),SC(24,12),TC(12)
      REAL PF(12),KF(12,24),PU1G(12,24),PU2G(12,24),PU3G(12,24)
      REAL PU1F(12,24),PU2F(12,24),PU3F(12,24),TSC(12,12)
      INTEGER N,NUMSTR,RETAGE,G,SN,RATE,V,M,PUR,SV,RC,OD,OC,ISP,P
      INTEGER HM,T,TZ,DEM,SUM,OPT,HORIZ,PER,CYCLE,AGE,HM1
      CHARACTER OE*1, OPTION*1, STATE*6, PERIOD*6, STAT*6, NAME*30
      REAL LAMDA,PMIN,C,K1,HAZ,H,MTBF,MTTR,MTB,MTR,CC
C***********************************************************************
C  READ MODEL DATA
C***********************************************************************
      READ (1,1) PERIOD
1     FORMAT (A6)
      READ (1,*) N,NUMSTR,RETAGE
      WRITE(59,*) NUMSTR
      WRITE(59,*) N
      WRITE(59,1) PERIOD
C***********************************************************************
C  INITIALIZE SUMMING ARRAYS
C***********************************************************************
      DO 3 I = 1, 12
      DO 2 J = 1, 24
         SC(J,I) = 0
2     CONTINUE
3     CONTINUE
      DO 4 I = 1, 12
         TC(I) = 0
4     CONTINUE
      DO 6 I = 1, 12
      DO 5 J = 1, 12
         TSC(I,J) = 0
5     CONTINUE
6     CONTINUE
C***********************************************************************
C   READ STREAM DATA
C***********************************************************************
      NS = 2*NUMSTR
      DO 1000 L = 10, NS+9
C***********************************************************************
C SINCE WE ARE TRYING TO FIND MINIMUMS, THE INITIAL VALUES ARE
C ASSIGNED VERY LARGE NUMBERS FOR COMPARISON PURPOSES
C***********************************************************************
C INITIALIZE VARIABLES AND ARRAYS
C***********************************************************************
      DO 8 I = 1, 12
      DO 7 J = 1, 24
         PU1G(I,J) = 999999999.
         PU2G(I,J) = 999999999.
         PU3G(I,J) = 999999999.
         PU1F(I,J) = 999999999.
         PU2F(I,J) = 999999999.
         PU3F(I,J) = 999999999.
```

407

```
          KE(I,J) = 999999999.
          RE(I,J) = 999999999.
7         CONTINUE
8         CONTINUE
C******************************************************************
C  INITIALIZE ARRAYS
C******************************************************************
          DO 9 I = 1, 12
            BUD(I) = 0
            CBUD(I) = 0
            PF(I) = 0
9         CONTINUE
          DO 12 K = 1, 12
          DO 11 M = 1, 24
            RF(K,M) = 0
            KF(K,M) = 0
            DE0(K,M) = 0
            DE1(K,M) = 0
            DE2(K,M) = 0
            DE3(K,M) = 0
            DE4(K,M) = 0
            POL12G(M) = 0
            POL12F(M) = 0
            POL11G(M) = 0
            POL11F(M) = 0
            POL10G(M) = 0
            POL10F(M) = 0
            POL9G(M) = 0
            POL9F(M) = 0
            POL8G(M) = 0
            POL8F(M) = 0
            POL7G(M) = 0
            POL7F(M) = 0
            POL6G(M) = 0
            POL6F(M) = 0
            POL5G(M) = 0
            POL5F(M) = 0
            POL4G(M) = 0
            POL4F(M) = 0
            POL3G(M) = 0
            POL3F(M) = 0
            POL2G(M) = 0
            POL2F(M) = 0
            POL1G(M) = 0
            POL1F(M) = 0
11        CONTINUE
12        CONTINUE
          READ (L,*,END=1001) SN
          WRITE(L+24,*) SN
          READ (L,13) OE
          WRITE(L+24,13) OE
13        FORMAT (A1)
          READ (L,14) NAME
          WRITE(L+24,*) NAME
          IF (MOD(L,2) .EQ. 0) WRITE(58,14) NAME
```

408

```
14      FORMAT (A30)
        IF (L .EQ. NS+9) THEN
        DO 15 I = NUMSTR+1, 12
           NAME = 'O'
           WRITE(58,14) NAME
15      CONTINUE
        ENDIF
        READ (L,*) G,PUR,SV,RC,OD,OC
        READ (L,16) CC
16      FORMAT (F10.2)
        READ (L,*) ISP,RATE,V
        READ (L,17) PGGP,PGGK,PFGP,PFGR
17      FORMAT (F3.2/F3.2/F3.2/F3.2)
        READ (L,*) HM
        READ (L,18) MTBF,MTTR
18      FORMAT (F7.4/F7.4)
        IF (HM .EQ. O) HM = 1
        IF (MTBF .EQ. O) MTBF = 1.
        IF (MTTR .EQ. O) MTTR = 1.
        WRITE(L+24,*) HM
        WRITE(L+24,*) V
        WRITE(L+24,*) G
        WRITE(L+24,19) MTBF
        WRITE(L+24,20) MTTR
19      FORMAT (F7.2)
20      FORMAT (F7.4)
C************************************************************************
C READ IN PERIOD BY PERIOD DATA IN REVERSE (BACKWARD RECURSION USED)
C************************************************************************
        DO 21 I = N, 1, -1
           READ (L,*) (PDATA(I,J), J = 1, 4)
21      CONTINUE
        LAMDA = .01*FLOAT(RATE)
        WRITE(L+24,*) RATE
C************************************************************************
C       PERFORM STREAM BY STREAM DYNAMIC PROGRAMMING CALCULATIONS
C************************************************************************
        CYCLE = 0
        P = PUR - SV
C************************************************************************
C CONSIDER THE STATE I = G AND EVALUATE THE PURCHASE ALTERNATIVE.
C************************************************************************
C  READ IN "INVENTORY CARRIED" REQUIREMENTS
        DO 30 I = 2, N+1
           IC(I) = PDATA(I-1,1)
30      CONTINUE
        SUM = IC(2)
C  READ IN "INVENTORY LIMIT" FOR EACH PERIOD
        DO 32 I = 2, N+1
           IL(I) = PDATA(I,4)
32      CONTINUE
C  READ IN "BUDGET LIMIT" FOR EACH PERIOD
        DO 34 I = 1, N
           BUD(I) = PDATA(I,2)
34      CONTINUE
```

```
C  DETERMINE CUMULATIVE BUDEGETARY CONSTRAINTS
      CBUD(1) = BUD(1)
      CBUD(2) = BUD(1)+BUD(2)
      CBUD(3) = BUD(1)+BUD(2)+BUD(3)
      CBUD(4) = BUD(1)+BUD(2)+BUD(3)+BUD(4)
      CBUD(5) = BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)
      CBUD(6) = BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)+BUD(6)
      CBUD(7) = BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)+BUD(6)+BUD(7)
      CBUD(8) = BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)+BUD(6)+BUD(7)+BUD(8)
      CBUD(9) = BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)+BUD(6)+BUD(7)+BUD(8)
    1 +BUD(9)
      CBUD(10)=BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)+BUD(6)+BUD(7)+BUD(8)
    1 +BUD(9)+BUD(10)
      CBUD(11)=BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)+BUD(6)+BUD(7)+BUD(8)
    1 +BUD(9)+BUD(10)+BUD(11)
      CBUD(12)=BUD(1)+BUD(2)+BUD(3)+BUD(4)+BUD(5)+BUD(6)+BUD(7)+BUD(8)
    1 +BUD(9)+BUD(10)+BUD(11)+BUD(12)
C  READ IN "REPAIR CAPACITY" REQUIREMENTS
      DO 42  I = 1, N
         RL(I) = PDATA(I,3)
42    CONTINUE
      RSUM = 0
C  READ IN DEMAND FOR EACH PERIOD
      DO 44 I = 1, N
         D(I) = PDATA(I,1)
44    CONTINUE
C*********************************************************************
C  PERFORM PERIOD BY PERIOD CALCULATIONS
C*********************************************************************
C  VARIABLE TZ KEEPS FORWARD TIME
      TZ = N + 1
      DO 890 T = 1, N
      TZ = TZ - 1
      WRITE(L+24,45) T,D(T)
45    FORMAT(I2,1X,I10)
      IF (T .EQ. N) THEN
      DO 48 I = N+1, 12
         D(I) = 0
         WRITE(L+24,45) I, D(I)
48    CONTINUE
      ENDIF
         IF (T .EQ. 1 .AND. G .LE. 1) IK = TZ
         IF (T .EQ. 2 .AND. G .LE. 1) IK = TZ-1
         IF (T .EQ. 3 .AND. G .LE. 1) IK = TZ-2
         IF (T .EQ. 4 .AND. G .LE. 1) IK = TZ-3
         IF (T .EQ. 5 .AND. G .LE. 1) IK = TZ-4
         IF (T .EQ. 6 .AND. G .LE. 1) IK = TZ-5
         IF (T .EQ. 7 .AND. G .LE. 1) IK = TZ-6
         IF (T .EQ. 8 .AND. G .LE. 1) IK = TZ-7
         IF (T .EQ. 9 .AND. G .LE. 1) IK = TZ-8
         IF (T .EQ. 10 .AND. G .LE. 1) IK = TZ-9
         IF (T .EQ. 11 .AND. G .LE. 1) IK = TZ-10
         IF (T .EQ. 12 .AND. G .LE. 1) IK = TZ-11
         IF (T .EQ. 1 .AND. G .GT. 1) IK = TZ-1
         IF (T .EQ. 2 .AND. G .GT. 1) IK = TZ-2
```

```
          IF (T .EQ. 3 .AND. G .GT. 1) IK = TZ-3
          IF (T .EQ. 4 .AND. G .GT. 1) IK = TZ-4
          IF (T .EQ. 5 .AND. G .GT. 1) IK = TZ-5
          IF (T .EQ. 6 .AND. G .GT. 1) IK = TZ-6
          IF (T .EQ. 7 .AND. G .GT. 1) IK = TZ-7
          IF (T .EQ. 8 .AND. G .GT. 1) IK = TZ-8
          IF (T .EQ. 9 .AND. G .GT. 1) IK = TZ-9
          IF (T .EQ. 10 .AND. G .GT. 1) IK = TZ-10
          IF (T .EQ. 11 .AND. G .GT. 1) IK = TZ-11
          IF (T .EQ. 12 .AND. G .GT. 1) IK = TZ
52    IF (CYCLE .EQ. 0) THEN
          STATE = 'GOOD'
      ELSE
          STATE = 'FAILED'
      ENDIF
C*******************************************************************
C  GET TRANSITION FUNCTION VALUES FOR THE APPROP. HAZARD FUNCTION MODEL
      IF (HM .EQ. 1 .AND. STATE .EQ. 'FAILED') THEN
          PGGP = PFGP
          GO TO 54
      ENDIF
      CALL TRANS(HM,STATE,TZ,PGGP,PGGK,PFGP,PFGR,MTBF,MTTR,LAMDA)
      IF (STATE .EQ. 'FAILED') THEN
          PGGP = PFGP
      ENDIF
C*******************************************************************
C  CHECK INVENTORY CAPACITY CONSTRAINT (PHYSICAL CONSTRAINT)
C*******************************************************************
C  IF T = 1 PERIOD TO GO, DEMAND MUST BE MET, SO GO TO P1 AND K1 OPTIONS
C  AND DISREGARD ALL REMAINING OPTIONS
54    IF (T .EQ. 1) THEN
          HORIZ = 1
          GO TO 250
      ENDIF
C  IF T = 2 PERIODS TO GO, AND SUM EXCEEDS INVENTORY LIMIT, THEN
C  DISREGARD P2,P3 OPTIONS; KEEP P1 OPTION
      IF (T .EQ. 2 .AND. SUM .GT. IL(2)) THEN
          HORIZ = 1
          GO TO 250
      ELSE
      IF (T.EQ. 2 .AND. SUM .LE. IL(2)) THEN
          HORIZ = 2
          GO TO 240
      ENDIF
      ENDIF
C  IF T = 3 AND SUM EXCEEDS INVENTORY LIMIT, THEN DISREGARD P3 OPTION;
C  KEEP P2, P1 OPTIONS
      IF (T .EQ. 3 .AND. SUM .GT. IL(3)) THEN
          HORIZ = 2
          GO TO 240
      ELSE
      IF (T .EQ. 3 .AND. SUM .LE. IL(3)) THEN
          HORIZ = 3
          GO TO 230
      ENDIF
```

```
          ENDIF
C  NOTE:   THERE IS A LIMIT OF 3 DIFFERENT PURCHASE OPTIONS; DETERMINE
C  HORIZON FOR T > 3
          IF (T .GT. 3 .AND. SUM .GT. IL(3)) THEN
             HORIZ = 3
             GO TO 230
          ELSE
          IF (T .GT. 3 .AND. SUM .LE. IL(2)) THEN
             HORIZ = 2
             GO TO 240
          ELSE
          IF (T .GT. 3 .AND. SUM .LE. IL(1)) THEN
             HORIZ = 1
             GO TO 250
          ENDIF
          ENDIF
          ENDIF
C     P3 OPTION
230       IF (N .EQ. T .AND. G .EQ. 0) THEN
             A = 0
             CALL HAZARD(HM,A,MTBF,H,R)
             GO TO 262
          ENDIF
          IF (N .EQ. T .AND. G .GT. 0) THEN
             A = G
             CALL HAZARD(HM,A,MTBF,H,R)
             GO TO 235
          ENDIF
             DO 233 A = 1, IK
             IF (A .EQ. RETAGE) GO TO 240
             CALL HAZARD(HM,A,MTBF,H,R)
          DE3(T,A) = (D(T)+D(T-2)+D(T-1))
          DEM  = .96*DE3(T,A)
          ISUM = IC(T)+IC(T-1)
          X1 = ((DEM)*P*(1-LAMDA*(A)))
          X2 = (D(T)*(OC*EXP(LAMDA*(A))))
          X  = (X1+X2)*PGGP
          Y  = (ISP*D(T))+(CC*ISUM*2)
          IF (T .EQ. 3) THEN
             Z1 = 0
          ELSE
             Z1 = PF(T-3)*PGGP
          ENDIF
          P3 = R*(X+Y+Z1)
          IF (STATE .EQ. 'GOOD') THEN
             PU3G(T,A) = P3
          ELSE
          IF (STATE .EQ. 'FAILED') THEN
             PU3F(T,A) = P3
          ENDIF
          ENDIF
233       CONTINUE
          IF (G .EQ. 0) THEN
             GO TO 240
          ELSE
```

```
                A = (G+(TZ-3))
                IF (A .EQ. RETAGE) GO TO 240
                CALL HAZARD(HM,A,MTBF,H,R)
                GO TO 235
            ENDIF
235     DE3(T,A) = (D(T)+D(T-2)+D(T-1))
        DEM = .96*DE3(T,A)
        ISUM = IC(T)+IC(T-1)
        X1  =((DEM)*P*(1-LAMDA*(A)))
        X2  = (D(T)*(OC*EXP(LAMDA*(A))))
        X   = (X1+X2)*PGGP
        Y   = (ISP*D(T))+(CC*ISUM*2)
        IF (T .EQ. 3) THEN
            Z1 = 0
        ELSE
            Z1 = PF(T-3)*PGGP
        ENDIF
        P3 = R*(X+Y+Z1)
        IF (STATE .EQ. 'GOOD') THEN
            PU3G(T,A) = P3
        ELSE
        IF (STATE .EQ. 'FAILED') THEN
            PU3F(T,A) = P3
        ENDIF
        ENDIF
C    P2 OPTION
240     IF (N .EQ. T .AND. G .EQ. 0) THEN
            A = 0
            CALL HAZARD(HM,A,MTBF,H,R)
            GO TO 262
        ENDIF
        IF (N .EQ. T .AND. G .GT. 0) THEN
            A = G
            CALL HAZARD(HM,A,MTBF,H,R)
            GO TO 245
        ENDIF
            DO 243 A = 1, IK
            IF (A .EQ. RETAGE) GO TO 250
            CALL HAZARD(HM,A,MTBF,H,R)
        DE2(T,A) = (D(T)+D(T-1))
        DEM = .98*DE2(T,A)
        ISUM = IC(T)
        X1 = ((DEM)*P*(1-LAMDA*(A)))
        X2 = (D(T)*(OC*EXP(LAMDA*(A))))
        X  = (X1 + X2)*PGGP
        Y  = (ISP*D(T))+(CC*ISUM*(1))
        IF (T .EQ. 2) THEN
            Z1 = 0
        ELSE
            Z1 = PF(T-2)*PGGP
        ENDIF
        P2 = R*(X+Y+Z1)
        IF (STATE .EQ. 'GOOD') THEN
            PU2G(T,A) = P2
        ELSE
```

```
         IF (STATE .EQ. 'FAILED') THEN
            PU2F(T,A) = P2
         ENDIF
         ENDIF
243      CONTINUE
         IF (G .EQ. 0) THEN
            GO TO 250
         ELSE
            A = (G+(TZ-2))
            IF (A .EQ. RETAGE) GO TO 250
            CALL HAZARD(HM,A,MTBF,H,R)
            GO TO 245
         ENDIF
245      DE2(T,A) = (D(T)+D(T-1))
         DEM = .98*DE2(T,A)
         ISUM = IC(T)
         X1 = ((DEM)*P*(1-LAMDA*(A)))
         X2 = (D(T)*(OC*EXP(LAMDA*(A))))
         X  = (X1+X2)*PGGP
         Y  = (ISP*D(T))+(CC*ISUM*1)
         IF (T .EQ. 2) THEN
            Z1 = 0
         ELSE
            Z1 = PF(T-2)*PGGP
         ENDIF
         P2 = R*(X+Y+Z1)
         IF (STATE .EQ. 'GOOD') THEN
            PU2G(T,A) = P2
         ELSE
         IF (STATE .EQ. 'FAILED') THEN
            PU2F(T,A) = P2
         ENDIF
         ENDIF
C    P1 OPTION
250      IF (N .EQ. T .AND. G .EQ. 0) THEN
            A = 0
            PU1F(T,A) = 999999999.
            CALL HAZARD(HM,A,MTBF,H,R)
            GO TO 262
         ENDIF
         IF (N .EQ. T .AND. G .GT. 0) THEN
            A = G
            CALL HAZARD(HM,A,MTBF,H,R)
            GO TO 255
         ENDIF
            DO 253  A = 1, IK
            IF (A .EQ. RETAGE) GO TO 262
            CALL HAZARD(HM,A,MTBF,H,R)
         DE1(T,A) = D(T)
         DEM = DE1(T,A)
         ISUM = 0
         X1 =  DEM*(P*(1-LAMDA*(A)))
         X2 =  D(T)*(OC*EXP(LAMDA*(A)))
         X = (X1+X2)*PGGP
         Y = (ISP*D(T))+(CC*ISUM)
```

414

```
         IF (T .EQ. 1) THEN
             Z1 = 0
         ELSE
             Z1 = PF(T-1)*PGGP
         ENDIF
         P1 = R*(X+Y+Z1)
         IF (STATE .EQ. 'GOOD') THEN
             PU1G(T,A) = P1
         ELSE
         IF (STATE .EQ. 'FAILED') THEN
             PU1F(T,A) = P1
         ENDIF
         ENDIF
253      CONTINUE
         IF (G .EQ. 0) THEN
             GO TO 262
         ELSE
             A = (G+(TZ-1))
             IF (A .EQ. RETAGE) GO TO 262
             CALL HAZARD(HM,A,MTBF,H,R)
             GO TO 255
         ENDIF
255      DE1(T,A) = D(T)
         DEM = DE1(T,A)
         ISUM = 0
         X1 = DEM*(P*(1-LAMDA*(A)))
         X2 = D(T)*(OC*EXP(LAMDA*(A)))
         X  = (X1+X2)*PGGP
         Y  = (ISP*D(T))+(CC*ISUM)
         IF (T .EQ. 1) THEN
             Z1 = 0
         ELSE
             Z1 = PF(T-1)*PGGP
         ENDIF
         P1 = R*(X+Y+Z1)
         IF (STATE .EQ. 'GOOD') THEN
             PU1G(T,A) = P1
         ELSE
         IF (STATE .EQ. 'FAILED') THEN
             PU1F(T,A) = P1
         ENDIF
         ENDIF
C******************************************************************
C  CONSIDER THE STATE I = G AND EVALUATE THE KEEP ALTERNATIVE
C******************************************************************
262      IF (STATE .EQ. 'FAILED') THEN
             GO TO 381
         ENDIF
C******************************************************************
C   K OPTION
375      IF (N .EQ. T .AND. G .EQ. 0) THEN
             A = 0
             CALL HAZARD(HM,A,MTBF,H,R)
             GO TO 380
         ENDIF
```

415

```
        IF (N .EQ. T .AND. G .GT. 0) THEN
           A = G
           CALL HAZARD(HM,A,MTBF,H,R)
           GO TO 380
        ENDIF
           DO 378 A = 1, IK
           IF (A .EQ. RETAGE) GO TO 381
           CALL HAZARD(HM,A,MTBF,H,R)
        DEO(T,A) = D(T)
        X = (D(T)*(OD*EXP(LAMDA*A)))*PGGK
        Y = ISP*D(T)
        IF (T .EQ. 1) THEN
           Z1 = 0
        ELSE
           Z1 = KF(T-1,A+1)*PGGK
        ENDIF
        K = R*(X+Y+Z1)
        KE(T,A) = K
378     CONTINUE
        IF (G .EQ. 0) THEN
           GO TO 381
        ELSE
           A = (G+(TZ-1))
           IF (A .EQ. RETAGE) GO TO 381
           CALL HAZARD(HM,A,MTBF,H,R)
           GO TO 380
        ENDIF
380     DEO(T,A) = D(T)
        X = (D(T)*(OD*EXP(LAMDA*A)))*PGGK
        Y = ISP*D(T)
        IF (T .EQ. 1) THEN
           Z1 = 0
        ELSE
           Z1 = KF(T-1,A+1)*PGGK
        ENDIF
        K = R*(X+Y+Z1)
        KE(T,A) = K
C******************************************************************
C    DETERMINE "BEST THING TO DO"
C******************************************************************
381     IF (T .EQ. 11) GO TO 386
        IF (T .EQ. 10) GO TO 388
        IF (T .EQ. 9) GO TO 400
        IF (T .EQ. 8) GO TO 402
        IF (T .EQ. 7) GO TO 404
        IF (T .EQ. 6) GO TO 406
        IF (T .EQ. 5) GO TO 408
        IF (T .EQ. 4) GO TO 410
        IF (T .EQ. 3) GO TO 412
        IF (T .EQ. 2) GO TO 414
        IF (T .EQ. 1) GO TO 416
C EVALUATE PURCHASE CASE FOR STATES "GOOD" AND "FAILED"
386     PF(T-10) = AMIN1(PU1G(T-10,1),PU2G(T-10,1),PU3G(T-10,1),
     1 KE(T-10,1))
388     PF(T-9) = AMIN1(PU1G(T-9,1),PU2G(T-9,1),PU3G(T-9,1),KE(T-9,1))
```

```
400     PF(T-8) = AMIN1(PU1G(T-8,1),PU2G(T-8,1),PU3G(T-8,1),KE(T-8,1))
402     PF(T-7) = AMIN1(PU1G(T-7,1),PU2G(T-7,1),PU3G(T-7,1),KE(T-7,1))
404     PF(T-6) = AMIN1(PU1G(T-6,1),PU2G(T-6,1),PU3G(T-6,1),KE(T-6,1))
406     PF(T-5) = AMIN1(PU1G(T-5,1),PU2G(T-5,1),PU3G(T-5,1),KE(T-5,1))
408     PF(T-4) = AMIN1(PU1G(T-4,1),PU2G(T-4,1),PU3G(T-4,1),KE(T-4,1))
410     PF(T-3) = AMIN1(PU1G(T-3,1),PU2G(T-3,1),PU3G(T-3,1),KE(T-3,1))
412     PF(T-2) = AMIN1(PU1G(T-2,1),PU2G(T-2,1),PU3G(T-2,1),KE(T-2,1))
414     PF(T-1) = AMIN1(PU1G(T-1,1),PU2G(T-1,1),PU3G(T-1,1),KE(T-1,1))
416     PF(T) = AMIN1(PU1G(T,1),PU2G(T,1),PU3G(T,1),KE(T,1))
C  EVALUATE KEEP CASE (APPLIES TO BOTH STATES)
500     DO 524 A = 1, IK
        IF (T .EQ. 11) GO TO 502
        IF (T .EQ. 10) GO TO 504
        IF (T .EQ. 9) GO TO 506
        IF (T .EQ. 8) GO TO 508
        IF (T .EQ. 7) GO TO 510
        IF (T .EQ. 6) GO TO 512
        IF (T .EQ. 5) GO TO 514
        IF (T .EQ. 4) GO TO 516
        IF (T .EQ. 3) GO TO 518
        IF (T .EQ. 2) GO TO 520
        IF (T .EQ. 1) GO TO 522
502     KF(T-10,A)=AMIN1(PU1G(T-10,A),PU2G(T-10,A),PU3G(T-10,A),
     1  KE(T-10,A))
504     KF(T-9,A)=AMIN1(PU1G(T-9,A),PU2G(T-9,A),PU3G(T-9,A),KE(T-9,A))
506     KF(T-8,A)=AMIN1(PU1G(T-8,A),PU2G(T-8,A),PU3G(T-8,A),KE(T-8,A))
508     KF(T-7,A)=AMIN1(PU1G(T-7,A),PU2G(T-7,A),PU3G(T-7,A),KE(T-7,A))
510     KF(T-6,A)=AMIN1(PU1G(T-6,A),PU2G(T-6,A),PU3G(T-6,A),KE(T-6,A))
512     KF(T-5,A)=AMIN1(PU1G(T-5,A),PU2G(T-5,A),PU3G(T-5,A),KE(T-5,A))
514     KF(T-4,A)=AMIN1(PU1G(T-4,A),PU2G(T-4,A),PU3G(T-4,A),KE(T-4,A))
516     KF(T-3,A)=AMIN1(PU1G(T-3,A),PU2G(T-3,A),PU3G(T-3,A),KE(T-3,A))
518     KF(T-2,A)=AMIN1(PU1G(T-2,A),PU2G(T-2,A),PU3G(T-2,A),KE(T-2,A))
520     KF(T-1,A)=AMIN1(PU1G(T-1,A),PU2G(T-1,A),PU3G(T-1,A),KE(T-1,A))
522     KF(T,A)=AMIN1(PU1G(T,A),PU2G(T,A),PU3G(T,A),KE(T,A))
524     CONTINUE
        IF (G .EQ. 0) THEN
           GO TO 550
        ENDIF
        IF (T .EQ. 11) THEN
           A = (G+(N-11))
           GO TO 528
        ENDIF
        IF (T .EQ. 10) THEN
           A = (G+(N-10))
           GO TO 530
        ENDIF
        IF (T .EQ. 9) THEN
           A = (G+(N-9))
           GO TO 532
        ENDIF
        IF (T .EQ. 8) THEN
           A = (G+(N-8))
           GO TO 534
        ENDIF
        IF (T .EQ. 7) THEN
```

417

```
            A = (G+(N-7))
            GO TO 536
         ENDIF
         IF (T .EQ. 6) THEN
            A = (G+(N-6))
            GO TO 538
         ENDIF
         IF (T .EQ. 5) THEN
            A = (G+(N-5))
            GO TO 540
         ENDIF
         IF (T .EQ. 4) THEN
            A = (G+(N-4))
            GO TO 542
         ENDIF
         IF (T .EQ. 3) THEN
            A = (G+(N-3))
            GO TO 544
         ENDIF
         IF (T .EQ. 2) THEN
            A = (G+(N-2))
            GO TO 546
         ENDIF
         IF (T .EQ. 1) THEN
            A = (G+(N-1))
            GO TO 548
         ENDIF
528      KF(T-10,A)=AMIN1(PU1G(T-10,A),PU2G(T-10,A),PU3G(T-10,A),
     1   KE(T-10,A))
530      KF(T-9,A)=AMIN1(PU1G(T-9,A),PU2G(T-9,A),PU3G(T-9,A),KE(T-9,A))
532      KF(T-8,A)=AMIN1(PU1G(T-8,A),PU2G(T-8,A),PU3G(T-8,A),KE(T-8,A))
534      KF(T-7,A)=AMIN1(PU1G(T-7,A),PU2G(T-7,A),PU3G(T-7,A),KE(T-7,A))
536      KF(T-6,A)=AMIN1(PU1G(T-6,A),PU2G(T-6,A),PU3G(T-6,A),KE(T-6,A))
538      KF(T-5,A)=AMIN1(PU1G(T-5,A),PU2G(T-5,A),PU3G(T-5,A),KE(T-5,A))
540      KF(T-4,A)=AMIN1(PU1G(T-4,A),PU2G(T-4,A),PU3G(T-4,A),KE(T-4,A))
542      KF(T-3,A)=AMIN1(PU1G(T-3,A),PU2G(T-3,A),PU3G(T-3,A),KE(T-3,A))
544      KF(T-2,A)=AMIN1(PU1G(T-2,A),PU2G(T-2,A),PU3G(T-2,A),KE(T-2,A))
546      KF(T-1,A)=AMIN1(PU1G(T-1,A),PU2G(T-1,A),PU3G(T-1,A),KE(T-1,A))
548      KF(T,A)=AMIN1(PU1G(T,A),PU2G(T,A),PU3G(T,A),KE(T,A))
         IF (STATE .EQ. 'FAILED') GO TO 556
C******************************************************************
C   EVALUATE STATE I = F
C******************************************************************
550      IF (HM .EQ. 1 .AND. CYCLE .EQ. 0) THEN
            PGGP = PFGP
            CYCLE = 1
            GO TO 52
         ENDIF
         CALL TRANS(HM,STATE,T,PGGP,PGGK,PFGP,PFGR,MTBF,MTTR,LAMDA)
         IF (CYCLE .EQ. 0 ) THEN
            PGGP = PFGP
            CYCLE = 1
            GO TO 52
         ENDIF
C******************************************************************
```

413

```
C  CONSIDER THE STATE I = F AND EVALUATE THE REPAIR OPTION
C*******************************************************************
C R OPTION
556      IF (N .EQ. T .AND. G .EQ. 0) THEN
            A = 0
            CALL HAZARD(HM,A,MTBF,H,R)
            GO TO 562
         ENDIF
         IF (N .EQ. T .AND. G .GT. 0) THEN
            A = G
            CALL HAZARD(HM,A,MTBF,H,R)
            GO TO 562
         ENDIF
            DO 560 A = 1, IK
            IF (A .EQ. RETAGE) GO TO 563
            CALL HAZARD(HM,A,MTBF,H,R)
            RSUM = D(T)*(1-R)
C*******************************************************************
C  DETERMINE IF REPAIR CAPACITY EXCEEDED (PHYSICAL CONSTRAINT)
C*******************************************************************
558      IF (T .EQ. 1 .AND. RSUM .GT. RL(1)) GO TO 563
         IF (T .EQ. 2 .AND. RSUM .GT. RL(2)) GO TO 563
         IF (T .EQ. 3 .AND. RSUM .GT. RL(3)) GO TO 563
         IF (T .EQ. 4 .AND. RSUM .GT. RL(4)) GO TO 563
         IF (T .EQ. 5 .AND. RSUM .GT. RL(5)) GO TO 563
         IF (T .EQ. 6 .AND. RSUM .GT. RL(6)) GO TO 563
         IF (T .EQ. 7 .AND. RSUM .GT. RL(7)) GO TO 563
         IF (T .EQ. 8 .AND. RSUM .GT. RL(8)) GO TO 563
         IF (T .EQ. 9 .AND. RSUM .GT. RL(9)) GO TO 563
         IF (T .EQ. 10 .AND. RSUM .GT. RL(10)) GO TO 563
         IF (T .EQ. 11 .AND. RSUM .GT. RL(11)) GO TO 563
         IF (T .EQ. 12 .AND. RSUM .GT. RL(12)) GO TO 563
C*******************************************************************
         DE4(T,A) = D(T)
         X1 = (D(T)*(OD*EXP(LAMDA*A)))*PFGR
         Y = ISP*D(T)
         W = (RC*D(T)*1)*PFGR
         IF (T .EQ. 1) THEN
            Z1 = 0
         ELSE
            Z1 = KF(T-1,A+1)*PFGR
         ENDIF
         R1 = R*(X1+Y+W+Z1)
         RE(T,A) = R1
560      CONTINUE
         IF (G .EQ. 0) THEN
            GO TO 563
         ELSE
            A = (G+(TZ-1))
            IF (A .EQ. RETAGE) GO TO 563
            CALL HAZARD(HM,A,MTBF,H,R)
            RSUM = D(T)*(1-R)
C*******************************************************************
C  DETERMINE IF REPAIR CAPACITY EXCEEDED (PHYSICAL CONSTRAINT)
C*******************************************************************
```

419

```
          IF (T .EQ. 1 .AND. RSUM .GT. RL(1)) GO TO 563
          IF (T .EQ. 2 .AND. RSUM .GT. RL(2)) GO TO 563
          IF (T .EQ. 3 .AND. RSUM .GT. RL(3)) GO TO 563
          IF (T .EQ. 4 .AND. RSUM .GT. RL(4)) GO TO 563
          IF (T .EQ. 5 .AND. RSUM .GT. RL(5)) GO TO 563
          IF (T .EQ. 6 .AND. RSUM .GT. RL(6)) GO TO 563
          IF (T .EQ. 7 .AND. RSUM .GT. RL(7)) GO TO 563
          IF (T .EQ. 8 .AND. RSUM .GT. RL(8)) GO TO 563
          IF (T .EQ. 9 .AND. RSUM .GT. RL(9)) GO TO 563
          IF (T .EQ. 10 .AND. RSUM .GT. RL(10)) GO TO 563
          IF (T .EQ. 11 .AND. RSUM .GT. RL(11)) GO TO 563
          IF (T .EQ. 12 .AND. RSUM .GT. RL(12)) GO TO 563
C****************************************************************************
          GO TO 562
          ENDIF
562       DE4(T,A) = D(T)
          X1 = (D(T)*(OD*EXP(LAMDA*A)))*PFGR
          Y  = ISP*D(T)
          W  = (RC*D(T)*1)*PFGR
          IF (T .EQ. 1) THEN
             Z1 = 0
          ELSE
             Z1 = KF(T-1,A+1)*PFGR
          ENDIF
          R1 = R*(X1+Y+W+Z1)
          RE(T,A) = R1
C****************************************************************************
563       IF (T .EQ. 1) GO TO 880
          SUM = SUM + IC(T+1)
880       CYCLE = 0
890       CONTINUE
C****************************************************************************
C  POLICY DETERMINATION FOR STATE "GOOD"
C****************************************************************************
900       STATE = 'GOOD'
          WRITE (L+24,901) STATE
901       FORMAT (A6)
          IF (STATE .NE. 'GOOD') GO TO 931
          IF (N .EQ. 12) GO TO 902
          IF (N .EQ. 11) GO TO 904
          IF (N .EQ. 10) GO TO 906
          IF (N .EQ. 9) GO TO 908
          IF (N .EQ. 8) GO TO 910
          IF (N .EQ. 7) GO TO 912
          IF (N .EQ. 6) GO TO 914
          IF (N .EQ. 5) GO TO 916
          IF (N .EQ. 4) GO TO 918
          IF (N .EQ. 3) GO TO 920
          IF (N .EQ. 2) GO TO 922
          IF (N .EQ. 1) GO TO 924
C  POLICY 12
902       IF (N .EQ. 12) A = G
          NT = 12
          POL12 = AMIN1(PU1G(12,A),PU2G(12,A),PU3G(12,A),KE(12,A))
          CALL HAZARD(HM,A,MTBF,H,R)
```

420

```
        CALL REQ(STATE,POL12,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
        IF (POL12 .EQ. 0) OPT = 5
          AGE = G
903     FORMAT(F20.2,1X,I1,1X,I2,1X,I6,1X,F9.6,1X,F9.6,1X,F12.2)
        IF (OPT .EQ. 0) THEN
          A = G+1
        ELSE
        IF (OPT .NE. 0) THEN
          A = 1
        ENDIF
        ENDIF
        TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL12G(L-9) = AVAIL*POL12
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL12,CBUD,PC)
        WRITE(L+24,*) POL12,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 11
904     IF (N .EQ. 11) A = G
        NT = 11
        POL11 = AMIN1(PU1G(11,A),PU2G(11,A),PU3G(11,A),KE(11,A))
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL11,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
        IF (POL11 .EQ. 0) OPT = 5
          AGE = IFIX(A)
        IF (N .EQ. 11) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 0 .AND. IN .EQ. 11) THEN
          A = G+1
        ELSE
        IF (OPT .EQ. 0 .AND. IN .GT. 11) THEN
          A = A+1
        ELSE
        IF (OPT .NE. 0) THEN
          A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 11) TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL11G(L-9) = AVAIL*POL11
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL11,CBUD,PC)
        WRITE(L+24,903) POL11,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 10
906     IF (N .EQ. 10) A = G
        NT = 10
        POL10 = AMIN1(PU1G(10,A),PU2G(10,A),PU3G(10,A),KE(10,A))
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL10,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
        IF (POL10 .EQ. 0) OPT = 5
```

```
          AGE = IFIX(A)
       IF (N .EQ. 10) CALL ZERO(N,NT,L)
       IF (OPT .EQ. 0 .AND. N .EQ. 10) THEN
          A = G+1
       ELSE
       IF (OPT .EQ. 0 .AND. N .GT. 10) THEN
          A = A+1
       ELSE
       IF (OPT .NE. 0) THEN
          A = 1
       ENDIF
       ENDIF
       ENDIF
       IF (N .EQ. 10) TIME = 0
       CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
       POL10G(L-9) = AVAIL*POL10
       TIME = TIME +1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
       CALL BUDGET(NT,POL10,CBUD,PC)
       WRITE(L+24,903) POL10,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 9
908    IF (N .EQ. 9) A = G
       NT = 9
       POL9 = AMIN1(PU1G(9,A),PU2G(9,A),PU3G(9,A),KE(9,A))
       CALL HAZARD(HM,A,MTBF,H,R)
       CALL REQ(STATE,POL9,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
       IF (POL9 .EQ. 0) OPT = 5
          AGE = IFIX(A)
       IF (N .EQ. 9) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 0 .AND. N .EQ. 9) THEN
           A = G+1
        ELSE
        IF (OPT .EQ. 0 .AND. N .GT. 9) THEN
           A = A+1
        ELSE
        IF (OPT. NE. 0) THEN
           A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 9) TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL9G(L-9) = AVAIL*POL9
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
       CALL BUDGET(NT,POL9,CBUD,PC)
       WRITE(L+24,903) POL9,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 8
910    IF (N .EQ. 8) A = G
       NT = 8
       POL8 = AMIN1(PU1G(8,A),PU2G(8,A),PU3G(8,A),KE(8,A))
       CALL HAZARD(HM,A,MTBF,H,R)
       CALL REQ(STATE,POL8,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
```

```
      IF (POL8 .EQ. 0) OPT = 5
         AGE = IFIX(A)
      IF (N .EQ. 8) CALL ZERO(N,NT,L)
      IF (OPT .EQ. 0 .AND. N .EQ. 8) THEN
         A = G+1
      ELSE
      IF (OPT .EQ. 0 .AND. N .GT. 8) THEN
         A = A+1
      ELSE
      IF (OPT .NE. 0) THEN
         A = 1
      ENDIF
      ENDIF
      ENDIF
      IF (N .EQ. 8) TIME = 0
      CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
      POL8G(L-9) = AVAIL*POL8
      TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
      CALL BUDGET(NT,POL8,CBUD,PC)
      WRITE(L+24,903) POL8,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 7
912   IF (N .EQ. 7) A = G
      NT = 7
      POL7 = AMIN1(PU1G(7,A),PU2G(7,A),PU3G(7,A),KE(7,A))
      CALL HAZARD(HM,A,MTBF,H,R)
      CALL REQ(STATE,POL7,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
      IF (POL7 .EQ. 0) OPT = 5
         AGE = IFIX(A)
      IF (N .EQ. 7) CALL ZERO(N,NT,L)
      IF (OPT .EQ. 0 .AND. N .EQ. 7) THEN
         A = G+1
      ELSE
      IF (OPT .EQ. 0 .AND. N .GT. 7) THEN
         A = A+1
      ELSE
      IF (OPT .NE. 0) THEN
         A = 1
      ENDIF
      ENDIF
      ENDIF
      IF (N .EQ. 7) TIME = 0
      CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
      POL7G(L-9) = AVAIL*POL7
      TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
      CALL BUDGET(NT,POL7,CBUD,PC)
      WRITE(L+24,903) POL7,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 6
914   IF (IN .EQ. 6) A = G
      NT = 6
      POL6 = AMIN1(PU1G(6,A),PU2G(6,A),PU3G(6,A),KE(6,A))
      CALL HAZARD(HM,A,MTBF,H,R)
      CALL REQ(STATE,POL6,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
```

```
      1 NT,A,NREQ,OPT)
        IF (POL6 .EQ. 0) OPT = 5
           AGE = IFIX(A)
        IF (N .EQ. 6) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 0 .AND. N .EQ. 6) THEN
           A = G+1
        ELSE
        IF (OPT .EQ. 0 .AND. N .GT. 6) THEN
           A = A+1
        ELSE
        IF (OPT .NE. 0) THEN
           A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 6) TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL6G(L-9) = AVAIL*POL6
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL6,CBUD,PC)
        WRITE(L+24,903) POL6,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 5
916     IF (N .EQ. 5) A = G
        NT = 5
        POL5 = AMIN1(PU1G(5,A),PU2G(5,A),PU3G(5,A),KE(5,A))
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL5,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
      1 NT,A,NREQ,OPT)
        IF (POL5 .EQ. 0) OPT = 5
           AGE = IFIX(A)
        IF (N .EQ. 5) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 0 .AND. N .EQ. 5) THEN
           A = G+1
        ELSE
        IF (OPT .EQ. 0 .AND. N .GT. 5) THEN
           A = A+1
        ELSE
        IF (OPT .NE. 0) THEN
           A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 5) TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL5G(L-9) = AVAIL*POL5
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL5,CBUD,PC)
        WRITE(L+24,903) POL5,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 4
918     IF (N .EQ. 4) A = G
        NT = 4
        POL4 = AMIN1(PU1G(4,A),PU2G(4,A),PU3G(4,A),KE(4,A))
        CALL HAZARD(HM,A,MTBF,H,R)
```

```
          CALL REQ(STATE,POL4,PU1G,PU2G,PU3G,KE,DEO,DE1,DE2,DE3,DE4,
    1 NT,A,NREQ,OPT)
          IF (POL4 .EQ. 0) OPT = 5
              AGE = IFIX(A)
          IF (N .EQ. 4) CALL ZERO(N,NT,L)
           IF (OPT .EQ. 0 .AND. N .EQ. 4) THEN
              A = G+1
           ELSE
           IF (OPT .EQ. 0 .AND. N .GT. 4) THEN
              A = A+1
           ELSE
           IF (OPT .NE. 0) THEN
              A = 1
           ENDIF
           ENDIF
           ENDIF
           IF (N .EQ. 4) TIME = 0
           CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
           POL4G(L-9) = AVAIL*POL4
           TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
           CALL BUDGET(NT,POL4,CBUD,PC)
           WRITE(L+24,903) POL4,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 3
920       IF (N .EQ. 3) A = G
          NT = 3
          POL3 = AMIN1(PU1G(3,A),PU2G(3,A),PU3G(3,A),KE(3,A))
          CALL HAZARD(HM,A,MTBF,H,R)
          CALL REQ(STATE,POL3,PU1G,PU2G,PU3G,KE,DEO,DE1,DE2,DE3,DE4,
    1 NT,A,NREQ,OPT)
          IF (POL3 .EQ. 0) OPT = 5
              AGE = IFIX(A)
           IF (N .EQ. 3) CALL ZERO(N,NT,L)
           IF (OPT .EQ. 0 .AND. N .EQ. 3) THEN
              A = G+1
           ELSE
           IF (OPT .EQ. 0 .AND. N .GT. 3) THEN
              A = A+1
           ELSE
           IF (OPT .NE. 0) THEN
              A = 1
           ENDIF
           ENDIF
           ENDIF
           IF (N .EQ. 3) TIME = 0
           CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
           POL3G(L-9) = AVAIL*POL3
           TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
           CALL BUDGET(NT,POL3,CBUD,PC)
           WRITE(L+24,903) POL3,OPT,AGE,NREQ,R,AVAIL,PC
C  POLICY 2
922       IF (N .EQ. 2) A = G
          NT = 2
          POL2 = AMIN1(PU1G(2,A),PU2G(2,A),KE(2,A))
```

```
            CALL HAZARD(HM,A,MTBF,H,R)
            CALL REQ(STATE,POL2,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
        1 NT,A,NREQ,OPT)
            IF (POL2 .EQ. 0) OPT = 5
                AGE = IFIX(A)
            IF (N .EQ. 2) CALL ZERO(N,NT,L)
            IF (OPT .EQ. 0 .AND. N .EQ. 2) THEN
                A = G+1
            ELSE
            IF (OPT .EQ. 0 .AND. N .GT. 2) THEN
                A = A+1
            ELSE
            IF (OPT .NE. 0) THEN
                A = 1
            ENDIF
            ENDIF
            ENDIF
            IF (N .EQ. 2) TIME = 0
            CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
            POL2G(L-9) = AVAIL*POL2
            TIME = TIME +1.
C   CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
            CALL BUDGET(NT,POL2,CBUD,PC)
            WRITE(L+24,903) POL2,OPT,AGE,NREQ,R,AVAIL,PC
C   POLICY 1
924     IF (N .EQ. 1) A = G
            NT = 1
            POL1 = AMIN1(PU1G(1,A),KE(1,A))
            CALL HAZARD(HM,A,MTBF,H,R)
            CALL REQ(STATE,POL1,PU1G,PU2G,PU3G,KE,DE0,DE1,DE2,DE3,DE4,
        1 NT,A,NREQ,OPT)
            IF (POL1 .EQ. 0) OPT = 5
                AGE = IFIX(A)
            CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
            POL1G(L-9) = AVAIL*POL1
            IF (N .EQ. 1) CALL ZERO(N,NT,L)
            CALL BUDGET(NT,POL1,CBUD,PC)
            WRITE(L+24,903) POL1,OPT,AGE,NREQ,R,AVAIL,PC
C*******************************************************************
C   POLICY DETERMINATION FOR STATE "FAILED"
C*******************************************************************
931     STATE = 'FAILED'
            WRITE(L+24,932) STATE
932     FORMAT (A6)
            IF (STATE .NE. 'FAILED') GO TO 957
            IF (N .EQ. 12) GO TO 933
            IF (N .EQ. 11) GO TO 934
            IF (N .EQ. 10) GO TO 936
            IF (N .EQ. 9) GO TO 938
            IF (N .EQ. 8) GO TO 940
            IF (N .EQ. 7) GO TO 942
            IF (N .EQ. 6) GO TO 944
            IF (N .EQ. 5) GO TO 946
            IF (N .EQ. 4) GO TO 948
            IF (N .EQ. 3) GO TO 950
```

```
        IF (N .EQ. 2) GO TO 952
        IF (N .EQ. 1) GO TO 954
C  POLICY 12
933     IF (N .EQ. 12) A = G
        NT = 12
        POL12 = AMIN1(PU1F(12,A),PU2F(12,A),PU3F(12,A),RE(12,A))
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL12,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
        IF (POL12 .EQ. 0) OPT = 5
          AGE = G
        IF (OPT .EQ. 4) THEN
          A = G+1
        ELSE
          A = 1
        ENDIF
        TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL12F(L-9) = (1-AVAIL)*POL12
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL12,CBUD,PC)
        WRITE(L+24,903) POL12,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 11
934     IF (N .EQ. 11) A = G
        NT = 11
        POL11 = AMIN1(PU1F(11,A),PU2F(11,A),PU3F(11,A),RE(11,A))
        CALL HAZARD(HM,A,MRBF,H,R)
        CALL REQ(STATE,POL11,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
        IF (POL11 .EQ. 0) OPT = 5
          AGE = IFIX(A)
        IF (N .EQ. 11) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 4 .AND. IN .EQ. 11) THEN
          A = G+1
        ELSE
        IF (OPT .EQ. 4 .AND. IN .GT. 11) THEN
          A = A+1
        ELSE
        IF (OPT .NE. 4) THEN
          A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 11) TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL11F(L-9) = (1-AVAIL)*POL11
        TIME = TIME +1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL11,CBUD,PC)
        WRITE(L+24,903) POL11,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 10
936     IF (N .EQ. 10) A = G
        NT = 10
        POL10 = AMIN1(PU1F(10,A),PU2F(10,A),PU3F(10,A),RE(10,A))
```

427

```
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL10,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
    1 NT,A,NREQ,OPT)
        IF (POL10 .EQ. 0) OPT = 5
           AGE = IFIX(A)
        IF (N .EQ. 10) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 4 .AND. N .EQ. 10) THEN
           A = G+1
        ELSE
        IF (OPT .EQ. 4 .AND. N .GT. 10) THEN
           A = A+1
        ELSE
        IF (OPT .NE. 4) THEN
           A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 10) TIME = 0
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL10F(L-9) = (1-AVAIL)*POL10
        TIME = TIME +1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL10,CBUD,PC)
        WRITE(L+24,903) POL10,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 9
938     IF (N .EQ. 9) A = G
        NT = 9
        POL9 = AMIN1(PU1F(9,A),PU2F(9,A),PU3F(9,A),RE(9,A))
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL10,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
    1 NT,A,NREQ,OPT)
        IF (POL9 .EQ. 0) OPT = 5
           AGE = IFIX(A)
        IF (N .EQ. 9) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 4 .AND. N .EQ. 9) THEN
           A = G+1
        ELSE
        IF (OPT .EQ. 4 .AND. N .GT. 9) THEN
           A = A+1
        ELSE
        IF (OPT .NE. 4) THEN
           A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 9) TIME = 0.
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL9F(L-9) = (1-AVAIL)*POL9
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL9,CBUD,PC)
        WRITE(L+24,903) POL9,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 8
940     IF (N .EQ. 8) A = G
        NT = 8
```

```
       POL8 = AMIN1(PU1F(8,A),PU2F(8,A),PU3F(8,A),RE(8,A))
       CALL HAZARD(HM,A,MTBF,H,R)
       CALL REQ(STATE,POL8,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
        IF (POL8 .EQ. 0) OPT = 5
           AGE = IFIX(A)
         IF (N .EQ. 8) CALL ZERO(N,NT,L)
         IF (OPT .EQ. 4 .AND. N .EQ. 8) THEN
             A = G+1
         ELSE
         IF (OPT .EQ. 4 .AND. N .GT. 8) THEN
             A = A+1
         ELSE
         IF (OPT .NE. 4) THEN
             A = 1
         ENDIF
         ENDIF
         ENDIF
         IF (N .EQ. 8) TIME = 0.
         CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
         POL8F(L-9) = (1-AVAIL)*POL8
         TIME = TIME + 1.
C   CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
         CALL BUDGET(NT,POL8,CBUD,PC)
         WRITE(L+24,903) POL8,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C   POLICY 7
942      IF (N .EQ. 7) A = G
         NT = 7
         POL7 = AMIN1(PU1F(7,A),PU2F(7,A),PU3F(7,A),RE(7,A))
         CALL HAZARD(HM,A,MTBF,H,R)
         CALL REQ(STATE,POL7,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
        IF (POL7 .EQ. 0) OPT = 5
           AGE = IFIX(A)
         IF (N .EQ. 7) CALL ZERO(N,NT,L)
         IF (OPT .EQ. 4 .AND. N .EQ. 7) THEN
             A = G+1
         ELSE
         IF (OPT .EQ. 4 .AND. N .GT. 7) THEN
             A = A+1
         ELSE
         IF (OPT .NE. 4) THEN
             A = 1
         ENDIF
         ENDIF
         ENDIF
         IF (N .EQ. 7) TIME = 0
         CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
         POL7F(L-9) = (1-AVAIL)*POL7
         TIME = TIME +1.
C   CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
         CALL BUDGET(NT,POL7,CBUD,PC)
         WRITE(L+24,903) POL7,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C   POLICY 6
944      IF (IN .EQ. 6) A = G
```

```
          NT = 6
          POL6 = AMIN1(PU1F(6,A),PU2F(6,A),PU3F(6,A),RE(6,A))
          CALL HAZARD(HM,A,MTBF,H,R)
          CALL REQ(STATE,POL8,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
     1    NT,A,NREQ,OPT)
          IF (POL6 .EQ. 0) OPT = 5
             AGE = IFIX(A)
           IF (N .EQ. 6) CALL ZERO(N,NT,L)
           IF (OPT .EQ. 4 .AND. N .EQ. 6) THEN
             A = G+1
           ELSE
           IF (OPT .EQ. 4 .AND. N .GT. 6) THEN
             A = A+1
           ELSE
           IF (OPT .NE. 4) THEN
             A = 1
           ENDIF
           ENDIF
           ENDIF
           IF (N .EQ. 6) TIME = 0
           CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
           POL6F(L-9) = (1-AVAIL)*POL6
           TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
          CALL BUDGET(NT,POL6,CBUD,PC)
          WRITE(L+24,903) POL6,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 5
946       IF (N .EQ. 5) A = G
          NT = 5
          POL5 = AMIN1(PU1F(5,A),PU2F(5,A),PU3F(5,A),RE(5,A))
          CALL HAZARD(HM,A,MTBF,H,R)
          CALL REQ(STATE,POL5,PU1F,PU2F,PU3F,RE,DE0,DE1,DE2,DE3,DE4,
     1    NT,A,NREQ,OPT)
          IF (POL5 .EQ. 0) OPT = 5
             AGE = IFIX(A)
           IF (N .EQ. 5) CALL ZERO(N,NT,L)
           IF (OPT .EQ. 4 .AND. N .EQ. 5) THEN
             A = G+1
           ELSE
           IF (OPT .EQ. 4 .AND. N .GT. 5) THEN
             A = A+1
           ELSE
           IF (OPT .NE. 4) THEN
             A = 1
           ENDIF
           ENDIF
           ENDIF
           IF (N .EQ. 5) TIME = 0
           CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
           POL5F(L-9) = (1-AVAIL)*POL5
           TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
          CALL BUDGET(NT,POL5,CBUD,PC)
          WRITE(L+24,903) POL5,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 4
```

```
948      IF (N .EQ. 4) A = G
         NT = 4
         POL4 = AMIN1(PU1F(4,A),PU2F(4,A),PU3F(4,A),RE(4,A))
         CALL HAZARD(HM,A,MTBF,H,R)
         CALL REQ(STATE,POL4,PU1F,PU2F,PU3F,RE,DEO,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
         IF (POL4 .EQ. 0) OPT = 5
            AGE = IFIX(A)
         IF (N .EQ. 4) CALL ZERO(N,NT,L)
         IF (OPT .EQ. 4 .AND. N .EQ. 4) THEN
            A = G+1
         ENDIF
         IF (OPT .EQ. 4 .AND. N .GT. 4) THEN
            A = A+1
         ELSE
            A = 1
         ENDIF
         IF (N .EQ. 4) TIME = 0
         CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
         POL4F(L-9) = (1-AVAIL)*POL4
         TIME = TIME + 1.
C   CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
         CALL BUDGET(NT,POL4,CBUD,PC)
         WRITE(L+24,903) POL4,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 3
950      IF (N .EQ. 3) A = G
         NT = 3
         POL3 = AMIN1(PU1F(3,A),PU2F(3,A),PU3F(3,A),RE(3,A))
         CALL HAZARD(HM,A,MTBF,H,R)
         CALL REQ(STATE,POL3,PU1F,PU2F,PU3F,RE,DEO,DE1,DE2,DE3,DE4,
     1 NT,A,NREQ,OPT)
         IF (POL3 .EQ. 0) OPT = 5
            AGE = IFIX(A)
         IF (N .EQ. 3) CALL ZERO(N,NT,L)
         IF (OPT .EQ. 4 .AND. N .EQ. 3) THEN
            A = G+1
         ELSE
         IF (OPT .EQ. 4 .AND. N .GT. 3) THEN
            A = A+1
         ELSE
         IF (OPT .NE. 4) THEN
            A = 1
         ENDIF
         ENDIF
         ENDIF
         IF (N .EQ. 3) TIME = 0
         CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
         POL3F(L-9) = (1-AVAIL)*POL3
         TIME = TIME + 1.
C   CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
         CALL BUDGET(NT,POL3,CBUD,PC)
         WRITE(L+24,903) POL3,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 2
952      IF (N .EQ. 2) A = G
         NT = 2
```

431

```
        POL2 = AMIN1(PU1F(2,A),PU2F(2,A),RE(2,A))
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL2,PU1F,PU2F,PU3F,RE,DEO,DE1,DE2,DE3,DE4,
      1 NT,A,NREQ,OPT)
        IF (POL2 .EQ. 0) OPT = 5
          AGE = IFIX(A)
        IF (N .EQ. 2) CALL ZERO(N,NT,L)
        IF (OPT .EQ. 4 .AND. N .EQ. 2) THEN
          A = G+1
        ELSE
        IF (OPT .EQ. 4 .AND. N .GT. 2) THEN
          A = A+1
        ELSE
        IF (OPT .NE. 4) THEN
          A = 1
        ENDIF
        ENDIF
        ENDIF
        IF (N .EQ. 2) TIME = O
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL2F(L-9) = (1-AVAIL)*POL2
        TIME = TIME + 1.
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL2,CBUD,PC)
        WRITE(L+24,903) POL2,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C  POLICY 1
954     IF (N .EQ. 1) A = G
        NT = 1
        POL1 = AMIN1(PU1F(1,A),RE(1,A))
        CALL HAZARD(HM,A,MTBF,H,R)
        CALL REQ(STATE,POL1,PU1F,PU2F,PU3F,RE,DEO,DE1,DE2,DE3,DE4,
      1 NT,A,NREQ,OPT)
        IF (POL1 .EQ. 0) OPT = 5
          AGE = IFIX(A)
        IF (N .EQ. 1) CALL ZERO(N,NT,L)
        IF (N .EQ. 1) TIME = O
        CALL AVAL(HM,MTBF,MTTR,TIME,AVAIL)
        POL1F(L-9) = (1-AVAIL)*POL1
C  CHECK CUMULATIVE BUDGET LIMIT CONSTRAINT (NON-PHYSICAL CONSTRAINT)
        CALL BUDGET(NT,POL1,CBUD,PC)
        WRITE(L+24,903) POL1,OPT,AGE,NREQ,1-R,1-AVAIL,PC
C*********************************************************************
C  AGGREGATE STREAM COSTS FOR STATES "GOOD" AND "FAILED"
C*********************************************************************
957        SC(L-9,12) = POL12G(L-9)+POL12F(L-9)
           SC(L-9,11) = POL11G(L-9)+POL11F(L-9)
           SC(L-9,10) = POL10G(L-9)+POL10F(L-9)
           SC(L-9,9) = POL9G(L-9)+POL9F(L-9)
           SC(L-9,8) = POL8G(L-9)+POL8F(L-9)
           SC(L-9,7) = POL7G(L-9)+POL7F(L-9)
           SC(L-9,6) = POL6G(L-9)+POL6F(L-9)
           SC(L-9,5) = POL5G(L-9)+POL5F(L-9)
           SC(L-9,4) = POL4G(L-9)+POL4F(L-9)
           SC(L-9,3) = POL3G(L-9)+POL3F(L-9)
           SC(L-9,2) = POL2G(L-9)+POL2F(L-9)
```

```
            SC(L-9,1) = POL1G(L-9)+POL1F(L-9)
C*********************************************************************
C  EVALUATE A NEW STREAM
1000    CONTINUE
1001    ENDFILE 74
C*********************************************************************
C  AGGREGATE OPERATING ENVIRONMENTS PER PERIOD
C*********************************************************************
        DO 1002 I = 1, 12
            TSC(1,I) = SC(1,I)+SC(2,I)
            TSC(2,I) = SC(3,I)+SC(4,I)
            TSC(3,I) = SC(5,I)+SC(6,I)
            TSC(4,I) = SC(7,I)+SC(8,I)
            TSC(5,I) = SC(9,I)+SC(10,I)
            TSC(6,I) = SC(11,I)+SC(12,I)
            TSC(7,I) = SC(13,I)+SC(14,I)
            TSC(8,I) = SC(15,I)+SC(16,I)
            TSC(9,I) = SC(17,I)+SC(18,I)
            TSC(10,I) = SC(19,I)+SC(20,I)
            TSC(11,I) = SC(21,I)+SC(22,I)
            TSC(12,I) = SC(23,I)+SC(24,I)
1002    CONTINUE
        DO 1004 I = 1, 12
            WRITE(58,*) I
            WRITE(58,1003) TSC(1,I)
            WRITE(58,1003) TSC(2,I)
            WRITE(58,1003) TSC(3,I)
            WRITE(58,1003) TSC(4,I)
            WRITE(58,1003) TSC(5,I)
            WRITE(58,1003) TSC(6,I)
            WRITE(58,1003) TSC(7,I)
            WRITE(58,1003) TSC(8,I)
            WRITE(58,1003) TSC(9,I)
            WRITE(58,1003) TSC(10,I)
            WRITE(58,1003) TSC(11,I)
            WRITE(58,1003) TSC(12,I)
1003    FORMAT (F20.2)
1004    CONTINUE
C*********************************************************************
C  DETERMINE TOTAL COSTS PER PERIOD BY AGGREGATING STREAMS
C*********************************************************************
        DO 1006 I = 1, 12
        TC(I) = TSC(1,I)+TSC(2,I)+TSC(3,I)+TSC(4,I)+TSC(5,I)+TSC(6,I)+
       1TSC(7,I)+TSC(8,I)+TSC(9,I)+TSC(10,I)+TSC(11,I)+TSC(12,I)
1006    CONTINUE
        DO 1008 I = 12, 1, -1
            WRITE(59,1007) I, TC(I)
1007    FORMAT(I2,1X,F20.2)
1008    CONTINUE
*********************************************************************
*  DETERMINE TOTAL POPULATION COST
*********************************************************************
        POP = TC(1)+TC(2)+TC(3)+TC(4)+TC(5)+TC(6)+TC(7)+TC(8)+TC(9)+
       1TC(10)+TC(11)+TC(12)
            WRITE(59,1010) POP
```

```
1010   FORMAT (F20.2)
C*******************************************************************
       STOP
       END
C*******************************************************************
C   LIBRARY OF HAZARD FUNCTION MODELS
C*******************************************************************
       SUBROUTINE HAZARD(J,Q,MTB,HAZ,REL)
       REAL MTB
       IF (J .EQ. 1) GO TO 260
       IF (J .EQ. 2) GO TO 270
       IF (J .EQ. 3) GO TO 275
       IF (J .EQ. 4) GO TO 310
       IF (J .EQ. 5) GO TO 320
C*******************************************************************
C   CONSTANT HAZARD FUNCTION MODEL
C*******************************************************************
C   NOTE:  WITH A CONSTANT HAZARD FUNCTION MODEL, THE CUMULATIVE
C   FAILURE DISTRIBUTION IS EXPONENTIAL.  THUS, AN OLDER UNIT AND A
C   NEW ONE ARE EQUALLY LIKELY TO CONTINUE OPERATING AT ANY POINT IN
C   TIME.  THEREFORE, NOTHING IS GAINED BY REPLACING AN OLDER UNIT
C   BEFORE FAILURE.  THE NEW UNITS ARE NO BETTER THAN THE ONES REPLACED.
C   THEREFORE, THE MAINTENANCE POLICY IS SIMPLY TO REPLACE THE EQUIPMENT
C   UPON FAILURE.
C
260        HAZ = 1./MTB
           REL = EXP(-(HAZ*Q))
       RETURN
C*******************************************************************
C     LINEARLY INCREASING HAZARD FUNCTION MODEL
C
270    IF (Q .LT. 4.*MTB .OR. Q .GE. 4.*MTB) GO TO 272
272        HAZ = .025*Q
           REL = EXP(-((.025*Q**2)/2))
       RETURN
C*******************************************************************
C     PIECEWISE LINEAR BATHTUB HAZARD FUNCTION MODEL
C
275    IF (0 .LT. Q .AND. Q .LE. MTB) GO TO 280
       IF (MTB .LT. Q .AND. Q .LE. 3.*MTB) GO TO 290
       IF (Q .LT. 4.*MTB) GO TO 300
       IF (Q .GE. 4.*MTB) GO TO 300
280    HAZ = .05-((.025/MTB)*Q)
       C1  = ((.05*Q)-((.025/MTB)*(Q**2)/2.))
       REL = EXP(-C1)
       GO TO 301
290    HAZ =.025
       C1  =((.05*MTB)-((.025/MTB)*(MTB**2)/2.))*EXP(-.025*(Q-MTB))
       REL = EXP(-C1)
       GO TO 301
300    HAZ = .025 + (.05/MTB) * (Q-(3.*MTB))
       C1   = ((.05*MTB)-((.025/MTB)*(MTB**2)/2.))
       REL1 = EXP(-C1)
       C2   = ((.025*((3.*MTB)-MTB)))*EXP(-(.025*(Q-(3.*MTB))))
       REL2 = EXP(-C2)
```

434

```
        C3   =((.025*(Q-(3.*MTB))+((.05/MTB))*((Q-(3.*MTB))**2)/2.))
        REL3 = EXP(-C3)
        REL  = REL1 +REL2 +REL3
301     ZK = 1
        RETURN
C****************************************************************
C       WEIBULL HAZARD FUNCTION MODEL
C
310     IF (Q .LT. 4.*MTB .OR. Q .GE. 4.*MTB) GO TO 312
312        HAZ  = ((1./2.)*(1./6.))*((Q)**(-.5)))
           REL  = EXP(-(1./6.)*(Q**(.5)))
        RETURN
C****************************************************************
C       EXPONENTIAL HAZARD FUNCTION MODEL
C
320     IF (Q .LT. 4.*MTB .OR. Q .GE. 4.*MTB) GO TO 322
322        HAZ  = 2.*EXP(.10*Q)
           C1   = ((.05*EXP((.025*Q)-1.)))
           REL  = EXP(-C1)
        RETURN
        END
C****************************************************************
C   SUBROUTINE TRANS DETERMINES TRANSITION FUNCTION VALUES
C****************************************************************
        SUBROUTINE TRANS(NHM,ASTATE,NZ,APGP,APGK,APFP,APFR,MTB,MTR,LAMD)
        CHARACTER*6 ASTATE
        INTEGER Z
        REAL LAM,MU,MTB,MTR,LAMD,LAM1,MU1,APGP,APFP,APGK,APFR
        LAM = 1./MTB
        MU = 1./MTR
        IF (NHM .NE. 1 .AND. ASTATE .EQ. 'GOOD') THEN
           LAM1 = 1./((1+LAMD)*MTB)
           MU1 = 1./((1-LAMD)*MTR)
           APGP = MU1/(LAM1+MU1)+((LAM1/(LAM1+MU1))*EXP(-(LAM1+MU1)*NZ))
           APGK = MU/(LAM+MU)+((LAM/(LAM+MU))*EXP(-(LAM+MU)*NZ))
        ELSE
        IF (NHM .NE. 1 .AND. ASTATE .EQ. 'FAILED') THEN
           LAM1 = 1./((1+LAMD)*MTB)
           MU1 = 1./((1-LAMD)*MTR)
           APFP = MU1/(LAM1+MU1)+((LAM1/(LAM1+MU1))*EXP(-(LAM1+MU1)*NZ))
           APFR = MU/(LAM+MU)-((MU/(LAM+MU))*EXP(-(LAM+MU)*NZ))
        ENDIF
        ENDIF
        RETURN
        END
C****************************************************************
C  SUBROUTINE AVAL DETERMINES AVAILABILITY
C****************************************************************
        SUBROUTINE AVAL(J,MTB,MTR,TIM,AVL)
        REAL MTB,MTR,MTTF
C  IF CONSTANT HAZARD MODEL, DETERMINE TIME DEPENDENT AVAILABILITY
        IF (J .EQ. 1) THEN
           MTTF = MTB-MTR
           IF (MTTF .EQ. 0) MTTF = 1.
           AV1 = (1./MTR)/(1./MTTF+1./MTR)
```

```
        AV2=(1./MTTF)/(1./MTTF+1./MTR)*EXP(-(((1./MTTF)+(1./MTR))*TIM))
        AVL = AV1+AV2
      ELSE
C  IF NOT CONSTANT HAZARD MODEL, DETERMINE THE INHERENT OR
C  "STEADY-STATE" AVAILABILITY
      IF (J .NE. 1) THEN
        AVL = MTB/(MTB+MTR)
      ENDIF
      ENDIF
      RETURN
      END
C*****************************************************************
C  SUBROUTINE BUDGET DETERMINES IF BUDGET CONSTRAINT VIOLATED
C*****************************************************************
      SUBROUTINE BUDGET(NN,POL,CBUD,PPC)
      INTEGER CBUD(12)
      IF (POL .GT. FLOAT(CBUD(NN))) THEN
        PPC = ABS(FLOAT(CBUD(NN))-POL)
      ELSE
      IF (POL .LE. FLOAT(CBUD(NN))) THEN
        PPC = 0
      ENDIF
      ENDIF
      RETURN
      END
C*****************************************************************
C  SUBROUTINE REQ DETERMINES PERIOD REQUIREMENTS
C*****************************************************************
      SUBROUTINE REQ(STAT,POL,PU1,PU2,PU3,ZE,DE0,DE1,DE2,DE3,DE4,
     1NT,A,NREQ,OPT)
      CHARACTER STAT*6
      REAL POL,PU1(12,24),PU2(12,24),PU3(12,24),ZE(12,24),A
      INTEGER NT,NREQ,OPT,DE(12,24),B
      INTEGER DE0(12,24),DE1(12,24),DE2(12,24),DE3(12,24),DE4(12,24)
      B = IFIX(A)
        IF (POL .EQ. PU1(NT,B)) THEN
          OPT = 1
          NREQ = DE1(NT,B)
        ELSE
        IF (POL .EQ. PU2(NT,B)) THEN
          OPT = 2
          NREQ = DE2(NT,B)
        ELSE
        IF (POL .EQ. PU3(NT,B)) THEN
          OPT = 3
          NREQ = DE3(NT,B)
        ENDIF
        ENDIF
        ENDIF
        IF (STAT .EQ. 'GOOD' .AND. POL .EQ. ZE(NT,B)) THEN
          OPT = 0
          NREQ = DE0(NT,B)
        ELSE
        IF (STAT .EQ. 'FAILED' .AND. POL .EQ. ZE(NT,B)) THEN
          OPT = 4
```

```
              NREQ = DE4(NT,B)
          ENDIF
          ENDIF
      RETURN
      END
C******************************************************************
C  SUBROUTINE ZERO FILLS IN STREAM OUTPUT FILES WITH BLANKS IF THERE
C  ARE NO COMPUTED VALUES
C******************************************************************
      SUBROUTINE ZERO(NN,NZ,LL)
      INTEGER NN,LL,X,NZ
      X = 0
      IF (NN .EQ. 11 .AND. NN .EQ. NZ) GO TO 10
      IF (NN .EQ. 10 .AND. NN .EQ. NZ) GO TO 12
      IF (NN .EQ. 9 .AND. NN .EQ. NZ) GO TO 14
      IF (NN .EQ. 8 .AND. NN .EQ. NZ) GO TO 16
      IF (NN .EQ. 7 .AND. NN .EQ. NZ) GO TO 18
      IF (NN .EQ. 6 .AND. NN .EQ. NZ) GO TO 20
      IF (NN .EQ. 5 .AND. NN .EQ. NZ) GO TO 22
      IF (NN .EQ. 4 .AND. NN .EQ. NZ) GO TO 24
      IF (NN .EQ. 3 .AND. NN .EQ. NZ) GO TO 26
      IF (NN .EQ. 2 .AND. NN .EQ. NZ) GO TO 28
      IF (NN .EQ. 1 .AND. NN .EQ. NZ) GO TO 30
10    WRITE(LL+24,100) X,X,X,X,X,X,X
      GO TO 50
12    DO 13 I = 1, 2
      WRITE(LL+24,100) X,X,X,X.Y,X,X
13    CONTINUE
      GO TO 50
14    DO 15 I = 1, 3
      WRITE(LL+24,100) X,X,X,X,X,X,X
15    CONTINUE
      GO TO 50
16    DO 17 I = 1, 4
      WRITE(LL+24,100) X,X,X,X,X,X,X
17    CONTINUE
      GO TO 50
18    DO 19 I = 1, 5
      WRITE(LL+24,100) X,X,X,X,X,X,X
19    CONTINUE
      GO TO 50
20    DO 21 I = 1, 6
      WRITE(LL+24,100) X,X,X,X,X,X,X
21    CONTINUE
      GO TO 50
22    DO 23 I = 1, 7
      WRITE(LL+24,100) X,X,X,X,X,X,X
23    CONTINUE
      GO TO 50
24    DO 25 I = 1, 8
      WRITE(LL+24,100) X,X,X,X,X,X,X
25    CONTINUE
      GO TO 50
26    DO 27 I = 1, 9
      WRITE(LL+24,100) X,X,X,X,X,X,X
```

437

```
27      CONTINUE
        GO TO 50
28      DO 29 I = 1, 10
        WRITE(LL+24,100) X,X,X,X,X,X,X
29      CONTINUE
        GO TO 50
30      DO 31 I = 1, 11
        WRITE(LL+24,100) X,X,X,X,X,X,X
31      CONTINUE
50      X = 1
100     FORMAT(I1,1X,I1,1X,I1,1X,I1,1X,I1,1X,I1,1X,I1)
        RETURN
        END
```

APPENDIX B.5

OUTPUT EXEC

```
&TRACE OFF
EUDEXEC2
*****************************************************************************
*   NOTE:  DMS RUNS IN THE USER AREA.  OTHER USER AREA CMS COMMANDS
*          CANNOT BE ISSUED UNTIL DMS HAS BEEN TERMINATED.
*****************************************************************************
&PRESUME &SUBCOMMAND DISPLAY
&I = 1
&S = 1
*****************************************************************************
&LOOP 1 24
    &CALL -DISPLAY
&CALL -CLEANUP
&EXIT
*****************************************************************************
*    DISPLAY
*****************************************************************************
-DISPLAY
&SUBCOMMAND DISPLAY MSGMODE OFF
&SUBCOMMAND DISPLAY
&D1 =
        &PRESUME &COMMAND
        EXECIO 1 DISKR DATA OPTION A1 1 (FINIS
        &READ VAR &A1
        &K1 = &A1
        &PRESUME &COMMAND
        EXECIO 1 DISKR PRINT OPTION A1 1 (FINIS
        &READ VAR &A1
&IF &A1 = 1 &CALL -OUTPUT1
&IF &A1 = 2 &CALL -OUTPUT3
&IF &A1 = 3 &CALL -OUTPUT4
&SUBCOMMAND DISPLAY CURSOR &RCURSOR &RCURSOROFFSET
&RETURN
*****************************************************************************
*   OUTPUT1
*****************************************************************************
-OUTPUT1
&SUBCOMMAND DISPLAY MSGMODE OFF
*****************************************************************************
*   INITIALIZE PARAMETERS
*****************************************************************************
&G2 = 1
&G3 = 2
&G4 = 10
&G6 = 114
&G7 = 113
&G8 = 11
&G9 = 115
&G10 = 112
&G11 = 118
&G12 = 116
&G13 = 117
&F6 = 199
&F7 = 198
&F9 = 200
```

440

```
&F10 = 197
&F11 = 203
&F12 = 201
&F13 = 202
***********************************************************************
&PRESUME &COMMAND
&IF &K1 NE 2 &SKIP 2
&IF &K1 = 2 &IF &S = 5 &EXIT
    EXECIO 9 DISKR CASE&S OUTPUT A1 1 (FINIS
&IF &K1 = 2 &SKIP 1
    EXECIO 9  DISKR STREAM&S OUTPUT A1 1 (FINIS
    &READ VAR &A1
    &READ VAR &A2
    &READ VAR &A3
    &READ VAR &A4
    &READ VAR &A5
    &READ VAR &A6
    &READ VAR &A7
    &READ VAR &A8
    &READ VAR &A9
&G = 0
&H = 1
&LOOP -MOM 9
&H = &H + 1
&G = &G + 1
&D&H = &A&G
&IF &A3 = 0 &D4 = &STRING OF NO DATA AVAILABLE
&IF &A4 = 1 &D5 = &STRING OF CONSTANT
&IF &A4 = 2 &D5 = &STRING OF LINEARLY INCREASING
&IF &A4 = 3 &D5 = &STRING OF PIECE. LIN. BATH.
&IF &A4 = 4 &D5 = &STRING OF WEIBULL
&IF &A4 = 5 &D5 = &STRING OF EXPONENTIAL
-MOM
&IF &A3 NE 0 &SKIP 6
    &D5 =
    &D6 =
    &D7 =
    &D8 =
    &D9 =
    &D10 =
&SUBCOMMAND DISPLAY USE PANEL OUTPUT1
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &I = 2
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF3 &GOTO -OUTPUT1
&IF &A3 = 0 &GOTO -STREAM
&PRESUME &COMMAND
&IF &K1 NE 2 &SKIP 1
    EXECIO 38 DISKR CASE&S OUTPUT A1 10 (FINIS
&IF &K1 EQ 2 &SKIP 1
    EXECIO 38 DISKR STREAM&S OUTPUT A1 10 (FINIS
    &READ VAR &A10 &A11
    &READ VAR &A12 &A13
    &READ VAR &A14 &A15
```

```
        &READ VAR &A16 &A17
        &READ VAR &A18 &A19
        &READ VAR &A20 &A21
        &READ VAR &A22 &A23
        &READ VAR &A24 &A25
        &READ VAR &A26 &A27
        &READ VAR &A28 &A29
        &READ VAR &A30 &A31
        &READ VAR &A32 &A33
        &READ VAR &A34
        &READ VAR &A35 &A36 &A37 &A38 &A39 &A40 &A41
        &READ VAR &A42 &A43 &A44 &A45 &A46 &A47 &A48
        &READ VAR &A49 &A50 &A51 &A52 &A53 &A54 &A55
        &READ VAR &A56 &A57 &A58 &A59 &A60 &A61 &A62
        &READ VAR &A63 &A64 &A65 &A66 &A67 &A68 &A69
        &READ VAR &A70 &A71 &A72 &A73 &A74 &A75 &A76
        &READ VAR &A77 &A78 &A79 &A80 &A81 &A82 &A83
        &READ VAR &A84 &A85 &A86 &A87 &A88 &A89 &A90
        &READ VAR &A91 &A92 &A93 &A94 &A95 &A96 &A97
        &READ VAR &A98 &A99 &A100 &A101 &A102 &A103 &A104
        &READ VAR &A105 &A106 &A107 &A108 &A109 &A110 &A111
        &READ VAR &A112 &A113 &A114 &A115 &A116 &A117 &A118
        &READ VAR &A119
        &READ VAR &A120 &A121 &A122 &A123 &A124 &A125 &A126
        &READ VAR &A127 &A128 &A129 &A130 &A131 &A132 &A133
        &READ VAR &A134 &A135 &A136 &A137 &A138 &A139 &A140
        &PEAD VAR &A141 &A142 &A143 &A144 &A145 &A146 &A147
        &READ VAR &A148 &A149 &A150 &A151 &A152 &A153 &A154
        &READ VAR &A155 &A156 &A157 &A158 &A159 &A160 &A161
        &READ VAR &A162 &A163 &A164 &A165 &A166 &A167 &A168
        &READ VAR &A169 &A170 &A171 &A172 &A173 &A174 &A175
        &READ VAR &A176 &A177 &A178 &A179 &A180 &A181 &A182
        &READ VAR &A183 &A184 &A185 &A186 &A187 &A188 &A189
        &READ VAR &A190 &A191 &A192 &A193 &A194 &A195 &A196
        &READ VAR &A197 &A198 &A199 &A200 &A201 &A202 &A203
*************************************************************************
*  PRINT OUT STATE GOOD
*************************************************************************
-OUTPUT2
&D2 = &A&G2
&D3 = &A&G3
&D4 = &A&G4
&D5 = &A34
&D6 = &A&G6
&IF &A&G7 = 0 &D7 = K
&IF &A&G7 = 1 &D7 = P1
&IF &A&G7 = 2 &D7 = P2
&IF &A&G7 = 3 &D7 = P3
&IF &A&G7 = 4 &D7 = R
&D8 = &A&G8
&D9 = &A&G9
&D10 = &A&G10
&D11 = &A&G11
&D12 = &A&G12
&D13 = &A&G13
```

```
&IF &A&G10 NE 0 &SKIP 9
        &D5 = &STRING OF NO OUTPUT
        &D6 =
        &D7 =
        &D8 =
        &D9 =
        &D10 =
        &D11 =
        &D12 =
        &D13 =
&SUBCOMMAND DISPLAY USE PANEL OUTPUT2
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &I = &I + 1
&IF &RSTATUS = PF2 &GOTO -OUTPUT1
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF3 &GOTO -OUTPUT2
*********************************************************************
*   PRINT OUT STATE FAILED
*********************************************************************
&IF &A&G4 = 12 &GOTO -STREAM
&D5 = &A119
&D6 = &A&F6
&IF &A&F7 = 0 &D7 = K
&IF &A&F7 = 1 &D7 = P1
&IF &A&F7 = 2 &D7 = P2
&IF &A&F7 = 3 &D7 = P3
&IF &A&F7 = 4 &D7 = R
&D9 = &A&F9
&D10 = &A&F10
&IF &D10 = 0 &GOTO -INCREMENT
&D11 = &A&F11
&D12 = &A&F12
&D13 = &A&F13
&SUBCOMMAND DISPLAY USE PANEL OUTPUT2
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &I = &I + 1
&IF &RSTATUS = PF2 &GOTO -OUTPUT1
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF3 &GOTO -OUTPUT2
&IF &A3 = 0 &GOTO -STREAM
&IF &G4 = 12 &GO TO -STREAM
-INCREMENT
&G4 = &G4 + 2
&G6 = &G6 - 7
&G7 = &G7 - 7
&G8 = &G8 + 2
&G9 = &G9 - 7
&G10 = &G10 - 7
&G11 = &G11 - 7
&G12 = &G12 - 7
&G13 = &G13 - 7
&F6 = &F6 - 7
&F7 = &F7 - 7
```

```
&F9 = &F9 - 7
&F10 = &F10 - 7
&F11 = &F11 - 7
&F12 = &F12 - 7
&F13 = &F13 - 7
&GOTO -OUTPUT2
-STREAM
&S = &S + 1
&CALL -OUTPUT1
&RETURN
*************************************************************************
*   OUTPUT3
*************************************************************************
-OUTPUT3
&SUBCOMMAND DISPLAY MSGMODE OFF
&PRESUME &COMMAND
&IF &K1 NE 2 &SKIP 1
   EXECIO 168 DISKR CASE SUMMARY A1 1 (FINIS
&IF &K1 = 2 &SKIP 1
   EXECIO 168 DISKR STREAM SUMMARY A1 1 (FINIS
   &READ VAR &Z1
   &READ VAR &Z2
   &READ VAR &Z3
   &READ VAR &Z4
   &READ VAR &Z5
   &READ VAR &Z6
   &READ VAR &Z7
   &READ VAR &Z8
   &READ VAR &Z9
   &READ VAR &Z10
   &READ VAR &Z11
   &READ VAR &Z12
   &READ VAR &Z13
   &READ VAR &Z14
   &READ VAR &Z15
   &READ VAR &Z16
   &READ VAR &Z17
   &READ VAR &Z18
   &READ VAR &Z19
   &READ VAR &Z20
   &READ VAR &Z21
   &READ VAR &Z22
   &READ VAR &Z23
   &READ VAR &Z24
   &READ VAR &Z25
   &READ VAR &Z26
   &READ VAR &Z27
   &READ VAR &Z28
   &READ VAR &Z29
   &READ VAR &Z30
   &READ VAR &Z31
   &READ VAR &Z32
   &READ VAR &Z33
   &READ VAR &Z34
   &READ VAR &Z35
```

```
&READ VAR &Z36
&READ VAR &Z37
&READ VAR &Z38
&READ VAR &Z39
&READ VAR &Z40
&READ VAR &Z41
&READ VAR &Z42
&READ VAR &Z43
&READ VAR &Z44
&READ VAR &Z45
&READ VAR &Z46
&READ VAR &Z47
&READ VAR &Z48
&READ VAR &Z49
&READ VAR &Z50
&READ VAR &Z51
&READ VAR &Z52
&READ VAR &Z53
&READ VAR &Z54
&READ VAR &Z55
&READ VAR &Z56
&READ VAR &Z57
&READ VAR &Z58
&READ VAR &Z59
&READ VAR &Z60
&READ VAR &Z61
&READ VAR &Z62
&READ VAR &Z63
&READ VAR &Z64
&READ VAR &Z65
&READ VAR &Z66
&READ VAR &Z67
&READ VAR &Z68
&READ VAR &Z69
&READ VAR &Z70
&READ VAR &Z71
&READ VAR &Z72
&READ VAR &Z73
&READ VAR &Z74
&READ VAR &Z75
&READ VAR &Z76
&READ VAR &Z77
&READ VAR &Z78
&READ VAR &Z79
&READ VAR &Z80
&READ VAR &Z81
&READ VAR &Z82
&READ VAR &Z83
&READ VAR &Z84
&READ VAR &Z85
&READ VAR &Z86
&READ VAR &Z87
&READ VAR &Z88
&READ VAR &Z89
&READ VAR &Z90
```

```
&READ VAR &Z91
&READ VAR &Z92
&READ VAR &Z93
&READ VAR &Z94
&READ VAR &Z95
&READ VAR &Z96
&READ VAR &Z97
&READ VAR &Z98
&READ VAR &Z99
&READ VAR &Z100
&READ VAR &Z101
&READ VAR &Z102
&READ VAR &Z103
&READ VAR &Z104
&READ VAR &Z105
&READ VAR &Z106
&READ VAR &Z107
&READ VAR &Z108
&READ VAR &Z109
&READ VAR &Z110
&READ VAR &Z111
&READ VAR &Z112
&READ VAR &Z113
&READ VAR &Z114
&READ VAR &Z115
&READ VAR &Z116
&READ VAR &Z117
&READ VAR &Z118
&READ VAR &Z119
&READ VAR &Z120
&READ VAR &Z121
&READ VAR &Z122
&READ VAR &Z123
&READ VAR &Z124
&READ VAR &Z125
&READ VAR &Z126
&READ VAR &Z127
&READ VAR &Z128
&READ VAR &Z129
&READ VAR &Z130
&READ VAR &Z131
&READ VAR &Z132
&READ VAR &Z133
&READ VAR &Z134
&READ VAR &Z135
&READ VAR &Z136
&READ VAR &Z137
&READ VAR &Z138
&READ VAR &Z139
&READ VAR &Z140
&READ VAR &Z141
&READ VAR &Z142
&READ VAR &Z143
&READ VAR &Z144
&READ VAR &Z145
```

```
      &READ VAR &Z146
      &READ VAR &Z147
      &READ VAR &Z148
      &READ VAR &Z149
      &READ VAR &Z150
      &READ VAR &Z151
      &READ VAR &Z152
      &READ VAR &Z153
      &READ VAR &Z154
      &READ VAR &Z155
      &READ VAR &Z156
      &READ VAR &Z157
      &READ VAR &Z158
      &READ VAR &Z159
      &READ VAR &Z160
      &READ VAR &Z161
      &READ VAR &Z162
      &READ VAR &Z163
      &READ VAR &Z164
      &READ VAR &Z165
      &READ VAR &Z166
      &READ VAR &Z167
      &READ VAR &Z168
-PERIOD1
&D2 = &Z13
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 13
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD2
&IF &RSTATUS = PF2 &GOTO -PERIOD1
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD1
-PERIOD2
&D2 = &Z26
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
```

```
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 26
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD3
&IF &RSTATUS = PF2 &GOTO -PERIOD1
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD2
-PERIOD3
&D2 = &Z39
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 39
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD4
&IF &RSTATUS = PF2 &GOTO -PERIOD2
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD3
-PERIOD4
&D2 = &Z52
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 52
&K = 2
```

```
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = O &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD5
&IF &RSTATUS = PF2 &GOTO -PERIOD3
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD4
-PERIOD5
&D2 = &Z65
&J = O
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = O &D&K =
-STR1
&J = 65
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = O &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD6
&IF &RSTATUS = PF2 &GOTO -PERIOD4
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD5
-PERIOD6
&D2 = &Z78
&J = O
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = O &D&K =
-STR1
&J = 78
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = O &D&K =
```

```
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD7
&IF &RSTATUS = PF2 &GOTO -PERIOD5
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD6
-PERIOD7
&D2 = &Z91
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 91
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD8
&IF &RSTATUS = PF2 &GOTO -PERIOD6
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD7
-PERIOD8
&D2 = &Z104
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 104
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD9
```

```
&IF &RSTATUS = PF2 &GOTO -PERIOD7
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD8
-PERIOD9
&D2 = &Z117
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 117
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD10
&IF &RSTATUS = PF2 &GOTO -PERIOD8
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD9
-PERIOD10
&D2 = &Z130
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 130
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD11
&IF &RSTATUS = PF2 &GOTO -PERIOD9
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD10
-PERIOD11
&D2 = &Z143
```

```
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 143
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &GOTO -PERIOD12
&IF &RSTATUS = PF2 &GOTO -PERIOD10
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD11
-PERIOD12
&D2 = &Z156
&J = 0
&K = 1
&LOOP -STR1 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR1
&J = 156
&K = 2
&LOOP -STR2 12
&J = &J + 1
&K = &K + 2
&D&K = &Z&J
&IF &Z&J = 0 &D&K =
-STR2
&SUBCOMMAND DISPLAY USE PANEL OUTPUT3
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS = PF1 &EXIT
&IF &RSTATUS = PF2 &GOTO -PERIOD11
&IF &RSTATUS = PF3 &EXIT
&IF &RSTATUS NE PF1 &IF &RSTATUS NE PF2 &IF &RSTATUS NE PF3 &GOTO -PERIOD12
&RETURN
**********************************************************************
*  OUTPUT4
**********************************************************************
-OUTPUT4
&SUBCOMMAND DISPLAY MSGMODE OFF
&PRESUME &COMMAND
```

```
&IF &K1 NE 2 &SKIP 1
       EXECIO 16 DISKR DEMO SUMMARY A1 1 (FINIS
&IF &K1 = 2 &SKIP 1
       EXECIO 16 DISKR POP SUMMARY A1 1 (FINIS
       &READ VAR &L1
       &READ VAR &L2
       &READ VAR &L3
       &READ VAR &L4 &L5
       &READ VAR &L6 &L7
       &READ VAR &L8 &L9
       &READ VAR &L10 &L11
       &READ VAR &L12 &L13
       &READ VAR &L14 &L15
       &READ VAR &L16 &L17
       &READ VAR &L18 &L19
       &READ VAR &L20 &L21
       &READ VAR &L22 &L23
       &READ VAR &L24 &L25
       &READ VAR &L26 &L27
       &READ VAR &L28
&J = 0
&K = 1
&LOOP -POP 28
&J = &J + 1
&K = &K + 1
&D&K = &L&J
-POP
&SUBCOMMAND DISPLAY USE PANEL OUTPUT4
&SUBCOMMAND DISPLAY DISPLAY
&WPOS = &POSITION OF &RSTATUS ENTER PF1 PF2 PF3 PF4 PF5 PF6 PF7 PF8 PF9 PF10
&IF &RSTATUS NE PF3 &GOTO -OUTPUT4
&IF &RSTATUS = PF3 &EXIT
************************************************************************
*  CLEAR VARIABLES
************************************************************************
-CLEAR
&C = 1
&LOOP -VAR 220
&C = &C + 1
&D&C =
-VAR
&RETURN
************************************************************************
*  TERMINATE - RESTORE ENVIRONMENT
************************************************************************
-CLEANUP
CLEAR NEXT
&RETURN
************************************************************************
```

453

The vita has been removed from
the scanned document