A MATHEMATICAL MODEL FOR
MAINTENANCE SCHEDULING AND
BUDGETING OF AN OFF-HIGHWAY
TRUCK HAULAGE SYSTEM

By

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ABSTRACT

The performance of engine modules is the most important factor affecting the reliability of an off-highway truck haulage system. Therefore, engine replacement and maintenance policies have a major influence on truck fleet size and engine standby redundancy for given production requirements.

The mathematical model presented in this thesis deals with the optimization of the maintenance and replacement policies of engine modules in a truck haulage system under varying production requirements.

Net present value of costs per ton hauled associated with a given policy is used as the evaluation criteria.

Fleet ownership cost, engine maintenance cost and engine replacement cost are estimated for each policy. The effect of a given policy on the economics of the entire system is evaluated based on these costs.

The model separates downtime due to truck repairs from that due to engine repairs and classifies the engine repair time into three categories: rebuilds, major repairs and minor repairs. Time lost due to reasons not related to mechanical failure is considered separately.

Each of the downtime groups considered is modeled by an adequate probabilistic or deterministic function and
the system's operation is simulated using a FORTRAN-IV computer program which evaluates all alternative policies following a selected search strategy. The program also generates a quarterly schedule of fleet size, engine standby requirements and costs over the time period considered.

The model can be applied to optimize the engine replacement and maintenance policies and also to schedule fleet requirements, maintenance cost and capital expenditures once an optimum policy has been selected.

The model was applied to the analysis of a truck fleet composed of fifteen 100-ton trucks hauling ore at an open pit mine. The results of the analysis showed that the engine replacement policy significantly affects the system's productive capacity thus affecting the number of trucks and standby engines required for given production requirements.
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I. INTRODUCTION

General

During the last decades, the mining industry has faced the challenge of mining orebodies of increasingly marginal grade where the profitability of the operation is no longer inherent to the quality of the ore but depends on productivity and efficiency.

Daily tonnages have become enormous and the materials handling systems have evolved, within a few years, from manual operation to total automation. As a consequence maintenance costs have become the largest single unit cost and hence a key to profitability.

In the case of truck haulage systems, the evolution has been impressive. The first truck expressly designed for open pit mining was introduced during the 1930's (Burton, 1975), it hauled 15 tons and was no more than a standard highway truck adapted to heavy-duty continuous operation. By the mid 1950's maximum size had reached 60 tons but popular sizes were in the 25 to 30 ton range. Power transmissions were of standard highway type, double power trains were required and thus, tire costs were high.

Today, off-highway haulage trucks can carry up to 350 tons and a common size is in the 150-200 ton range. The electric drive has almost entirely taken over mechanical transmissions in trucks with payload above the 100-ton
level. Tires and boxes are specially designed for each particular duty, and high speed diesel engines in the 700-1000 BHP range have increased performance and decreased the weight to payload ratio.

Today management can no longer afford to ignore or disregard the efficiency and costs of multi-million dollar truck fleets which normally account for 50% of total mining costs (Burton, 1975). Proper information is now required in order to make sure that haulage costs are kept as low as possible.

Importance of the Problem

As mentioned in the previous section, Maintenance cost in modern off-highway trucks amounts to 45-55% of total ownership and operating costs. Moreover, the relative importance of maintenance costs with respect to total costs tends to increase as trucks become larger.

Table 1 shows the relative importance of several cost components on total truck maintenance costs. About 35% of the total corresponds to tire costs. The engine's maintenance accounts for 21% and the maintenance of the remaining components accounts for 25% of total costs.

Mutmansky (1968) studied the maintenance policies for tires and concluded that in the normal case, the optimum policy is the replacement at failure only. This means that tire costs can only be decreased by decisions external to the system such as road improvement and proper operation.
TABLE 1: Relative importance of truck maintenance cost components.

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<th>COST ACCOUNT</th>
<th>% OF TOTAL MAINTENANCE COST</th>
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<td>Engine module</td>
<td>21 %</td>
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<tr>
<td>Fuel and lube</td>
<td>19 %</td>
</tr>
<tr>
<td>Tires</td>
<td>35 %</td>
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<td>Other maintenance</td>
<td>25 %</td>
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The maintenance of truck elements other than the engine can be studied as if they were independant systems since their individual reliability has little influence on the overall reliability of the truck fleet. In this case it can be assumed that the optimal maintenance policy for a given element depends only on its own characteristics and is independant of the rest of the system.

Engine maintenance and replacement can only be properly studied within the truck haulage system taking into consideration the following factors:

i) When a major engine failure occurs, the engine has to be exchanged. Thus, the reliability of engines has a significant effect on the number of spare engines required and hence, on the overall economics of the system.

ii) Engine deterioration has an important effect on the system's mechanical availability and hence, on its output.

iii) Engine reliability and fleet ownership cost per
tion are interdependant whenever the fleet operates under a minimum production constraint. An excessively high engine retirement age causes an increase of fleet size to meet production or an increase in the number of spare engines required or both, thus increasing fleet ownership cost.

iv) Rebuilt engines are never as reliable as new engines and rebuild cost may amount to 50% of the costs of a new engine, thus the rebuild vs. buy alternative requires a very close analysis.

v) Another important problem is to decide whether to rebuild engines in the company's shop or to contract the work with an outside specialist and how to evaluate in economical terms the bids of two different contractors, and select the best, using engine performance records.

Purpose And Scope of the Thesis

The purpose of this work is to solve the problem of engine replacement and maintenance in such a manner as to produce valid answers to the problems outlined in the previous section. To achieve that purpose, the problem must be formulated considering the engine as a part of a truck fleet system under production requirement constraints.

The scope of the work can be formulated as follows:

1) To determine the optimum engine replacement and major repair policies.

2) To determine the size of the truck fleet and the number of spare engines required through time for a given engine
maintenance and replacement policy.

3) To obtain a capital investment schedule for trucks and engines and forecast maintenance costs and mechanical availability for a given policy.

Since the application of the model requires the use of machine computation a computer program (written in FORTRAN IV language) was developed. The listing of the program and related documentation is presented in Appendix A.

As a result of the study, a method for recording operation and maintenance data will be outlined in Appendix B.
II. THE PREVENTIVE MAINTENANCE PROBLEM: THEORY AND PRACTICE

The Theory of Reliability

The problem of establishing maintenance and replacement policies can be properly solved only by studying the behavior of equipment with respect to failure. Intuition and past experience may lead to costly practice and yet not achieve any practical purpose.

The theory of reliability was initially developed to study failure patterns of complex electronic systems used in aeronautics, but soon its scope was broadened to cover the entire range of industrial applications.

Polovko (1968) defines reliability as the ability of equipment to preserve its output characteristics through time. Any electro-mechanical system has many different failure modes, each related to some element of the system and hence the reliability of a complex system is a function of the probability of occurrence of all possible failure modes.

Failure can be defined as an event after whose occurrence the output characteristics of equipment shift outside permissible limits, Polovko (1968).

Failure has been classified in many different ways throughout the literature: instantaneous or gradual, relating
to the mode of development; dependant or independant, relating to whether or not it results in the failure of the system. In reliability theory only those events leading to a loss of performance are considered as failures. Events not affecting the performance of the system are referred to as malfunctions.

The Measurement of Reliability

Reliability can be quantified by several mathematical functions. In general, it is not possible to characterize the reliability of a system by means of a single mathematical expression and a combination of two or more is required.

A complete discussion of the different methods for the measurement of reliability can be found in any general text-book on the field. Here only those methods of special interest in relation to this thesis will be described.

**Probability of Failure.** \( f(t) \).

The probability of failure is defined as the probability that a device put into service at time \( t=0 \) will fail at time \( t \), where:

\[
f(t) = \begin{cases} 
\lim_{t \to 0} \frac{P(t < T < t + \Delta t)}{t} & \text{for } t > 0 \\
0 & \text{for } t < 0
\end{cases}
\]
The function $f(t)$ is referred to as failure density function.

Of more common application than $f(t)$ are the cumulative probability functions $F(t)$ and $R(t)$, where:

$$F(t) = P(T \leq t) = \int_0^t f(u) \, du$$

$$R(t) = P(T > t) = 1 - F(t)$$

$F(t)$ is referred to as probability of failure and also, hazard function. The function $R(t)$ is called probability of failure-free operation, survival function and sometimes reliability function.

**Failure Rate $r(t)$.**

The failure rate can be defined as the ratio of the number of failed devices per unit time to the average number of surviving devices at a given time. When the failure rate is computed for systems not subject to repair or replacement (each device operates until failure only), then the value of $r(t) \, dt$ is the conditional probability that a device will fail in the interval $dt$ after time $t$ given that it survived until then.

The failure rate is related to the failure and survival functions by the following expression:

$$r(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)}$$
Typically, the failure rate function has the shape shown in Fig. 1. Three distinct regions can be defined. Between times 0 and $t_1$ it is a decreasing function of time (burn-in period) since at time $t=0$ the probability of failure caused by manufacturing defects is relatively high and decreases rapidly as operation goes on. Between $t_1$ and $t_2$ the function can either be increasing, decreasing or monotone depending on the type of device. This period is referred to as the normal operation period and its duration is 90% of the device life or greater. Beyond $t_2$ the failure rate sharply increases due to the increasing probability of wear-out failures (wear-out period).

The shape of $r(t)$ in the normal operation region is extremely significant in failure analysis since it determines the type of mathematical model which is more appropriate to characterize reliability. It also indicates whether or not replacement policies based on age are indicated.

Monotone failure rate systems, are those where the probability of failure does not change with time, thus they can be represented by the exponential probability law since $r(t) = \lambda = \text{cte}$. 

$$F(t) = 1 - e^{-\int_0^t r(t) \, dt} = 1 - e^{-\lambda t}$$

When the failure rate is not assumed to be constant, other
FIGURE 1: Time regions of the failure rate function.
probability functions should be used to characterize reliability. In APPENDIX C, a discussion of the most significant and widely applied failure models, is presented.

For 'Aging' systems (IFR), age replacement would probably result in substantial savings, since the reliability of the system, and hence, the system's output, would be increased. Moreover, the cost of a planned repair is frequently lower than the cost of repairs performed at failure.

In most practical problems, the burn-in period is not considered since its duration and relative significance is small. However, in some cases where maximum accuracy is required, the entire life span of the system must be modeled and more sophisticated failure models are necessary (see APPENDIX C).

Maintainability.— In its conceptual meaning, Gnedenko et al (1969) define maintainability of a device as its susceptibility to prediction, discovery and elimination of failures.

Maintainability can be characterized by the probability of repair function \( G(t) \). The value of the probability of repair function is the probability that a device or equipment which went down for repair at time \( t = 0 \), will be repaired before time \( t \).
Then: \[ G(t) = P(T < t) \]

where \( T \) is the repair time.

The repair function \( G(t) \), together with the function \( F(t) \) can fully characterize the reliability of systems assuming no deterioration. When deterioration exists, the failure rate would also have to be studied.

**Availability.** \( A(t) \). The availability function is the basic characteristic of reliability for complex systems under long-term operation subject to renewal. It is defined as the probability that the system will be functioning at an instant \( t \) after it went into service.

Availability is probably the only function that can fully characterize reliability but in most industrial applications it cannot be obtained explicitly, except for the case of exponential models for both failure and repair functions.

Most often in the literature, availability is defined as the steady-state behavior of \( A(t) \) and denoted by the availability coefficient \( K_a \) where:

\[
K_a = \lim_{t \to \infty} A(t)
\]

Shooman (1968) and other authors have shown that:

\[
K_a = \frac{T_1}{T_1 + T_2}
\]
where $T_1$ and $T_2$ are the mean time to failure and the mean repair time, respectively.

For exponential failure and exponential repair, the availability coefficient is expressed as follows:

$$K_a = \frac{T_1}{T_1 + T_2} = \frac{1/\lambda}{1/\lambda + 1/\mu} = \frac{\mu}{\mu + \lambda}$$

where $\lambda$ and $\mu$ are the constant failure and repair rates.

However, for complex systems under deterioration, operating for a finite time span (as is the case of an off-highway truck), the availability function $A(t)$ may not reach a steady-state constant value within the life span of the system and hence, the coefficient $K_a$, as defined above, may not exist.

Later in Chapter IV, the concept of "average availability rate" will be defined for complex systems under discrete deterioration, as the average availability rate of the system over a given time interval $\Delta t$, after $t$ hours of operation.

**The Renewal Process of a Complex System**

Most of the theoretical developments found by the author in the field of renewal processes are based on the assumption that the system does not deteriorate. Under this assumption, replacement and repair are equivalent terms since the repaired equipment are considered as good as new.

Mathematically, the above assumption implies that the
failure and repair functions $F(t)$ and $G(t)$ are invariants of the system throughout its economical life span. Hence, the probability of a failure after the system has failed $(n - 1)$ times is obtained in terms of an integral equation relating the Laplace transforms of $F(t)$ and $G(t)$ which can be solved either explicitly or using numerical analysis (Barlow and Proschan, 1965).

Unfortunately, most of the industrial applications and in particular mine transportation systems, have to deal with deterioration due to the economic limitations of preventive maintenance and the complexity of the systems themselves.

Some complex systems under deterioration can be studied as a stochastic Markov process. In a Markov process, the system is characterized by a finite or infinite number of possible states and it is assumed that the future course of the system depends only on its state at present (Markovian property).

Under the Markovian assumption, a system can be described by its initial state and the set of probabilities $P_{ij}(t)$ (transition probability matrix) defining the probability that the system being at state $i$ at time $t$ will be at state $j$ in the next time step, where:

$$\sum_j P_{ij}(t) = 1$$
A complete treatment of the theory of Markov Processes can be found in Kemeny and Snell (1960) and Bharucha-Reid (1960). Because of the many difficulties involved with analytical techniques, stochastic simulation will be used in this thesis. The main reason for the use of simulation is that it makes it possible to overcome difficult analytical problems without seriously diminishing the practical usefulness of the model with unrealistic or highly restricting assumptions. Furthermore, the use of simulation is also justified in this case by the wide and ambitious scope of the problem to be dealt with.

The objectives of this thesis are:

i) To develop a method through which an optimal engine replacement and maintenance policy for an off-highway truck system may be obtained.

ii) To obtain the time schedule of expected capital expenditures and maintenance costs, and;

iii) To obtain estimated truck and engine requirements through time.

The above objectives are formulated within a system where production requirements and average truck cycle time are considered as time-dependent variables and deterioration is assumed.

Thus, the system considered here cannot be studied as an stationary process (which would be required for the application of the Markov theory), nor by any other analytical method of the reliability theory, unless severe restrictions
Optimum Maintenance And Replacement Policies

It is a fact in most of the mechanical systems under continuous operation and deterioration that unexpected failures are more costly in time and money than scheduled repairs.

In the mining industry, individual systems performing specific functions, such as haulage, crushing, loading, etc., are linked in series or parallel series and it is common that the failure of a link implies the interruption of the entire mining operation.

Through the knowledge of the operating characteristics of the system, its failure pattern and its boundary constraints competing maintenance policies can be evaluated and ranked according to a suitable merit function, selecting that of maximum merit.

The method of evaluation and the merit function to be used are the two main decisions to be made when optimizing a maintenance policy.

The selection of the method of evaluation requires, among others the following considerations:

1. Failure Characteristics.— A failure model must be chosen for each failure mode. It is necessary to use historical records of failure to determine the appropriate model. The selection of an adequate probability function to characterize a failure pattern should be based on the
analysis of the failure rate function (increasing, monotone, or decreasing), the requirements of the model and the availability and quality of failure data (see Appendix C).

2) **Type of Maintenance Policy.** - Three main types of maintenance policies are described in the literature:

   a) Age Replacement. - Under age replacement, a unit is repaired or replaced at the time of failure or after T hours of failure-free operation. This policy is the most widely used for cases of IFR under strictly economical considerations. A particular type of age replacement, the random age replacement, replaces a unit at failure or at T hours where T is a random variable chosen from a fixed distribution.

   b) Block Replacement. - Under block replacement all components of a given type are replaced simultaneously at fixed intervals of time or at failure, whichever comes first. This policy is used for IFR systems whenever reliability is the dominant optimization criteria. Such is the case of computer systems and electronic control systems where the greatest part of failure cost is not due to repair but to the interruption of service.

   c) Opportunistic Replacement. - Under this type of policy, which is applied to systems of several units where some can be periodically monitored and some cannot, the replacement of the unmonitored units depends on the state of those units under surveillance (failed or operational states) and the age of the unmonitored units at the moment of inspection.
3) Merit Function.- The merit function is the objective or evaluation criterion under which competing policies are compared.

The most frequently used merit functions are those optimizing the expected economical benefits. Among them:
- Total expected cost through a finite time span
- Unit cost through an infinite time span
- Net present value of costs

In other cases maximum reliability is the objective with or without economical constraints. Such is the case in some electronic systems where safety considerations are dominant.
III. A REVIEW OF RELATED STUDIES

The literature relating to reliability is quite voluminous but it is a difficult task to find references on its application to transportation and materials handling systems. Most of the applied work has been devoted to the field of electronics and other fields where reliability is a must due to both economics and safety considerations. In the field of mine systems the references are almost non-existent and those found are devoted to the description of good maintenance practice rather than to the development of optimum maintenance models.

However, the author has found that a rather large number of mining companies have reported using Operations Research (OR) to analyze their maintenance. Milton (1972) made a survey of 47 mining companies and he concluded that 24 of them were currently using OR and computer data processing in their maintenance problems and that maintenance was the third largest field of applied OR in the mining industry. This situation, in the author's opinion, is the result of a remarkable divorce between industry and university where the former is reluctant to release failure information for independent studies and to publish the results of the work made by their staff. Fortunately there are exceptions to the rule and, in the author's case, a mining company made available the historical records which made this thesis possible.
General Mining Maintenance

Robinson (1975) describes the techniques used at the Iron Ore Co. of Canada for maintenance scheduling and inventory control. An article by Caterpillar Tractor Co. (1970) compares company versus contracted maintenance on cost and quality bases. A complete analysis of current mine maintenance practice was published by Coal Age Magazine (Oct, 1975) dealing with both open pit and underground equipment lubrication, shop organization and preventive maintenance. Hanks (1961) emphasizes the importance of sound maintenance practices, planning and inspection, for the performance of mobile equipment. Hillebrand (1960) deals specifically with the maintenance of continuous miners.

Other articles emphasize the importance of keeping proper failure records and present methods to obtain the maximum amount of information from their analysis, Greer (1960), Hanks (1961) and anonymous (1963).

Whiton (1975) deals in his article with programmed maintenance as a means to increase productivity, and points out the savings that can be achieved by reusing lubricants.

Mining Equipment Replacement Analysis

Gentry and Johnson (1974) thoroughly analyze the financial aspects of equipment replacement. In this paper the replacement problem is considered as an investment problem where all possible investment alternatives are compared on the basis of net present value or Internal Rate of Return (DCF-ROI) or Profitability Index (PI).
Mutmansky (1968) applies reliability theory to the problem of tire replacement in off-highway truck systems using expected hourly cost as the evaluation criterion. He also suggests the general applicability of the model to the replacement analysis of any other equipment in the system.

Clapham (1957) develops a cost model to determine the optimum economic life of mine transportation equipment.

Optimum Truck Fleet Size

One of the early applications found for simulation to a mining problem is the determination of the optimum number of trucks required to meet production requirements. Probably most of the open pit mining companies have developed or used simulation models to solve this problem but only a few of them have been published. Westinghouse Air Brake Co. and Caterpillar Tractor Co. have developed their own computer programs and provide them as a service to customers.

Deshmuck (1970) develops a simulation model to compare unit cost for several truck-shovel combinations. Burton (1975) presents a similar approach to the problem.

Other Related Literature

The literature dealing with maintenance is rather voluminous. Here, some works related to the scope of this thesis are referenced.
Morse (1958) studied the optimization of age replacement policies minimizing the expected cost per unit time through an infinite time span. Derman (1961) deals with the same problem but uses a linear programming approach and defines the conditions for which an optimum exists.

Howard (1960) and Blackwell (1962) approach the renewal problem using the theory of Markov Chains and discounted net present value of expected unit costs as an objective function.

McCall (1965) and Jorgenson et al. (1967) present a comprehensive review of different replacement policies and maintenance optimization methods.

Flehinger (1962) analyses the reliability of systems under various replacement policies with special emphasis on block and random age replacement policies. Jorgenson and Radner (1965) deal with the optimization of opportunistic replacement policies.

Barlow and Proschan (1965) develop a method for the determination of the optimum number of spare units which maximizes the expected increase in reliability per dollar spent and show the application of their model to series and parallel systems operating under constraints.

In the field of financial modeling of equipment replacement Rathbun (1971) defines the "Return on Investment Index (ROI)" as the discount rate for which the discounted annual machine cost for two different equipment alternatives are equal, and proposes the use of ROI to determine the optimum replacement age and for the selection of the exchange unit among several
possible alternatives.

Finally, several textbooks on the general theory of reliability will be referenced.

Barlow and Proschan (1965) present a comprehensive analysis of the renewal process and a complete mathematical development of reliability of exponential failure models.

Gnedenko et al (1969) present the fundamentals of reliability theory from a practical point of view including a description of data collection and model fitting methods and tests of hypothesis and a chapter on industrial quality control as well as a useful set of tables in an appendix.

Polovko (1968) presents a comprehensive text on reliability theory, from the basic definition of the science to the analysis of sophisticated systems and a complete list of references, most of them from the Russian School.
IV. THE MATHEMATICAL MODEL

The model developed in this thesis can be classified as semistochastic and its main objective is two fold: (1) To determine the best engine maintenance policy for an off-highway truck system and (2) To develop a time schedule of truck fleet size, engine standby requirements and expected costs for a given engine maintenance policy throughout the time period considered. Other potential uses are:

i) To provide the means for the comparison of several engine maintenance alternatives.

ii) To help management on the preparation of the investment and operating costs budgets.

iii) To provide a method which can take advantage of the historical records of operation and maintenance as feed back for continuous policy improvement.

Definition of the System

The system considered by the model is an off-highway truck haulage fleet composed of several trucks of the same characteristics and capacity and the corresponding engine-modules (operating and spare). The system is assumed to be in operation and subject to varying production requirements.

When studying engine maintenance and replacement policies, the engines have to be considered as a part of a
truck fleet under some production constraints. Otherwise, an erroneous policy decision may be made by disregarding the effect of engine deterioration on the expected number of trucks and engines required to meet the production constraints.

An early engine retirement policy might be considered too costly if only engine cost was used for the analysis, but when the total ownership and operating costs of the fleet are included, such a policy may prove to be optimal.

In Figure 2, a general flow-chart of the mathematical model is shown. Major engine failures (requiring the rebuild or major repair of the engine) are characterized individually by probabilistic submodels while minor failures and service downtime is estimated by least square methods.

The repair time models for major engine failures are stochastic, and characterized by the truncated-exponential function.

The repair costs for both major and minor repairs are also considered to be truncated-exponential random variables. For major repairs, the random variable is the cost of a single repair, and planned repair costs are assumed to belong to a population different than that of costs of repairs performed after failure. For minor repair costs, the random variable is the cost per hour of downtime resulting from minor repairs or service.

The initial state of the system is characterized by the ages of the trucks and the engines composing the
FIGURE 2: General Flow-Chart of the Model

**GENERAL PARAMETERS**
- Initial fleet data
- Production schedule
- Average cycle time schedule
- Cost data
- Financial data
- Operation data
- Simulation period

**MINOR ENGINE FAILURE MODEL PARAMETERS**
Deterministic least square model:
\[ EAV_{i}^{'} = \text{Exp}(\text{-}K_{1} - K_{2}T_{i}) \]
\[ EAV_{i}^{'} = \text{Availability for period } i \]
\[ T_{i} = \text{Engine age(average)} \]

**TRUCK FAILURE AND SERVICES MODEL PARAMETERS**
Deterministic least square model:
\[ TAV_{i}^{'} = \text{Exp}(\text{-}K_{1} - K_{2}T_{i}) \]
\[ TAV_{i}^{'} = \text{Availability for period } i \]
\[ T_{i} = \text{Truck age(rage)} \]

**DEFINE INPUT AND OUTPUT FILES**

**INITIALIZE**

**MAJOR ENGINE FAILURE MODEL PARAMETERS**
- Wear-out failure: Weibull
- Chance failure: Exponent
  (The model assumes discrete deterioration after each rebuild)

**INPUT : MODEL PARAMETERS**

**DEFINE POLICY, Engine replacement and major repair policies**

**SIMULATION AND POLICY EVALUATION**

**OUTPUT: System schedule by quarters:**
- Fleet size(trucks & engines)
- Truck & Engine purchase
- Rebuilds & Major repair
- System's renewal and maintenance budget

**LAST POLICY?**

**OUTPUT: Policy evaluation**
- Truck requirements
- Engine standby required
- Expected no. of repairs
- Expected availability
- Unit NPV of costs: Truck and engine purchase, engine rebuild, major repair.

**STOP**
T-1826

Initial fleet and the number of rebuilds already performed on each engine.

The length of the simulation period, and the parameters of the operation (truck capacity, utilization, etc.) are also considered in the model.

The future production requirements and average truck cycle time are input to the model as a quarterly schedule throughout the time period considered.

The parameters required by the model to evaluate the cost of maintenance and replacement for a given policy are the following:

- Truncated-exponential parameters of the repair cost models.
- Average delivery price of trucks and engines at the beginning of the simulation period.
- Average inflation rate for purchases and repair cost
- Truck salvage value and depreciable life.
- Firm's cost of capital

The Replacement Policies

The replacement policies to be applied to the engines are basically 'age replacement'. However, several differences with respect to the standard age replacement are introduced in order to account for common mining practices. The major modifications are:

1. Engines are retired from service at the moment the first major failure occurs after retirement age has been
reached, and hence a random component is added to the nominal age (random age replacement).

2. When an engine is retired from service, it is not replaced by a new purchase unless the system's production requirements make it necessary. Otherwise the engine is replaced with a used standby unit.

Trucks are retired independent of engines according to the standard age replacement policy, but when a truck is purchased, an engine is assumed to be included.

Types of Failures

Three different types of failures are considered in the model, depending on causes, importance and type of decision required after its occurrence.

1. Major Wear-out Failures.— Are those failures related to a generalized wear-out of most or all of the engines major elements (pistons, liners, bearings, etc.). This type of failure requires a complete engine rebuild and the exchange of the engine. Although wear-out failures are caused by the failure of one or a few internal elements, the inspection of the remaining major elements (its state of wear), will indicate whether or not a rebuild is required.

2. Major Chance Failures.— Their cause is generally related to chance and they normally affect one or several major internal parts while the state of wear of the unfailed elements is light and hence a major repair, not a rebuild is required. The exchange of the engine is also required.
3. Minor Failure and Engine Service Maintenance

This group includes those failures not considered in the other two types and also includes the engine downtime resulting from service and maintenance..

For this type of failure, the exchange of the engine is not required.

Major and minor failures are treated differently. Major failures are studied individually and their probability of occurrence is modeled by means of a suitable probability function. Minor failures and service are characterized collectively by the engine downtime resulting from their repair, expressed in terms of the "minor failure availability rate" (the ratio of engine running time to the sum of engine running time and the downtime due to minor failures, for a given period of operation).

The Preventive Maintenance Policies

Both types of major engine failures are subject to a planned repair policy which could be referred to as an "equivalent age repair policy". Equivalent age policy can be regarded as a generalization of age repair for systems under deterioration, where it is assumed that the reliability function changes after each repair. Therefore, the repaired equipment is considered a different unit with lower reliability and thus, the time to the following planned repair must be modified accordingly.

Figure 3 shows the typical reliability functions
FIGURE 3: 'Equivalent age' policy for a system subject to discontinuous stepwise degradation after each rebuild.

a) Rebuild policy: $T_0 > T_1 > T_2$ ....

b) Major repair policy: $T'_0 > T'_1 > T'_2$ ....

NEW ENGINE

R(T)

T0

T1

T2

$R_O(T)$

$R_1(T)$

$R_2(T)$

$R'_0(T)$

$R'_1(T)$

$R'_2(T)$

AFTER 1-ST REBUILD

AFTER 2-ND REBUILD

AFTER 1-ST REBUILD

AFTER 2-ND REBUILD
throughout the life of an engine. After each rebuild is performed the engine is assumed to follow a new reliability curve having a higher failure probability for a given failure-free time than the previous curve.

If the first rebuild was planned at time $T_0$ which corresponds to a reliability $R_0(T_0)$, then the successive rebuilds must be planned after failure-free times $T_1$, $T_2$, $T_3$, ... $T_i$ such that:

$$R_0(T_0) = R_1(T_1) = \ldots = R_i(T_i)$$

Where $R_1$, $R_2$, ... $R_i$ are the reliability function for each operative period between successive rebuilds.

Similarly if major repairs for new engines are planned after $T_0$ hours of failure-free operation, they will be planned at times $T_1$, $T_2$, ... $T_i$ for engines having had 1, 2, 3, ... , $i$ rebuilds, such that:

$$R_0'(T_0') = R_1'(T_1') = \ldots = R_i'(T_i')$$

Where $R_0'$, $R_1'$, ... $R_i'$ are the reliability functions relative to chance major failures for engines having had 0, 1, 2, ... $i$ rebuilds.

It can be said that an equivalent age policy is an extension of an age replacement policy to systems under discrete deterioration where the system reliability characteristics are considered to change after every
The Failure Submodel

In this section, those methods used in the model to quantify the reliability of the system are discussed.

1. Major Wear-out Failures.- The three-parameter Weibull distribution has been selected to characterize this type of failure. The Weibull model was chosen mainly because of its ability to assume a great variety of shapes.

The Weibull cumulative probability function can be linearized by a double logarithmic transformation, thus making possible the use of least square techniques for the estimation of parameters. The density function of the Weibull model is given by:

\[ f(t) = \frac{\alpha}{\beta} \left[ \frac{t - \gamma}{\beta} \right]^{\alpha-1} e^{-\left(\frac{t - \gamma}{\beta}\right)^\alpha} \quad \text{for } t > \gamma. \]

and the cumulative probability function (failure function),

\[ F(t) = \int_0^t f(t) dt = 1 - e^{-\left(\frac{t - \gamma}{\beta}\right)^\alpha} \]

\( F(t) \) can be linearized to the form:

\[ y = Ax + B \]
where: \[ y = \ln \ln \left[ \frac{1}{1 - F(t)} \right] \]
\[ x = \ln (t - \gamma) \]
\[ A = \alpha \]
\[ B = -\alpha \ln \beta \]

Another important advantage of the Weibull model is that for \( \beta = 1 \) it becomes the exponential distribution (monotone failure rate), for \( \beta > 1 \) it has an increasing failure rate function, whereas for \( \beta < 1 \) it has a decreasing failure rate function. Also as \( \alpha \) increases the Weibull distribution approaches the normal law asymptotically and it becomes practically normal for \( \alpha > 3 \). These characteristics make the Weibull model one of the most widely applied in reliability theory and failure modeling.

The method used to estimate the values of \( F(t) \) from the failure data is called 'Mean Ranks Method' and is due to Herdt (1960). The times between failures are ranked in ascending order and the probability of failure is estimated at each failure time \( t_i \) by,

\[ F(t_i) = \frac{i}{N + 1} \]

where \( i \) is the rank for the failure \( t_i \) and \( N \) is the total number of failures available for the test.

Once the values of \( F(t_i) \) have been estimated, a least square method is used to fit the linearized Weibull failure
distribution. A computer code written by Mutmansky (1968) was used to estimate the Weibull parameters, and is explained in Appendix B.

2. Major Chance Failures.- The literature on failure theory generally admits the adequacy of the exponential law to characterize failures related to chance. This assumption proved to be valid when tested with the failure data used for the case study and consequently, the exponential probability law was used in the model to characterize major chance failures.

Since the model assumes discrete deterioration, where reliability characteristics change after each engine rebuild, the exponential parameter for the chance failure distribution was assumed to change after each rebuild is performed.

Then:

\[ F(t) = 1 - e^{\lambda_i t} \quad i = 0, 1, 2 \ldots \]

where \( \lambda_i \) is the constant failure rate parameter for major chance failures for engines having had \( i \) rebuilds.

3. Minor Failures and Service Maintenance.- Minor failures and service maintenance producing system downtime are characterized collectively by the minor failure availability rate. The minor failure availability rate is the ratio of engine running hours to the sum of engine running
hours plus minor failure and service downtime for a given time period.

*Availability* is obtained from actual engine operation and failure records and fitted by a least square (regression) model:

\[ K_{ae}(t_e) = \exp(-s + d \cdot t_e) \]

where: \( K_{ae}(t_e) = \) Engine minor failure availability rate for an engine \( t_e \) engine hours old. 

\( s \) and \( d \) = parameters of the model

Besides the theoretical justification for this model which will be presented later in this section, the model can be intuitively justified for a system under age deterioration resulting from a great number of failure modes since:

\[
\begin{align*}
\text{for } t_e &= 0 \text{ (new engine)} \quad \Rightarrow K_{ae}(0) = \exp(-s) \\
\text{for } t_e &= t \text{ } (0 < t < \infty) \quad \Rightarrow K_{ae}(t_e) = K_{ae}(0) \exp(-d \cdot t_e) \\
\text{for } t_e &= \infty \quad \Rightarrow K_{ae}(\infty) = 0
\end{align*}
\]

then the parameter \( s \) is related to service downtime and the parameter \( d \) represents the deterioration characteristics of the system. Also, as it would be expected for a system under deterioration, the availability tends to zero as
the engine age tends to infinity. Another consideration is the simplicity and the "handling" advantages of the exponential function.

The theoretical justification for this model was obtained from the generalization and adaptation of a model proposed by Barlow and Proschan (1965) for complex systems under steady-state operation.

Barlow and Proschan show that if a system is composed of a great number of independent elements each subject to independent failure and repair patterns and all making up the failure pattern of the entire system, then 'under some reasonably general conditions the distribution of time between failures for the system tends to the exponential law as complexity and time of operation increases'.

For example, assume a complex system of \( n \) elements, each having a different (and unknown) failure distribution \( F_i(t) \) of mean \( t_i \) \( (i=1, \ldots, n) \).

The referenced authors show that as time of operation of the element \( i \) tends to infinity the expected total number of failures during the interval \( 0-t \), \( M_i(t) \), tends to become proportional to \( t \) regardless of the type of failure law and is expressed by:

\[
\lim_{t \to \infty} M_i(t) = \frac{t}{t_i}
\]

and the failure rate
\[ \lim_{t \to \infty} \frac{M_i(t)}{t} = \frac{1}{t_i} = \lambda = \text{Constant} \]

Then, assuming that the system has been operating since time \( t_0 = -\infty \) (a very long time), so that each possible failure mode has reached asymptotic behavior, the failure pattern of the entire system will converge to the exponential law of parameter \( \Lambda \) and mean time to failure \( T \) such that:

\[ \Lambda = \frac{1}{t_1} + \frac{1}{t_2} + \frac{1}{t_3} + \ldots + \frac{1}{t_n} \]

and:

\[ T = \frac{1}{\Lambda} \]

The above can also be expressed as follows:

\[ \lim_{t \gg t_i} \frac{\sum_{i=1}^{n} M_i(t)}{t} = \Lambda \]

Obviously the condition of a very long operating time with respect to the mean time to failure of any of the system's elements is never satisfied by an engine, since not all of the possible failure modes have had the chance to take place a great number of times and some of them may never have occurred during the life span of an engine.

Therefore, in the case of an engine, as time of operation increases, new failure modes that never occurred before will take place and the overall failure pattern
of the unit will have an increasing failure rate throughout its entire life span. It can also be expected that the overall failure rate will increase over time with decreasing speed since the probability of a failure occurring for the first time decreases as the age of the engine increases.

Based on the above, it can be said (and it is valid for any complex system of the type described above), that the overall failure rate characteristic has two time regions (Figure 4). Initially, the failure rate of the system increases (transition region) and after a certain time of operation, a steady-state failure rate is reached (steady-state region), where the entire system becomes exponential (monotone failure rate).

Thus the variation of the overall failure rate for a complex system can be characterized by the following equation:

\[ r(t) = K_1 + K_2 t^p \]

where: \( t = \) System's Age
\( K_1, K_2 = \) Constants
\( 1 > p > 0 \)

then:

\[ \frac{dr(t)}{dt} = K_2 pt^{p-1} > 0 \] (INCREASING FAILURE RATE)

\[ \frac{d^2 r(t)}{dt^2} = -K_2 p(1-p)t^{p-2} < 0 \] (DECREASING SLOPE)

Although the above equation is empirical, and hence it is not based on analytical developments, it describes
FIGURE 4: The failure rate of a complex system operating for an infinite time span.
the failure pattern of a complex system in the transition region with reasonable accuracy when, as it is the case of truck and engine minor failures, the total system's repair time results from many types of minor failures.

To characterize the 'time to repair', the same model can be applied, but the time required for the repair of a minor engine failure is short enough with respect to the life span of an engine, to assume that the repair function \( G(t) \) is exponential (the transition region is not considered).

Now, let us analyze the availability rate of the engine with respect to minor failures and service. Consider an engine of average age \( t \) operating during the interval \((t-\Delta t/2) \) to \((t+\Delta t/2)\). The period \( \Delta t \) is assumed long enough so that enough failures have taken place and the mean times \( T_1 \) and \( T_2 \) have closely approached their expected values. At the same time, \( \Delta t \) should be short enough so that the minor failure rate \( r(t) \) may be assumed constant over the interval.

Under the above assumptions;

\[
r(t) = \lambda = k_1 + k_2 t^p = \text{Constant over the interval } \Delta t
\]

Then, during the interval of operation \( \Delta t \), the
minor failure availability rate can be estimated (as shown in Chapter III) by the following expression;

\[ K_{ae} = \frac{T_1}{T_1 + T_2} \]

where \( T_1 \) is the mean time to failure and \( T_2 \) is the mean repair time. And since:

\[ T_1 = \frac{1}{k} = \frac{1}{K_1 + K_2 tP} \]
\[ T_2 = \text{constant (exponential repair time)} = \frac{1}{\lambda} \]

then for an engine of age \( t \) during the interval \( \Delta t \) the availability rate will be

\[ K_{ae}(t) = \frac{1}{1 + (K_1 + K_2 tP)T_2} \]

The above expression requires that during the interval \( \Delta t \) enough failures and repairs have taken place to ensure that the averages of time to failure and repair time can reach their expected values \( T_1 \) and \( T_2 \). A time interval of 2000 engine hours is appropriate according to the results obtained in the case study (Chapter V).

The expression obtained for \( K_{ae}(t) \) can be approached
by an exponentially decreasing function of time, as proposed in this section.

In order to test the practical validity of the above model, the exponential availability function was fitted to actual minor failure downtime data from a 20 unit-100 ton truck fleet operating 24 hours/day during two years.

Minor failure and service downtime was used to estimate the six-month period average availability and the exponential function was fitted to the data by linear regression methods.

The correlation was significant at the 99% level using the F-test, thus confirming the validity of the model.

Furthermore, the error resulting from the simplification of the model is negligible if compared with the error due to the inaccuracy of the minor failure records normally kept by mining companies and the error inherent to the assumption that the increase of the failure rate is discrete.

Truck failures not related to the engine were also characterized by the same model:

$$\text{Kat}(t) = \exp\left(- (m_t + d_t t)\right)$$

where: $\text{Kat}(t) = \text{truck availability rate with respect to failures and service maintenance not related to the engine modules, for a truck of age } t \text{ (operating hours)}$.

$m_t$ and $d_t$ are constants.
The Repair Downtime Submodel

For both types of major failures, the repair time was characterized by the truncated-exponential distribution. This decision was based on the following considerations:

i) Since in many cases, the accuracy of failure records is rather poor, it is advantageous to use a model with parameters that may be estimated with reasonable accuracy. The exponential law is ideal for this purpose since only the average repair time and maximum and minimum values are required.

ii) The physical activities involved in a given type of major repair are quite constant and the differences among repair times are mainly due to chance. Thus repair time may be assumed independent of the past repair history of the system.

iii) The histogram obtained from repair time records shows a clear exponential shape.

The repair time for minor failures and service was obtained directly from the availability model. The total repair time for a given time interval was computed from the definition of availability as shown in Appendix B.

The Repair Cost Submodel

For major repair cost, the cost per repair was assumed to follow the truncated-exponential distribution. The reasons stated above for repair time are also valid for repair cost, thus the same distribution was used.
Planned major repairs and major repairs performed after failure were modeled by different exponential functions. This distinction was made to recognize the fact that, in general, planned repairs cost less than after-failure repairs due to better labor and materials requirement planning and to the fact that engines suffer less damage and towing is not required.

Minor repair and service costs were treated similar to major repair costs. The difference being that since minor repairs are not studied individually, their cost is considered dependant on repair time and hourly repair cost for a given period of time, and hence the random variable (following the truncated exponential distribution) is hourly cost of minor repair.

The Cost Objective Function

Each engine replacement and maintenance policy is evaluated by the discounted net present value of costs per ton hauled, according to the following cost function:

\[
C(NQ) = \sum_{j=1}^{NQ} P(j) \left( \sum_{i=1}^{6} C_{ij} N_{ij} + C_{tav} t_j (1+r/4)^{-4j} \right) + \sum_{j=1}^{NQ} P(j)
\]

\[
C(NQ) = \sum_{j=1}^{NQ} P(j) \left( \sum_{i=1}^{6} C_{ij} N_{ij} + C_{tav} t_j (1+r/4)^{-4j} \right)
\]
where: $C_{ij}$ is the cash flow for cost resulting from event $i$ during quarter $j$.

$N_{ij}$ is the number of times that event $i$ occurred during quarter $j$.

$C'$ is the cash flow for engine minor repair and service hourly cost.

$t_{ij}^av$ is the engine downtime (hrs) resulting from engine minor repair and service during quarter $j$.

$P(j)$ total tons hauled by the system during quarter $j$.

$r$ nominal rate discounted quarterly.

$NQ$ total time period evaluated in quarters.

$j$ quarter number.

$i$ type of countable maintenance event, where:

$i=1$ truck purchase.

$i=2$ engine purchase.

$i=3$ engine rebuild (scheduled).

$i=4$ engine rebuild (at failure).

$i=5$ engine major repair (scheduled).

$i=6$ engine major repair (at failure).

Cash flows for truck purchases are obtained by deducting from the delivery cost, the net present value of the truck salvage and the net present value of the tax savings obtained by straight-line depreciation.

For the rest of the cost concepts the cash flow is computed as after-tax cost.

The model also allows for an average annual inflation
rate which overcharges cash flows proportionally to the time of occurrence.

The Operation Parameters

The following information is also required by the model:

i) Minimum production requirements schedule by quarters.

ii) Average truck cycle time schedule by quarters.

iii) Average scheduled working time rate: The average scheduled working time rate is the ratio of the expected working time to the total clock time over the period considered. This rate should also account for the expected time losses due to reasons other than mechanical failure, i.e: labor strikes, truck accidents, absenteeism, contract holidays, etc.

iv) Engine Hour Rate: Engine hour rate is the average ratio of the engine hours (engine hour meter reading) to the actual hauling time. This value depends on the road profile and other operation parameters and normally ranges between 0.95 and 1.05.

v) Operating delay Rate: Operating delay rate is the average ratio of actual hauling time to truck operating time over the time period considered. This value depends on the efficiency of the operation (mainly the loading and unloading facilities), and normally ranges between 0.90 and 0.95).

vi) Average Truck Payload: Average truck payload is the average tonnage hauled per haulage cycle. This value depends on
the size distribution and ore density and may range between 
0.90 and 1.05 times the nominal payload.

vii) Initial fleet parameters: Truck and engine ages and 
number of rebuilds already performed on each engine.

Usage and Accuracy

The model can be used with two different purposes: 1) To 
evaluate different engine maintenance-replacement policies.  
2) To obtain a time schedule by quarters for engine and truck 
requirements, capital expenditures and maintenance cost 
for a given engine maintenance-replacement policy.

1) For policy search.- An engine maintenance policy is 
defined by three parameters:
   - Engine replacement age (engine hours)
   - Planned rebuild age for the first rebuild on new engines 
     (engine hours)
   - Planned major repair age policy for new engines (engine hours)

The search method used is systematic and unidimensional. 
Maximum and minimum values and step size for the parameter 
to be varied are specified, while the other two parameters 
remain fixed.

This search method is more adequate for the model than 
two or three-dimensional search methods since a comparison 
among policy values rather than just the value of the best 
policy is desired. Moreover, unidimensional systematic 
search provides a better control of search parameters and the 
data generated is better suited to further graphical analysis.
Since the model is stochastic, accuracy and stability increases with the time period over which the policy is simulated. The computer program used to solve the model (see Appendix A) has been dimensioned for a maximum time span of 20 years which is more than sufficient.

Also, the time period required for adequate stability is highly dependant on the degree of randomness of truck and engine ages of the initial fleet. When the initial fleet is totally new, the simulation process would have to run for a large time period to 'randomize' the ages of the units. whereas, for widespread initial ages, a short time period is enough to produce stable results, since the average age of the fleet tends to reach constancy sooner. This eliminates the disturbing effect produced by the renewal of a great number of trucks within short time periods.

When analyzing a new fleet, it is advisable to use approximately random truck ages as input. By doing so, the relative value of policies is not affected and the simulation time span can be greatly reduced.

2) **For system scheduling.** - When the model is applied to obtain a time schedule, no special considerations are necessary. The actual truck and engine ages should be used as input and the simulation period should be selected in accordance with the time schedule required.

If actual costs are desired, the discount rate may be input at a zero level.
Other Features

i) Repair vs. Rebuild Decision. - When the major engine elements are almost worn out, both wear-out and chance failures may occur. If a chance failure occurs, the inspection of the unfailed elements will indicate whether or not a rebuild is necessary (opportunistic repair). The above decision process is simulated by the model as follows:

At every major chance failure, the engine reliability with respect to wear-out failure is estimated. A rebuild is performed when the reliability with respect to wear-out is less than 20% greater than the planned-rebuild reliability. Otherwise, a major repair is performed.

ii) Number of Standby Engines Required. - If at a given moment during the simulation process the system fails to meet the minimum production requirements, the purchase of either a new truck or a new engine module is simulated. A truck is purchased if the extra tonnage required could not have been hauled even by considering as operating time the time losses resulting from the lack of spare engines. Otherwise, an engine purchase is simulated.

When a truck is purchased, it is assumed that a new engine is acquired for the truck.

By the above process, the number of standby engines required at a given time is optimized by minimizing the system's downtime due to the lack of spare engines.
Computer Solution

The model can only be applied with the help of machine computation. A computer program written in Fortran IV language was developed to implement the model on a DECSYSTEM-10 computer at Colorado School of Mines. A listing and detail description of this program, and examples of input and output files, are shown in Appendix A. The version presented here, requires an approximate computer storage capacity of 10 Kilo-core but dimensioning of arrays can be greatly reduced if necessary by using array dimensions adequate to the actual system under study.

The input data can be obtained either from historical records or, if the analysis is performed for a feasibility study, it can be obtained from good judgement and experience from other operations of similar type. In Appendix B, a complete description of the information required, data processing, methods and recommended techniques for good record keeping is presented.

In chapter V a complete case study based on actual records provided by a Canadian mining company is presented.
V. A CASE STUDY

In this chapter the mathematical model developed in this thesis is applied to establish a maintenance and replacement policy for a Canadian open pit mine from whom the maintenance and operation historical records (used as basic information for the development and validation of the model) were obtained.

The Haulage System

The mine operates a truck fleet which at the beginning of the time period under study (Jan. 1, 1973) was composed of 15 M-85 Lectra-Haul trucks rated at 100 ton nominal payload.

The engine modules were CAT D-348 model, with 990 BHP.

The production requirements and cycle time taken from the actual production records for 1973 and 1974 were as follows:

<table>
<thead>
<tr>
<th>QUARTER</th>
<th>REQUIRED PRODUCTION</th>
<th>AVERAGE CYCLE TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 3</td>
<td>6,000,000 Tons</td>
<td>0.314 hrs.</td>
</tr>
<tr>
<td>4 - 8</td>
<td>7,000,000 Tons</td>
<td>0.314 hrs.</td>
</tr>
<tr>
<td>9 - on</td>
<td>8,500,000 Tons</td>
<td>0.314 hrs.</td>
</tr>
</tbody>
</table>
As shown above, production requirements and average cycle time were assumed to remain constant after Jan. 1, 1975, since no information on future production was available.

The simulation period used for the policy search was 15 years (60 quarters) and the truck ages for the initial fleet were scattered between zero and the truck replacement age considered (30,000 operating hours) in order to obtain good stability without needing a longer simulation period.

The complete set of input data required by the model is shown in Tables 2, 3, and 4.

The input data was obtained from two-year records and its processing method is discussed in Appendix B.

**Search Strategy**

The first search was performed on engine replacement age assuming that engine rebuilds and major repairs were not scheduled (repairs at failure). Table 5, shows the result of this search and in Figures 5, 6, and 7, the information obtained is graphed for better analysis.

In Figure 5, as engine replacement age increases, engine purchase cost decreases due to the need for fewer engine renewals and both engine rebuild and minor repair cost increase as a consequence of mechanical deterioration. Major repair costs remain approximately constant since the
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-343 99 HP, TRUCK: ELETRA-HAUL B-185 (100 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS

JOSE A. BOTIN* COLORADO SCHOOL OF MINES* MAR 1976***

INPUT DATA

**INITIAL FLEET PARAMETERS:**

<table>
<thead>
<tr>
<th><strong>NO.</strong></th>
<th><strong>TRUCK</strong></th>
<th><strong>AGE</strong></th>
<th><strong>ENGINE HOURS</strong></th>
<th><strong>NO. OF</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10000</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>30000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>50000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>70000</td>
<td>0</td>
<td>2</td>
<td>0</td>
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<td>5</td>
<td>90000</td>
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<td>7</td>
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<td>0</td>
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<tr>
<td>8</td>
<td>150000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>170000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>190000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
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<td>11</td>
<td>210000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>230000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>250000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>270000</td>
<td>0</td>
<td>2</td>
<td>0</td>
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<tr>
<td>15</td>
<td>290000</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

**SPARE ENGINE**

<table>
<thead>
<tr>
<th><strong>SPARE ENGINE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

**SAFETY ENGINE**

<table>
<thead>
<tr>
<th><strong>SAFETY ENGINE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

**OPERATION PARAMETERS:**

<table>
<thead>
<tr>
<th><strong>SIMULATION PERIOD</strong></th>
<th><strong>63 QUARTERS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AVERAGE PAYLOAD</strong></td>
<td><strong>93.5 TONS</strong></td>
</tr>
<tr>
<td><strong>EFFECTIVE SCHEDULE RATIO</strong></td>
<td><strong>0.899 ACTUAL WORK HRS. PER CLOCK HR.</strong></td>
</tr>
<tr>
<td><strong>OPER. DELAY RATE</strong></td>
<td><strong>0.29: HAULAGE HRS PER OPERAT. HRS.</strong></td>
</tr>
<tr>
<td><strong>ENGINE HOUR RATE</strong></td>
<td><strong>0.985 ENGINE HRS. PER HAULAGE HRS.</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>QUARTER TONS PLANNED</strong></th>
<th><strong>CYCLE TIME-HRS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40000</td>
</tr>
<tr>
<td>4</td>
<td>70000</td>
</tr>
<tr>
<td>9</td>
<td>90000</td>
</tr>
</tbody>
</table>

*(QUARTERS NOT SHOWN ARE SCHEDULED AS LAST SHOWN)*

**TABLE 2 :** Information Required by the Model: Initial Fleet parameters and operation parameters.
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BATN---COLORADO SCHOOL OF MINES---MAR 1976

INPUT DATA
-------------

FAILURE MODEL PARAMETERS:

ENGINE DOWNTIME

<table>
<thead>
<tr>
<th></th>
<th>MAXIMUM</th>
<th>AVERAGE</th>
<th>MINIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NON-SCHEDULED REBUILD</td>
<td>1350</td>
<td>1100</td>
<td>900</td>
</tr>
<tr>
<td>SCHEDULED REBUILD</td>
<td>975</td>
<td>610</td>
<td>500</td>
</tr>
<tr>
<td>NON-SCHEDULED MAJOR REPAIR</td>
<td>580</td>
<td>290</td>
<td>200</td>
</tr>
<tr>
<td>SCHEDULED MAJOR REPAIR</td>
<td>400</td>
<td>180</td>
<td>100</td>
</tr>
</tbody>
</table>

PROBABILITY OF A MAJOR ENGINE FAILURE

<table>
<thead>
<tr>
<th></th>
<th>ALPHA</th>
<th>BETA</th>
<th>GAMMA</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOR NEW ENGINES</td>
<td>2.350</td>
<td>5000</td>
<td>4100</td>
<td>0.43E-03</td>
</tr>
<tr>
<td>AFTER FIRST REBUILD</td>
<td>2.350</td>
<td>5000</td>
<td>1000</td>
<td>0.40E-03</td>
</tr>
<tr>
<td>AFTER SECOND REBUILD</td>
<td>2.350</td>
<td>5000</td>
<td>0</td>
<td>0.40E-03</td>
</tr>
<tr>
<td>AFTER THIRD REBUILD</td>
<td>2.352</td>
<td>4500</td>
<td>0</td>
<td>0.42E-03</td>
</tr>
<tr>
<td>AFTER FOURTH REBUILD</td>
<td>2.352</td>
<td>4020</td>
<td>0</td>
<td>0.42E-03</td>
</tr>
</tbody>
</table>

ALPHA, BETA AND GAMMA ARE PARAMETERS OF THE HARRULL MODEL FOR ENGINE REPAIRS. MU IS THE
MEAN FAILURE RATE FOR ENGINE MAJOR REPAIR
EXPONENTIAL MODEL (NO. OF REPAIRS PER ENG. HR.)

BASIC AVAILABILITY RATE PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>TRUCKS</th>
<th>ENGINES</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2</td>
<td>0.392</td>
<td>0.282</td>
</tr>
<tr>
<td>K1</td>
<td>0.333</td>
<td>2.152</td>
</tr>
</tbody>
</table>

MODEL: AVLR. RATE=EXP(-K2-K1T)
(T=TRUCK AGE-OPR HRS., OR ENGINE AGE-ENG HRS-
EXRESSED IN TEN THOUSAND HOUR UNITS)

TABLE 3: Information Required by the Model: Failure parameters.
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-34H 991 BHP. TRUCK ELECTRA-HAUL M-85 (120 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTINE** COLORADO SCHOOL OF MINES**MAR 1976****

INPUT DATA
-----

FINANCIAL MODEL PARAMETERS:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRUCK PRICE</td>
<td>$325,000</td>
</tr>
<tr>
<td>ENGINE PRICE</td>
<td>$62,000</td>
</tr>
<tr>
<td>ANNUAL INFLATION RATE</td>
<td>0.02</td>
</tr>
<tr>
<td>COST OF CAPITAL RATE</td>
<td>0.02</td>
</tr>
<tr>
<td>INCOME TAX RATE</td>
<td>0.50</td>
</tr>
<tr>
<td>TRUCK DEPRECIATION LIFE (YRS)</td>
<td>7</td>
</tr>
<tr>
<td>TRUCK SALVAGE VALUE RATE</td>
<td>0.02</td>
</tr>
</tbody>
</table>

ENGINE REBUILD AND MAJOR REPAIR COSTS ($US)

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum</th>
<th>Average</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-scheduled Rebuild</td>
<td>$35589.</td>
<td>$24523.</td>
<td>$19000.</td>
</tr>
<tr>
<td>Scheduled Rebuild</td>
<td>$29119.</td>
<td>$19466.</td>
<td>$17000.</td>
</tr>
<tr>
<td>Non-scheduled Major Repair</td>
<td>$21079.</td>
<td>$10583.</td>
<td>$8000.</td>
</tr>
<tr>
<td>Scheduled Major Repair</td>
<td>$14755.</td>
<td>$8108.</td>
<td>$7000.</td>
</tr>
<tr>
<td>Minor Repairs</td>
<td>$42.3</td>
<td>$25.3</td>
<td>$20.5</td>
</tr>
</tbody>
</table>

(MINOR REPAIR PARAMETERS IN DOLLARS PER ENGINE DOWNTIME HOURS DUE TO MINOR REPAIRS. OTHER PARAMETERS IN DOLLARS PER REPAIR)

TABLE 4: Information Required by the Model: Financial parameters.
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION

ENGINE: CAT D-348 993 BHP, TRUCK: ELECTRA-RAIL, M-85 (15 TON RML)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTTIN—COLORADO SCHOOL OF MINES—MAR 1976

POLICY SEARCH

POLICY PARAMETERS:
REPLA = ENGINE REPLACEMENT AGE (ENGINE HRS)
REBLT = ENGINE REBUILD SCHEDULE (ENGINE HRS)
WREP = ENGINE MAJOR REPAIR SCHEDULE (ENGINE HRS)

STRATEGY: REPLA VARYING BETWEEN 6000 AND 23000, AT 2000 HRS INCREMENTS
TRUCKS REPLACED AFTER 30000, HRS OPERATION
REBLT = 33000,
WREP = 33000.

OUTPUT CODE:

(1) = REPLA
(2) = TOTAL NO. OF TRUCK PURCHASES
(3) = TOTAL NO. OF ENGINE PURCHASES
(4) = TOTAL NO. OF REPAIRS
(5) = NO. OF ENGINE PURCHASES
(6) = NO. OF ENGINE REPAIRS
(7) = NO. OF ENGINE MAJOR REPAIRS
(8) = TOTAL COST (MILLIONS)
(9) = TRUCK REQUIREMENTS (MILLION TONS)
(10) = ENGINE REQUIREMENTS (MILLION TONS)
(11) = AVERAGE AVAILABILITY RATE
(12) = UNIT NPV TRUCK PURCHASES (C/TON)
(13) = UNIT NPV ENGINE PURCHASES (C/TON)
(14) = UNIT NPV ENGINE REPAIR (C/TON)
(15) = UNIT NPV ENGINE MAJOR REPAIR (C/TON)

<table>
<thead>
<tr>
<th>REPLA</th>
<th>TOTAL PURCHASES</th>
<th>PURCHASES</th>
<th>REPAIRS</th>
<th>ENGINE</th>
<th>ENGINE</th>
<th>ENGINE</th>
<th>TOTAL COST</th>
<th>REQUIREMENTS</th>
<th>ENGINE REQUIREMENTS</th>
<th>AVAILABILITY</th>
<th>TRUCK NPV</th>
<th>ENGINE NPV</th>
<th>ENGINE MAJOR NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>66 217 16</td>
<td>3 317</td>
<td>2 249</td>
<td>2.66</td>
<td>0.75</td>
<td>1.25</td>
<td>1.28</td>
<td>0.32</td>
<td>0.32</td>
<td>7.37</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>8000</td>
<td>65 169 65</td>
<td>3 312</td>
<td>2 152</td>
<td>2.79</td>
<td>0.74</td>
<td>1.24</td>
<td>1.27</td>
<td>0.35</td>
<td>0.45</td>
<td>7.45</td>
<td>1.27</td>
<td>1.27</td>
<td>1.27</td>
</tr>
<tr>
<td>10000</td>
<td>65 134 123</td>
<td>3 265</td>
<td>2.55</td>
<td>2.64</td>
<td>0.73</td>
<td>1.25</td>
<td>0.29</td>
<td>0.27</td>
<td>0.54</td>
<td>7.54</td>
<td>1.24</td>
<td>1.24</td>
<td>1.24</td>
</tr>
<tr>
<td>12000</td>
<td>67 113 146</td>
<td>3 237</td>
<td>2.59</td>
<td>2.59</td>
<td>0.72</td>
<td>1.28</td>
<td>0.27</td>
<td>0.25</td>
<td>0.59</td>
<td>7.64</td>
<td>1.27</td>
<td>1.27</td>
<td>1.27</td>
</tr>
<tr>
<td>14000</td>
<td>67 101 173</td>
<td>3 267</td>
<td>2.63</td>
<td>3.17</td>
<td>0.71</td>
<td>1.27</td>
<td>0.32</td>
<td>0.26</td>
<td>0.64</td>
<td>7.74</td>
<td>1.26</td>
<td>1.26</td>
<td>1.26</td>
</tr>
<tr>
<td>16000</td>
<td>66 88 179</td>
<td>3 345</td>
<td>2.63</td>
<td>3.25</td>
<td>0.73</td>
<td>1.29</td>
<td>0.42</td>
<td>0.36</td>
<td>0.73</td>
<td>7.84</td>
<td>1.29</td>
<td>1.29</td>
<td>1.29</td>
</tr>
<tr>
<td>18000</td>
<td>68 80 192</td>
<td>3 343</td>
<td>2.64</td>
<td>3.34</td>
<td>0.73</td>
<td>1.19</td>
<td>0.64</td>
<td>0.38</td>
<td>0.84</td>
<td>7.94</td>
<td>1.19</td>
<td>1.19</td>
<td>1.19</td>
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<tr>
<td>20000</td>
<td>68 74 220</td>
<td>3 318</td>
<td>2.61</td>
<td>3.59</td>
<td>0.69</td>
<td>1.05</td>
<td>0.44</td>
<td>0.35</td>
<td>0.86</td>
<td>8.04</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
</tr>
</tbody>
</table>

TABLE 5: Engine Replacement Policy Search for no Planned Repair
FIGURE 5: Engine costs vs. engine replacement age for no planned repair policy.
The probability of a major chance failure was input as a constant throughout the life of the engine. The graph shows a waving trend reflecting the differences in chance of major failure at the time of retirement for different retirement policies, which has some effect on the expected number of major repairs.

Figure 6 shows the effect of engine replacement policy upon fleet requirements and average mechanical availability.

Both number of trucks and number of engines per million ton-quarter production requirements increase as engine replacement age increases. Engine standby redundancy (number of standby engines required) also increases (its value is the difference between the ordinates of engine and truck requirement curves), and availability decreases.

Figure 7 shows the variation of total after-tax cost (engine total maintenance and renewal cost plus truck replacement cost) as engine replacement age increases. The curve shows a minimum for approximately 12,000 engine hours which represents the optimum engine replacement age under the assumption that engine major failures are not subject to preventive repair.

The above engine replacement age has an additional significance: by planning major engine repairs and rebuilds, the optimal engine replacement age might be
FIGURE 6: Fleet size and mechanical availability vs. engine replacement age for no planned repair policy.
FIGURE 7: After-tax total costs vs. engine replacement age for no planned repair policy.
delayed but never advanced. Therefore it can be stated that the optimum replacement age under no planned repair policy constitutes a 'minimax' engine replacement policy since by using it, the cost of the potentially worst repair policy (no policy at all) is minimized. It is also important to note that the actual optimum replacement policy age must lie above the minimax replacement policy.

The second search was performed on engine rebuild policy for three different engine replacement policies (12,000 hrs., 15,000 hrs., and 18,000 hrs.). The results of this search are shown in Tables 6, 7, and 8 and Figure 8.

Figure 8 shows that for this case study, that engine rebuilds should not be subject to preventive planning. This result can be explained by the important decrease of engine reliability with respect to wear-out failure after the first engine rebuild, which makes early replacement more economical than rebuild planning.

Finally, major engine repair policy was searched under the assumptions of 12,000 hrs. engine replacement and no rebuild policy. The results of the search are shown in Table 9 and graphed in Figure 9, and indicate an optimum major repair policy at approximately 2250 hrs. Above 4000 hrs., the cost shown in Table 9 became random since no scheduled major repairs are likely to take place.
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINECAT U-346 993 BHP , TRUCK SELLCO TRA-HAUL M-85 (100 TON 3.5X)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTIN*COLORADO SCHOOL OF MINES**MAR 1976***

POLICY SEARCH

POLICY PARAMETERS: REPLA = ENGINE REPLACEMENT AGE (ENGINE HRS)
REBLT = ENGINE REBUILD SCHEDULE (ENGINE HRS)
MRREP = ENGINE MAJOR REPAIR SCHEDULE (ENGINE HRS)

STRATEGY: REBLT VARYING BETWEEN 3000 AND 14000, AT 1500 HRS INCREMENTS
TRUCKS REPLACED AFTER 3000 HRS OPERATION
REPLA = 12000,
MRREP = 33000.

OUTPUT COLUMNS

(1) = REBLT
(2) = TOTAL NO. OF TRUCK PURCHASES
(3) = TOTAL NO. OF ENGINE PURCHASES
(4) = TOTAL NO. OF ENGINE REBUILD
(5) = NO. OF SCHEDULED REPAIRS
(6) = NO. OF SCHEDULED MAJOR REPAIRS
(7) = AVERAGE AVAILABILITY RATE
(8) = TRUCK REQUIREMENTS (NO. MILLION TONS)
(9) = TRUCK REQUIREMENTS (ENGINE REBUILD)
(10) = UNIT NPV ENGINE PURCHASES (CY/T)
(11) = UNIT NPV ENGINE MAJOR REPAIR (CY/T)
(12) = UNIT NPV ENGINE MAJOR REBUILD (CY/T)
(13) = UNIT NPV ENGINE MAJOR MAINT. (CY/T)
(14) = TOTAL NPV ENGINE PURCHASES (CY/T)
(15) = TOTAL NPV ENGINE MAJOR REPAIRS (CY/T)
(16) = TOTAL NPV ENGINE MAJOR REBUILDS (CY/T)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>5240</td>
<td>120</td>
<td>128</td>
<td>130</td>
<td>132</td>
<td>138</td>
<td>173</td>
<td>244</td>
<td>599</td>
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TABLE 6 : Engine Rebuild Policy Search (12,000 hrs. Engine Replacement Policy)
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-348 992 BHP, TRUCK ELECTRA-HAUL M-85 (100 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTIN* COLORADO SCHOOL OF MINES MAR 1976

POLICY SEARCH
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POLICY PARAMETERS:
- REPLA = ENGINE REPLACEMENT AGE (ENGINE HRS)
- REBLT = ENGINE REBUILD SCHEDULE (ENGINE HRS)
- MUREP = ENGINE MAJOR REPAIR SCHEDULE (ENGINE HRS)

STRATEGY:
- REBLT VARYING BETWEEN 632, AND 15224, AT 1500 HRS INCREMENTS
- TRUCKS REPLACED AFTER 3300, HRS OPERATION
- REPLA = 15000
- MUREP = 31000

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**TABLE 7**: Engine Rebuild Policy Search for 15,000 hrs. Engine Replacement Policy: Numerical Results
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-348 993 BHP , TRUCKS: ELECTRA-HAUL M-85 (16T TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BEY**COLORADO SCHOOL OF MINES**MAR 1976**

POLICY SEARCH

POLICY PARAMETERS:
REPLA = ENGINE REPLACEMENT AGE (ENGINE HRS)
REBLT = ENGINE REBUILD SCHEDULE (ENGINE HRS)
MEP = ENGINE MAJOR REPAIR SCHEDULE (ENGINE HRS)

STRATEGY:
REBLT VARYING BETWEEN 6000 AND 13000, AT 1500 HRS INCREMENTS
TRUCKS REPLACED AFTER 32000 HRS OPERATION
REPLA = 18000,
MEP = 34000.

OUTPUT CODE:

(1) = REBLT
(3) = TOTAL NO. OF ENGINE PURCHASES
(7) = NO. OF SCHEDULED MAJOR REPAIRS
(9) = TRUCK REQUIREMENTS (PER MILLION TONS)
(11) = AVERAGE AVAILABILITY RATE
(13) = UNIT AVG ENGINE PURCHASES (C/TON)
(15) = UNIT AVG ENGINE MAJOR REPAIRS (C/TON)
(2) = TOTAL NO. OF TRUCK PURCHASES
(4) = TOTAL NO. OF ENGINE REPAIRS
(6) = TOTAL NO. OF ENGINE REBUILDS
(8) = MAJOR REPAIR COST (TACADO T)
(10) = ENGINE REQUIREMENTS (PER MILLION TONS)
(12) = UNIT AVG TRUCK PURCHASES (C/TON)
(14) = UNIT AVG ENGINE REBUILDS (C/TON)
(16) = UNIT AVG ENGINE MAJOR REPAIRS (C/TON)

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TABLE 8: Engine Rebuild Policy Search for 18,000 hrs. Engine Replacement Policy: Numerical Results
FIGURE 8: After-tax total cost vs. engine rebuild policy for varying engine replacement policies.
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT 0-348 991 BHP, TRUCK: ELECTRA-RAIL M-85 (120 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BUIN****COLORADO SCHOOL OF MINES***MAR 1976****

POLICY SEARCH

POLICY PARAMETERS:
REPLA = ENGINE REPLACEMENT AGE (ENGINE HRS)
REHLT = ENGINE REBUILD SCHEDULE (ENGINE HRS)
MREP = ENGINE MAJOR REPAIR SCHEDULE (ENGINE HRS)

STRATEGY:
MREP VARYING BETWEEN 1000 AND 6000, AT 750 HRS INCREMENTS
TRUCKS REPLACED AFTER 30000 HRS OPERATION
REPLA = 12000,
REHLT = 30000.

OUTPUT CODE:
(1) = MREP
(3) = TOTAL NO. OF ENGINE PURCHASES
(5) = NO. OF SCHEDULED REPAIRS
(7) = NO. OF SCHEDULED MAJOR REPAIRS
(9) = TRUCK REQUIREMENTS (PER MILLION TONS)
(11) = AVERAGE AVAILABILITY RATE
(13) = UNIT NPV ENGINE PURCHASES ($/TON)
(15) = UNIT NPV ENGINE MAJOR REP ($/TON)

(2) = TOTAL NO. OF TRUCK PURCHASES
(4) = TOTAL NO. OF ENGINE REPAIRS
(6) = TOTAL NO. OF MAJOR REPAIRS
(8) = MILLION REPAIR COST (THOUSAND $)
(10) = ENGINE REQUIREMENTS (PER MILLION TONS)
(12) = UNIT NPV TRUCK PURCHASES ($/TON)
(14) = UNIT NPV ENGINE REPAIRS ($/TON)
(16) = UNIT NPV ENGINE MAJOR REP ($/TON)

TABLE 9: Engine Major Repair Policy Search for 12,000 hrs. Engine Replacement Policy and no Planned Rebuild Policy: Numerical Results
FIGURE 9: After-tax total cost vs. engine major repair policy for 12,000 hr. engine replacement policy and no planned rebuild policy.
Results and Conclusions

In table 10, a cost comparison between the best policy found and an alternative policy (20,000 hr. engine replacement and no planned repairs) is illustrated.

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POLICY 1: Engine replacement age: 20,000 hrs. rebuilds and major repairs not scheduled.

POLICY 2: Engine replacement age: 12,000 hrs.
Engine rebuilds: not scheduled
Engine major repair: every 2,250 hrs.

TABLE 10: Cost comparison between optimum and alternative policies
The difference in after-tax cost per ton between both policies is 0.21 cents which for the mine under study, (producing approximately 34 millions tons per year); results around $70,000/year after-tax or about $140,000 gross savings, not including the possible extra cost of operating a larger fleet.

Tables 11 through 16 show the quarterly schedule for the two policies compared above for a time span of 60 quarters. Note that mechanical availability for a given policy varies over time as an undulatory function of decreasing amplitude and tends to constancy after a large period of time (Figure 10). Equally, the number of trucks and engines tends to stability if production requirements and average cycle time are held constant.

In conclusion, the model can generate substantial savings and requires no special or costly record-keeping. It also produces a large amount of information which helps to analyse the behavior of the system under different assumptions and constraints and helps managers prepare operation and investment budgets.

In this case study, the application of the model was somewhat limited by the lack of reliable information. Separate engine repair time records were not kept and the author had to apply statistical analysis to estimate engine downtime. However, despite possible inaccuracies in
FIGURE 10: Average annual availability trend for optimum and alternative policy.
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT C-348 993 BHP, TRUCKS: ELECTRA-HAUL 4-5 (100 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTÍN, COLORADO SCHOOL OF MINES, MAR 1976

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TABLE 11.a: Quarterly Schedule for Alternative Policy (Quarters 1 to 20)
### ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION

#### ENGINE: CAT D-348 997 BHP, TRUCK: ELETTA-RAIN H-35 (140 TON BOX)

#### A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS

JOSÉ A. BORTI, COLORADO SCHOOL OF MINES, 1976

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**TABLE 11-b**: Quarterly Schedule for Alternative Policy (Quarters 1 to 20)
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINECAT 0-348 993 BHP . TRUCKS ELECTRA-HAUL H-65 (12 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BINTIAN, COLORADO SCHOOL OF MINES. MAR 1976

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TABLE 12-a : Quarterly Schedule for Alternative Policy (Quarters 21 to 40)
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-348 99% RPM, TRUCK: ELECTRA-HAUL M-85 (12 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BETH: COLORADO SCHOOL OF MINES MAR 1976

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TABLE 12-b: Quarterly Schedule for Alternative Policy (Quarters 21 to 40)
### ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION

**ENGINE: C-348 993 BHP, TRUCKS: ELECTRA-HAUL M-85 (100 Ton Box)**

A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS

JOSE A. BOTIN, COLORADO SCHOOL OF MINES

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**TABLE 13-a: Quarterly Schedule for Alternative Policy (Quarters 41 to 60)**
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-348 993 BHP, TRUCKS: ELECTRA-VALU M-85 (160 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTE: COLORADO SCHOOL OF MINES MAR 1976

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**TABLE 13-b**: Quarterly Schedule for Alternative Policy (Quarters 41 to 60)
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-348 993 BHP, TRUCKS: ELECTRA-HAUL M-85 (100 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSÉ A. BONÍ, COLORADO SCHOOL OF MINES, MAR 1976

POLICY SCHEDULE BY QUARTERS
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TABLE 14-a: Quarterly Schedule for Optimum Policy (Quarters 1 to 20)
## Engine Replacement and Repair Schedule Optimization

**Engine:** CAT D-348 993 BHP. **Truck:** ELECTRA-HAUL M-85 (16% TON 81X)

A case study for a system under varying production requirements

Jose A. Bottenberg, Colorado School of Mines, March 1979

### Truck Replacement Age (Oper Hrs) 3,500

### Engine Replacement Age (Eng Hrs) 12,000

### Engine Rebuild Schedule (Eng Hrs)

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**TABLE 14-b:** Quarterly Schedule for Optimum Policy (Quarters 1 to 20)
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT 0-348 991 BHP, TRUCKS: ELECTRA-HAUL M-85 (10T TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTIN
COLORADO SCHOOL OF MINES
MAR 1975

TRUCK REPLACEMENT AGE (OPER HRS) 37,000,
ENGINE REPLACEMENT AGE (ENG HRS) 120,000,
ENGINE REBUILD SCHEDULE (ENG HRS) 3,7,11, 26,9, 25,9, 23,3, 2,7,7,70,
ENGINE MAJOR REPAIR SCHEDULE (ENG HRS) 22,9, 22,3, 22,9, 22,3, 22,9.

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TABLE 15-a: Quarterly Schedule for Optimum Policy (Quarters 21 to 40)
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-348 990 BHP , TRUCK: ELECTRA-MAIL M-85 (150 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTIN** COLORADO SCHOOL OF MINES* MAR 197***

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TABLE 15-b: Quarterly Schedule for Optimum Policy (Quarters 21 to 40)
ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION

ENGINE: CAT D-348 993 BHP, TRUCKS: ELECTRA-HAUL M-85 (1/2 TON BOX)

A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS

JOSE A. BOTIN

COLORADO SCHOOL OF MINES

TRUCK REPLACEMENT AGE (OPHR HRS) 12,000
ENGINE REPLACEMENT AGE (ENGR HRS) 12,000
ENGINE REBUILD SCHEDULE (ENG HRS) 3,000, 2,900, 2,593, 2,542, 2,472, 2,376
ENGINE MAJOR REPAIR SCHEDULE (ENG HRS) 2,254, 2,253, 2,250, 2,242, 2,238

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TABLE 16-a : Quarterly Schedule For Optimum Policy (Quarters 41 to 60)
### Table 16-b: Quarterly Schedule for Optimum Policy (Quarters 41 to 60)

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**Net P.V. Truck Purchases = $5444**

**Net P.V. Engine Purchases = $3451**

**Net P.V. Engine Rebuilds = $1753**

**Net P.V. Engine Major Repairs = $1469**

**Net P.V. Engine Minor Repair = $3332**

All figures in thousands (3 or short tons)
the input data, the convenience of an early engine retirement is evident, due to the low reliability of rebuilt engines and the excessive time required to perform rebuilds.
VI. CONCLUSIONS

Remarks

As a result of this study, the following remarks are considered by the author to deserve special consideration:

1) The influence of engine maintenance and replacement policies upon capital expenditures on trucks and engines throughout time is highly significant when the system operates under minimum production requirements. Hence, engine replacement cannot be studied by the traditional approach of balancing engine replacement and maintenance costs.

2) The number of spare engines required for optimum operation is highly dependant on the engine policies followed.

3) The concept of "optimum truck fleet" for a given production and a given truck loader, as it is computed normally from operating data only, is misleading. Truck fleet requirements depend on maintenance policies and vary over time even under constant production requirements. Therefore, the problem should be solved within an overall operation-maintenance schedule optimization.

4) The engine-module is the most important single element of a truck haulage system with regard to its influence on overall performance, therefore it is
important to keep separate detailed engine records on failure, downtime and repair cost.

Suggestions for further research

The logical extension of the model proposed here would be its generalization for a mine haulage system composed of several loading and hauling units.

A maintenance model for the loading units, similar to the one proposed here could be linked together with the haulage model, to a mining operation simulator, thus allowing for the analysis of overall mining maintenance and operation scheduling.

Furthermore, the development of an integrated operation-maintenance model would bring together the objectives of production and maintenance management, two mining fields which traditionally have operated under independent and often antagonistic goals.

Summary

The continuous trend towards larger off-highway truck systems has made it necessary to regard the problem of operation and maintenance schedule optimization as a top priority management objective. These decisions often involve multi-million dollar investments which no longer can be left to intuition or trial and error approaches.

Yet, many mine managers decide truck and engine
renewals upon considerations totally unrelated to profit. Engines and trucks are kept in operation far beyond their economical life span just because they cannot justify, quantitatively, the profitability of new investments before the company's top executives.

The mathematical model developed here, provides a method for both maintenance policy optimization for engine modules and capital investment budgeting for fleet renewal. The model, being based on historical records, is capable of continuous policy improvement and reappraisal through periodic feed-back of the most recently recorded data. It also provides managers with a valuable tool for sensitivity analysis and evaluation of maintenance alternatives such as contractor vs. company shop for major repairs.

Although the purpose of the model is to optimize the major engine maintenance, truck failures not related to the engine are also analysed. Hence, the reliability of the entire truck haulage system can be estimated through time. Moreover, the model can be used to generate truck and engine requirements and purchase schedule for a given mine production plan.

Major engine failures are divided into 'wear-out' and 'chance' failures (depending on whether they generate a rebuild or a major repair decision) and are studied individually. Minor engine failures and engine service
are included in a group and characterized by means of a downtime model which assumes age deterioration.

The cost model is stochastic and costs are considered as random variables following the exponential distribution.

The type of repair and replacement policies applied to the model are based upon common mine maintenance practices. For engine replacement the "random age replacement policy" is used and engines are replaced at the first major failure after the unit has reached a given retirement age. For engine major repairs, the policy is opportunistic, thus when a major failure takes place, the decision of whether to rebuild the engine or simply repair it is based upon the inspection of the state of wear of the unfailed major engine parts.

The application of the model is only possible by the use of digital computers. For this reason, a FORTRAN-IV computer program is presented in Appendix A.

The actual use of the model is illustrated by the solution of a case study based on actual records obtained by the author from a large open pit mine in Canada.

Finally, operation and maintenance record-keeping methods are outlined and the analytical techniques for record processing are shown.


Morse, P.M., "Queues, Inventories and Maintenance ", Wiley & Sons, New York, 1958, Chap. 11.


Robinson, R.H., "Maintenance Scheduling and Inventory Control at the Iron Ore Co. of Canada", Prepnnt 75-AR-332, S.M.F. Fall meeting 1975.


APPENDIX A

The Computer Program: Description, Listing and Examples of Input and Output
General Description

The computer program was written in FORTRAN IV language. The code is machine independant and does not require any special 'built-in' features other than the standard FORTRAN functions.

The only part of the program which might require adaptation when the program is to be run in different machines is the random number generator function subroutine, which would require different parameters depending on the type of computer (binary or decimal), and the number of bits per word. The version presented here is suited for binary computers with 35 bits per word.

The capacity of the program is only limited by the storage capacity. This version can handle problems involving up to 100 engines at any given time and the simulation period can be up to 20 years (80 quarters).

Input

Operation, failure and financial parameters are read in from a precreated disk file. The name of the file is specified through on-line interactive conversation.

Policy parameters and search strategy are read in through on-line conversation as well.

An example of the arrangement of the input file is shown in Chapter V (Tables 2, 3 and 4).
Output

The program's output is stored in an output disk file which name is previously specified. Three distinct blocks of output are produced:

a) Input data
b) Policy search
c) Time schedule for a given policy

When the program is executed with the purpose of performing a search - evaluation of several policies in the same run-, input data and policy search blocks are printed out. When the program execution has the objective of producing the time schedule for a single policy, input data block and time schedule block will be printed out.

Examples of the print-out are shown in Chapter V (Tables 5 through 16).

Execution Time

The execution time depends on the size of the problem (for a given machine) and its amount in seconds can be accurately estimated by the following empirical formula:

\[
\text{CPU time (Sec)} = A + (B)(NT)(NQ)(NP)
\]

Where: \( NT = \) Average number of trucks in the fleet
NQ = Number of quarters to be simulated.
NP = Number of engine policies to be evaluated.
A and B = Machine dependent constants

The values estimated for the constants A and B in the DECSYSTEM-10 computer at Colorado School of Mines were 2.5 sec. and 0.01 sec. respectively.
An Example of the Interactive Input for Policy Parameters

```fortran
.EX SIMUL.F4
(11:40:47)

FORTRAN: SIMUL.F4
LINK: LOADING
(LNKXCT SIMUL EXECUTION)

INPUT FILE NAME ? DATA
OUTPUT FILE NAME ? TEST1

TRUCK REPLACEMENT POLICY-OPR. HRS.=? 30000.

ENTER ENGINE REPLACEMENT POLICY AND ENGINE REBUILT AND MAJOR REPAIR POLICIES, IN ENGINE HRS. IF A POLICY SEARCH IS DESIRED, ENTER ZERO IN PLACE OF THE POLICY PARAMETER TO BE SEARCHED. ONLY ONE PARAMETER CAN BE SEARCHED AT EACH RUN. ?? 0. 30000. 30000.

ENTER MINIMUM VALUE, MAXIMUM VALUE AND STEP SIZE FOR PARAMETER TO BE SEARCHED ?? 6000. 20000. 2000.

. .

END OF EXECUTION```
## Interrelations among Subprograms

<table>
<thead>
<tr>
<th>Subprogram</th>
<th>Called by</th>
<th>Calls to</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Prog.</td>
<td>---</td>
<td>POLICY</td>
<td>Input, output and control of the policy search.</td>
</tr>
<tr>
<td>POLICY</td>
<td>Main Pr.</td>
<td>OVHAUL, AVLB, FAIL, NPV</td>
<td>General control of the simulation, record keeping, production computations and truck and engine purchase and retirement.</td>
</tr>
<tr>
<td>FAIL</td>
<td>POLICY</td>
<td>OVHAUL, MREP</td>
<td>Calling control of the failure subroutines OVHAUL and MREP, failure counting.</td>
</tr>
<tr>
<td>OVHAUL</td>
<td>FAIL, WBL</td>
<td>EXPON</td>
<td>Generation of time to failure and repair times for major engine failures.</td>
</tr>
<tr>
<td>MREP</td>
<td>FAIL</td>
<td>EXPON</td>
<td>Returning times to major chance failures and repair times.</td>
</tr>
<tr>
<td>NPV</td>
<td>POLICY</td>
<td>EXPON</td>
<td>Financial analysis</td>
</tr>
<tr>
<td>AVLB</td>
<td>POLICY</td>
<td>---</td>
<td>Availability model</td>
</tr>
<tr>
<td>EXPOON</td>
<td>OVHAUL, MREP, NPV</td>
<td>RAND</td>
<td>Generation of an exponential random variable.</td>
</tr>
<tr>
<td>WBL</td>
<td>OVHAUL</td>
<td>RAND</td>
<td>Generation of a Weibull random variable.</td>
</tr>
<tr>
<td>RAND</td>
<td>EXPOON</td>
<td>---</td>
<td>Generation of a uniformly distributed random number between 0 and 1.</td>
</tr>
</tbody>
</table>
DESCRIPTION OF THE VARIABLES

INPUT - OUTPUT VARIABLES

ALPHA(I) .......... Shape parameter of the Weibull distribution of major wear-out failure probability for an engine having had (I-1) rebuilds.

AVENKØ .......... Age-independant parameter of the engine minor failure model.

AVENK1 .......... Age-dependant parameter of the engine minor failure model.

AVKØ ............ Age-independant parameter of the engine-unrelated truck failure model.

AVK1 ............ Age-dependant parameter of the engine-unrelated truck failure model.

AVLBLT(IQ) ........ Overall mechanical availability for quarter IQ.

BETA(I) .......... Scale parameter of the Weibull distribution of major wear-out failure probability for an engine having had (I-1) rebuilds.

CICLE(IQ) .......... Average cycle time (hrs.) for quarter IQ.

DLR. .............. Average operation delay rate.

EAGØ(I) .......... Age of engine I in the initial fleet.
EBCT(IQ) .......... Engine purchase cost for quarter IQ.
EDTCT(IQ) .......... Minor engine repair and service
                     maintenance cost for quarter IQ.
ENCT ............... Total delivery price of an engine
                     module.
ENR ............... Average engine hour rate (engine
                     hours per hauling hour ).
GAMMA(I) .......... Failure-free-period parameter of
                     the Weibull distribution of major
                     wear-out failures for engines having
                     had (I-1) rebuilds.
IEBUY(IQ) .......... Number of engines purchased during
                     quarter IQ.
IFL1(IQ) .......... Number of unscheduled engine rebuilds
                     during quarter IQ.
IFL1S(IQ) .......... Number of scheduled wear-out failures
                     during quarter IQ.
IFL2(IQ) .......... Number of unscheduled engine major
                     repairs during quarter IQ.
IFL2S(IQ) .......... Number of scheduled engine major
                     repairs during quarter IQ.
IOHT(I) .......... Number of rebuilds had by engine I.
IQ ................ Array subscript used to identify a
                     time period (quarter).
ISEED ............. Random number generator 'seed'.
ITBUY(IQ) . . . . . Number of trucks purchased during the quarter IQ.
NDEP . . . . . . . . Truck depreciation life (yrs.)
NE(IQ) . . . . . . . Number of engines at the end of quarter IQ.
NEN . . . . . . . . Total number of engines purchased under a given policy throughout the time period simulated.
NOHS . . . . . . . Number of scheduled engine rebuilds performed under a given policy throughout the time period simulated.
NQ . . . . . . . . Number of quarters simulated.
NRPS . . . . . . . Number of scheduled engine major repairs performed under a given policy throughout the time period simulated.
NTØ . . . . . . . Number of engines in the initial fleet.
NT(IQ) . . . . . . Number of trucks at the end of quarter IQ.
NTOH . . . . . . . Total number of engine rebuilds performed under a given policy throughout the time period simulated.
NTR . . . . . . . Total number of trucks purchased under a given policy throughout the time period simulated.
NTRP. . . . . Total number of major engine repairs
performed under a given policy throughout
the time period simulated.

OHCT(IQ). . . . Engine rebuild cost for quarter IQ.

OVH0(I) . . . . Engine hours for the most recent rebuild
on engine I (initial fleet).

PAYLD . . . . Average truck payload (Tons).

PLMN(I) . . . . Alphanumeric array with names of policy
parameters.

POL(I). . . . . Policy parameters. Engine replacement age
Engine planned rebuild age and engine
planned major repair age for new engines.
If one of the three parameters is input
at zero level, a search over its value
will be performed.

POL2(I) . . . . Engine rebuild policy (engine hours)
for the I-th rebuild.

POL3(I) . . . . Engine major repair policy after the
(I-1)-th rebuild.

PR(IQ). . . . . Tons hauled during quarter IQ.

PRMN(IQ). . . . Minimum production requirements for
quarter IQ(tons).

RCC. . . . . . Firm's rate of cost of capital.

RCT(IQ) . . . . Major engine repair cost for quarter IQ.
RINF . . . . Average annual rate of inflation for fleet repair and renewal cost throughout the time period simulated.

RAV(I) . . . . Average engine repair downtime for:
I=1 unscheduled rebuild.
I=2 scheduled rebuild.
I=3 unscheduled major repair.
I=4 scheduled major repair.

RMN(I) . . . . Minimum downtime for a major engine repair as for RAV(I).

RMX(I) . . . . Maximum downtime for a major engine repair as for RAV(I) and RMN(I).

SCHRT . . . . Average schedule rate (actual working time to total calendar time).

SSAV . . . . Average availability for the period of time simulated under a given policy.

SSNE . . . . Number of engines required per million ton-quarter of production requirements, under a given policy.

SSNT . . . . Number of trucks required per million ton-quarter of production requirements, under a given policy.

SVG . . . . . Salvage value rate for truck expressed as a fraction of total cost.

TAG . . . . . Truck replacement age (operating hours).
TAGØ(J) . . . . Truck ages for initial fleet.
TAX . . . . . . Average tax rate.
TBCT(IQ) . . . . Truck purchase capital expenditures for quarter IQ.
TITLE(I,J) . . . . Alphanumeric array for headings.
TRCT . . . . . . Total delivery price of a truck (engine module excluded) at the begining of the simulation period.
UPVEB . . . . . . Unit N.P.V. (per ton) of engine purchases, under a given policy.
UPVMR . . . . . . Unit N.P.V. (per ton) of engine major repairs under a given policy.
UPVOH . . . . . . Unit N.P.V. (per ton) of engine rebuilds under a given policy.
UPVRS . . . . . . Unit N.P.V. (per ton) of engine minor repair and service maintainance under a given policy.
UPVTB . . . . . . Unit N.P.V. (per ton) of truck purchases under a given policy.
VAL(I) . . . . . . Values of a policy parameter to be searched.
XMFR(I) . . . . . . Mean failure rate with respect to chance Major failures for engines having had (I-1) rebuilds.
XRA(I) . . . . . . Maximum engine repair cost for:
I=1  unscheduled rebuild.
I=2  scheduled rebuild.
I=3  unscheduled major repair.
I=4  scheduled major repair.
I=5  minor engine repair and service
    maintenance (per hour of engine
    repair time).

XRB(I) . . . . .  Average engine repair cost as for XRA(I).
XRC(I) . . . . .  Minimum engine repair cost as for XRA(I)
    and XRB(I).
OTHER IMPORTANT VARIABLES

AVENG(I) . . . . Engine minor repair availability rate.
AVL(J) . . . . Truck repair availability rate for truck J
CE(I) . . . . . Temporary storage for failure costs.
EAGE(I) . . . . Age of engine I
EH(I) . . . . . Engine hrs. run by engine I during quarter
H . . . . . . . Time to next major failure
HU(I) . . . . . Time at which engine I is back up after
a major repair or rebuild.
ICALL . . . . . Control flag for subroutine OVHAUL:
=-1 Compute time to major failure for
all the engines in the initial fleet.
= 0 Return time to the next rebuild
and rebuild downtime for engine I.
= 1 Compute times to major failure for
a new engine.
= 2 Array OVH(I,J) underdimensioned,
print error message and stop execution.
= 3 Array RPR(I,J) underdimensioned,
print error message and stop execution.
IENPOS(I) . . . . Its value indicates in which truck
engine I is currently running.
IOHT(I) . . . . Number of rebuilds had by engine I
ITPOS(J) . . . . Its value indicates which engine is
currently running in truck J
ISCH . . . . Subroutine argument flag:
          = 0 Repair was planned
          = 0 Repair was performed at failure
KF(I) . . . . Temporary storage for failure counting
arrays IFL1(I), IFL1S(I), IFL2(I), IFL2S(I).
NNE . . . . Current number of engines in the fleet.
NNT . . . . Current number of trucks in the fleet.
OH . . . . . Subroutine argument returning engine rebuild
time for a given rebuild.
OP(J) . . . . Indicates the time position of truck J
       within the quarter.
OVH(I,J) . . . Age of the engine I at the J-th major
       wear-out failure.
RP . . . . . Subroutine argument returning engine
       major repair time.
RPR(I,J) . . . Array containing the times to chance
       major failure for engine I after a given
       engine rebuild.
Flow-chart of Program

Legend of Flow-chart Symbols

3 2 ... Flow-chart connexions

... ... Computations

... ... Logical decision

... ... Call to subroutine

... ... Start, stop or return

... ... Do loop

... ... Input and output
Main Program

Start

Read in and
Print out
input data
file

Read:
Policy parameters and /
strategy

is
policy
search
desired
?

CALL
'POLICY'

Print out
Schedule for
Selected
Policy

Policies
I=1
Policy
I=I+1

CALL
'POLICY'

Compute:
Truck and en-
gine require-
ments and poli-
cy evaluation

PRINT OUT
Complete
Policy
Evaluation

Another
RUN
?

STOP
Subroutine 'POLICY'
Subroutine 'POLICY'

Engines
I = 1

more engines?
I > NNE

I = I + 1

is engine an spare unit?

YES

CALL 'FAIL'

NO

Advance truck operating time to time of 1st Major failure of the engine I
Subroutine 'POLICY'

End of Quarter

Engine more engines 
I=I+1

End of Quarter

spare engine 'IS' available

Exchange
gine IK by IS

IK = I
J = IENPOS(I)
OPMN = OP(J)

Update:
Operating time
Downtime

did quarter ended for engine

CALL 'FAIL'
Subroutine 'POLICY'

1. Compute Overall Availability
2. Update fleet parameters for next Quarter
3. Retire engines which reached retirement age and failed.
4. Compute Production for Quarter
   - Are requirements met?
     - YES
       - Buy a new engine module
         - CALL 'OVHAUL'
     - NO
       - Can requirements be met with more engines?
         - YES
           - Buy a new truck with a new engine module
             - CALL 'OVHAUL'
         - NO
           - Retire engines which reached retirement age and failed.
Subroutine 'FAIL'

Start

Has Engine I been Retired?

CALL 'OVHAUL'

Did Engine have a rebuild?

CALL 'MREP'

Did engine have a Major Repair?

Put engine down for the rest of the quarter.

Update: Failure counters, Truck operating time, engine downtime and engine age at the time of last failure.

Update truck oper. time, engine downtime and engine age during quarter

Put engine down for the rest of the quarter
Subroutine 'MREP'

Start

Will engine have a Major Repair before Quarter-end?

YES

Was Major Repair Planned?

YES

ISCH = 0

CALL 'EXPON'

NO

ISCH = 1

CALL 'EXPON'

Compute time to Failure and Repair time

Return

Return

NO
Subroutine 'OVHAUL'

Start

I=0 ?

NO

ICALL=0

YES

I=I+1

NO

Last Engine ? I > NNE ?

YES

Return

NO

Generate times to Chance Major Failure after Last Rebuild RPR(I,K)

ICALL=0 ?

YES

Return

NO

Generate time to next wear-out Failure for Engine I OVH(I,IO)

ICALL=0 ?

YES

Return

NO
Subroutine 'NPV'

Start

Initialize

Quarter
I = 1
I > NQ
Last Quart?

I = I + 1

Compute Cash-Flow of Truck Purchases for Quarter I.

Compute engine Purchase and Repair cost for Quarter I.

Update Net Present Values of Truck and engine costs.

Return
An Example of the Input Data File

ENGINE REPLACEMENT AND REPAIR SCHEDULE OPTIMIZATION
ENGINE: CAT D-348 990 BHP, TRUCKS: ELECTRA-HAUL M-85 (100 TON BOX)
A CASE STUDY FOR A SYSTEM UNDER VARYING PRODUCTION REQUIREMENTS
JOSE A. BOTIN
COLORADO SCHOOL OF MINES

```plaintext
43 15 17 61387
4.0 0.1007,
4.0 0.3000,
4.0 0.5000,
4.0 0.7000,
4.0 0.9000,
4.0 1.1000,
4.0 1.3000,
4.0 1.5000,
4.0 1.7000,
4.0 1.9000,
4.0 2.1000,
4.0 2.3000,
4.0 2.5000,
4.0 2.7000,
4.0 2.9000,
4.0 0.2000,
93.5 0.899 , 985
1350. 1100. 930.
975. 612. 520.
580. 290. 200.
480. 186. 190.
2.35 5000. .000 00.
2.35 5000. .000 00.
2.35 5000. .000 00.
2.35 4520 . .00040.
2.35 4002 . .00040.
2.35 392 0 . .00040.
2.35 25.3 20.5
32520. 62073. 29 . 00 . 50 . 00 7
35589. 24523. 19800.
29119. 19466. 17000.
21079. 13563. 8200.
14755. 8108. 7020.
42.3 25.3 27.5
1 62.0022 . 3137
4 72.0022 . 3137
9 85.0022 . 3137
```
ORE HAULAGE TRUCK SYSTEM MAINTENANCE SCHEDULING

This program solves the maintenance schedule, truck and engine requirements and budgeting for a truck fleet under varying probabilistic requirements and cycle time by applying simulation to a probabilistic failure and cost model which minimizes the expected unit present value of purchase and maintenance costs per ton through a selected time span.

Author: Jose Antonio Botin

Language: Fortran IV (C.S.M. CEC System-10 Version)

Input/output: Model parameters are input from a precreated disk file. Policy parameters are entered during execution through interactive conversation, as well as the names of input and output files. Output is stored in output file.

Capacity: The program can solve problems involving 100 engines, 20 years of operation (30 quarters) and up to 30 policy evaluations per run.

Subprograms: Policy, Fail, Mrep, Ovhaul, EXPcn, WBL, AVLB

Functions: Rand

```fortran
DIMENSION TITLE (13,4),PL,M(3),VAL(3), 
COMMON/BLK1/EAGE0(100),10HT0(120),TAG0(120),PR(80), 
1PRMN(80),CICLE(80),NT(80),AE(80),AVLBT(80),NE0,NT2, 
2PAYLD,TA6
COMMON/BLK2/ITHUY(80),IERLY(60),IFLI(80),IFL2(80), 
1IFL2(80),EDT(80),EDCT(80),NC,ICALL 
COMMON/BLK3/TRCT(80),EBCT(80),OHCT(80),RCT(80), 
1PVER,PVTB,PVOH,RINF,RCG,TAX,TRCT,EXT,RCX(5),XR5(5),XRC(5), 
2 PVXR,PVRP,HD,EP,SVG
COMMON/BLK4/OVH(128,32),RPR(128,32),RMX(5),RAV(5),RMN(5) 
COMMON/BLK5/IFPOS(100),AVL(100),10HT(120),EAGE(100),EH(100), 
10VH0(128),ALPHA(5),BETA(5),GAMMA(5),YFR(5),AVK, 
2AVK1,AVK2,AVK3(5),ENH,SCRT,SLR,AT,AL(100),OP(120),TM(100), 
3IQ,POL2(5),POL3(5),AVEG(120),AVENK2,AVENK1 
COMMON/BLK6/ISEED,ISEED 
DATA (PL,M(!),I=1,3)/5HREPLA,5HRELE1,5HMRP/
```
INAO=1
IOAO=3
WRITE(4,177)
177 FORMAT(' INPUT FILE NAME ? ',$) READ(4,178)FILE1
179 FORMAT(A5) WRITE(4,179)
179 FORMAT(' OUTPUT FILE NAME ? ',$) READ(4,178)FILE2 CALL IFILE(INA,FILE1) CALL OFILE(IOA,FILE2)

C*****
READ INPUT FILE THROUGH STAT. 12
C*****

INPUT=0
READ(INA,100) TITLE
100 FORMAT(13A5/) FORMAT(A5) READ(INA,1)NO,NT0,NE0,ISEED0
1 FORMAT(4)
DO 2 I=1,NE0
READ(INA,3)EAGE0(I),OVH0(I),ICHQ3(I),TAG0(I)
2 CONTINUE
3 FORMAT(2F,1,F)
READ(INA,4)PAYLD,SCHRT,DLR,ENR
READ(INA,5)RM0(I),RAV(I),RMN(I);I=1,4),(ALPHA(I),BETA(I),
1GAMMA(I),XMFREQ(I),I=1,5),AVK0,AVK1,AVKE0<AVENK1
4 FORMAT(4F)
5 FORMAT(4F/5.,2F/2F)
READ(INA,6)TRCT,ENCT,RCC,TAX,SVG,NDEF
6 FORMAT(6F/4F/3F,3F)
11 READ(INA,8,END=10)I,PRMN(I),CICLE(I)
GO TO 11
10 DO 9 I=1,NO
IF(1,PRMN(I),LT.,01)PRMN(I)=PRMN(I-1)
IF(CICLE(I),LT.,01)CICLE(I)=CICLE(I-1)
9 CONTINUE
3 FORMAT(1,F)
C*****
READ POLICY PARAMETERS DURING EXECUTION THROUGH STAT. 115
C*****

WRITE(4,111)
113 FORMAT(//' TRUCK REPLACEMENT POLICY-OPR. HRS.=? ',$) READ(4,114)TAG WRITE(4,114)
114 FORMAT(//' ENTER ENGINE REPLACEMENT POLICY AND ENGINE HRS./1X,1'REBUILD AND MAJOR REPAIR POLICIES, IN ENGINE HRS./1X, 2'IF A POLICY SEARCH IS DESIRED, ENTER 'EPC IN PLACE'/1X, 3'OF THE POLICY PARAMETER TO BE SEARCHED. ONLY ONE!'/1X, 4'PARAMETER CAN BE SEARCHED AT EACH RUN. '/?' ?? ',$) READ(4,114)(POL(I),I=1,3)
ISRC\(=0\)
DO 75 I=1,3
IF(POL(I),GT,.01)GO TO 75
ISRC=I
75 CONTINUE
IF(ISRC.EQ.0)GO TO 199

C****
C ENTER SEARCH STRATEGY
C****
WRITE(4,115)
115 FORMAT(' /' ENTER MINIMUM VALUE, MAXIMUM VALUE AND',/X,'1' STEP SIZE FOR PARAMETER TO BE SEARCHED?' /' ?? ')
READ(4,4)VAL(1),XHIGH,XSTEP
NVAL=(XHIGH-VAL(1))/XSTEP+1
IF(NVAL.GT.30)NVAL=30
DO 116 J=2,NVAL
116 VAL(J)=VAL(J-1)+XSTEP

C****
C PRINT OUT INPUT DATA THROUGH STAT, 217
C****
199 IF(IINPUT.EQ.1)GO TO 217
IINPUT=1
WRITE(IOA,13)TITLE
WRITE(IOA,200)
200 FORMAT(' INPUT DATA',/X,10(' ',/5X,'INITIAL FLEET PARAMETERS:'//5X,'1',/5X,'TRUCK',5*X,'ENGINE HOURS',4(' ',/5X,'NO.',/8X,'ENGINE',/5X,'AGE',/5X,'TO DATE LAST REBUILD',4/4X,'REBELSTS')
DO 201 I=1,NE
IF(I.GT.NT)GO TO 203
WRITE(IOA,204)I,REB(1),EAGE(I),O VH(I),IH0T(I)
204 FORMAT(5X,I5,F9.2,F10.2,5X,F10.2,'/19')
GO TO 202
202 WRITE(IOA,235)EAGE(I),O VH(I),IH0T(I)
235 FORMAT(4X,'SPARE ENGINE',F9.3,F9.3,'/19')
IF(NE.EQ.32.OR.I.NE.25)GO TO 202
WRITE(IOA,13)TITLE
WRITE(IOA,220)
202 CONTINUE
WRITE(IOA,246):3,PAYLD,SHRT,CLR,ER
246 FORMAT(4X,'OPERATION PARAMETERS:',//5X,'SIMULATION PERIOD',/5X,'QUARTERS',/5X,'AVERAGE PAYLOAD',/5X,'EFFECTIVE SCHEDULE RATE',/5X,'ACTUAL WORK HRS',/5X,'PER CLOCK HR',/5X,'OPERAT. DELAY RATE',/5X,'HRS PER HAULAGE HR',/5X,'QUARTER TONS PLAN'
6'CYCLE TIME-HRS')
DO 207 I=1,NO
IF(I.EQ.1)GO TO 201
IF(ABS(PRM(I)-PRM(I-1)).LT.1.)GO TO 207
WRITE(IOA,208)I,PRM(N(I),CICLE(I)
CONTINUE
WRITE(IOA,209)
FORMAT(5X,15.6X,F12.0,6X,F7.3)
WRITE(IOA,209)
FORMAT(1X,"QUARTERS NOT SHOWN ARE SCHEDULED AS LAST SHOWN")
WRITE(1OA,13)TITLE
WRITE(IOA,213)RMX(I),RAV(I),RNM(I),I=1,4)
WRITE(1OA,207)CDJTIMUE
WRITE(IOA,13)TITLE
WRITE(IOA,207)CDJTIMUE
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(1OA,14)
WRITE(IOA,216)
WRITE(IOA,14)
WRITE(IOA,216)
WRITE(1OA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)
WRITE(IOA,216)
WRITE(IOA,14)
WRITE(IOA,216)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)
WRITE(IOA,216)
WRITE(IOA,14)
WRITE(IOA,216)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
WRITE(IOA,14)
WRITE(IOA,14)TRCT,ENCT,R1,F,RCCT,TAX,DEP,SVG
WRITE(IOA,215)XRA(I),XRB(I),XRC(I),I=1,5)
WRITE(IOA,215)
C***)
PRINT OUT HEADINGS FOR POLICY SEARCH OUTPUT

C****
WRITE(IOA,13) TITLE
WRITE(IOA,43) PLNM, PLNM(ISRCH), VAL(1), XHIG, XSTEP, TAG
43 FORMAT(1X, 'POLICY SEARCH', 1X, 13('-'), 1X, 'POLICY PARAMETERS:',
1, 2X, 'A5,' = ENGINE REPLACEMENT AGE (ENGINE HRS)', 1X, T22, A5,
2' = ENGINE REBUILD SCHEDULE (ENGINE HRS)', 1X, T22, A5,
3' = ENGINE MAJOR REPAIR SCHEDULE (ENGINE HRS)', 1X,
4'STRATEGY: ', A5,' VARYING BETWEEN ', F7.0,' AND ', F7.0,' AT',
5F7.0,' HRS INCREMENTS', 1X, 'TRUCKS REPLACED AFTER', F7.0,
6' HRS OPERATION')
DO 65 LL=1, 3
IF (ISRCH.EQ.LL) GO TO 65
WRITE(IOA,66) PLNM(LL), POL(LL)
65 CONTINUE
66 FORMAT (1X, 'OUTPUT CODE:', 3X, ',(1) = ', A5, T50,
1 ' (2) = TOTAL NO. OF TRUCK PURCHASES', 3X, ',(3) = TOTAL
2 NO. OF ENGINE PURCHASES', 3X, ',(4) = TOTAL NO. OF
3 ENGINE REBUILDS', 3X, ',(5) = NO. OF SCHEDULED REBUILDS',
4T50, ' (6) = TOTAL NO. OF MAJOR REPAIRS', 3X, '(7) =
5 NO. OF SCHEDULED MAJOR REPAIRS', 3X, '(8) =
6 MINOR REPAIR COST (THOUSAND $)', 3X, '(9) =
7 TRUCK REQUIREMENTS (PER MILLION TONS)', 3X, '(10) = ENGINE
8 REQUIREMENTS (PER MILLION TONS)', 3X, '(11) = AVERAGE AVAILABILITY RATE', 3X, '(12) = UNIT NPV
9 TRUCK PURCHASES (C/TON)', 3X, '(13) = UNIT NPV ENGINE PURCHASES (C/TON)',
10 (C/TON)', 3X, '(14) = UNIT NPV ENGINE REBUILDS
11 (C/TON)', 3X, '(15) = UNIT NPV ENGINE MAJOR REPAIR (C/TON)',
12 (C/TON)', 3X, '(16) = UNIT NPV ENGINE MINOR REPAIR (C/TON)',
13 T52, ',(17) = UNIT NPV ENGINE MAJOR REPAIR (C/TON)',
16 (40) (41) (42) (43) (44) (45) (46) (47) (48) (49)
17 (50) (51) (52) (53) (54) (55) (56) (57) (58) (59)
18 (60) (61) (62) (63) (64) (65) (66) (67) (68) (69)
19 (70) (71) (72) (73) (74) (75) (76) (77) (78) (79)
20 (80) (81) (82) (83) (84) (85) (86) (87) (88) (89)
21 (90) (91) (92) (93) (94) (95) (96) (97) (98) (99)
22 (100) (101) (102) (103) (104) (105) (106) (107) (108) (109)
23 (110) (111) (112) (113) (114) (115) (116)')

C****
POLICY SEARCH THROUGH ST. 402
C****
DO 422 I=1,NVAL
NOH$=I
NRPS=I
XMINR=I
NTR=I
NEN=I
NTOH=I
NTRP=I
TTONS=I
SAV=I
SHLT=Q
SWE=I
POL(ISRCH)=VAL(I)
CALL POLICY
IF (ICALL.GE.2) GO TO 25
DO 402 J=1,NQ
SAV=SAV+PR(J)*AVLHL(J)
SNT=SNT+NT(J)*1.E3/PR(J)
SNE=SNE+NE(J)*1.E3/PR(J)
TTNS=TTNS+PR(J)
NOHS=NOHS+IFL1S(J)
NRPS=NRPS+IFL2S(J)
NTDH=NTDH+IFL1S(J)*IFL1(J)
NTRP=NTRP+IFL2S(J)+IFL2(J)
XMINR=XMINR+EDTCT(J)
NTR=NTR+ITBUY(J)
422 NEN=NEN+ITBUY(J)
UPVTB=PVTE*100./TTNS
UPVEB=PVER*100./TTNS
UPVCH=PVCH*100./TTNS
UPVHR=PVHR*100./TTNS
UPVRP=PVRP*100./TTNS
SSAV=SAV/TTNS
SSNT=SNT/NQ
SNE=SNE/NQ
WRITE(IOA,403)VAL(I),NTR,NEN,NCH,NCHS,NTRP,NRPS,XMINR,
1SSJT,SSNE,SSAV,UPVTB,UPVEB,UPVCH,UPVHR,UPVRP
423 FORMAT(F6.2,1X,5I5,14,F7.0,8F6.2)
430 CONTINUE
437 CALL POLICY
IF(ICALL.EQ.2)GO TO 25
C****
PRINT OUT RESULTS FOR SELECTED POLICY
C****
WRITE(IOA,13)TITLE
13 FORMAT(1H1,4(1X,13A5/),/)
WRITE(IOA,63)
63 FORMAT(1X,'POLICY SCHEDULE BY QUARTERS'/1X,27('-')//)
WRITE(IOA,14)TAG,POL(1),PCL2,FOL3
14 FORMAT(1X,T45,'NEW ****AFTER REBUILD********'/
11X,T45,'ENGINE FIRST SECOND THIRD FOURTH'/
21X,'TRUCK REPLACEMENT AGE(OPER HRS)',T35,F8.0/1X,'ENGINE'
3 REPLACEMENT AGE(ENG HRS)',T35,F8.0/1X,'ENGINE'
4 REBUILD SCHEDULE(ENG HRS)',T45,5F8.0/1X,'
5 ENGINE MAJOR REPAIR SCHEDULE(ENG HRS)',T45,5F8.0//)
WRITE(IOA,16)
16 FORMAT(16X,'TOTAL FLEET',9X,'PURCHASED',12X,'REBUILDS',
19X,'MAJOR REPAIRS'/4X,'QUARTER',4X,'TRUCKS',3X,'ENGINES',
24X,'TRUCKS',2X,'ENGINES',3X,'SCHED.',2X,'NOT SCHED.',
32X,'SCHED.',2X,'NOT SCHED.'//)
DO 17 I=1,NQ
WRITE(IOA,18)I,NT(I),NE(I),ITBUY(I),IEBUY(I),IFL1S(I),
1IFL1(I),IFL2S(I),IFL2(I)
17 IF(I.NE.27.AND.I.NE.40)GO TO 17
WRITE(IOA,13)TITLE
WRITE(10,14)TAG,POL(1),PCL2,POL3
WRITE(10,16)
CONTINUE
16 FORMAT(1X,18,I10,19,I11,19,4I12)
WRITE(10,13)TITLE
WRITE(10,14)TAG,POL(1),PCL2,POL3.
15 FORMAT(/'NET P.V TRUCK PURCHASES',T35,' = ',F10.0/1X,
1'NET P.V ENGINE PURCHASES',T35,' = ',F10.0/1X,
2'NET P.V ENGINE REBUILDS',T35,' = ',F10.0/1X,
3'NET P.V ENGINE MAJOR REPAIRS',T35,' = ',F10.0/1X,
4'NET P.V ENGINE MINOR REPAIR',T35,' = ',F10.0/1X,
5'ALL FIGURES IN THOUSANDS(US $ CHK SHRT TCNS)').
WRITE(10,19)
19 FORMAT(12X,'TONS',5X,'MECR.',4X,'COST OF PURCHASES',5X,
1'ENGINE REPAIR COST'/1X,'QUARTER',
22X,'PRODUCED',2X,'AVAILABLE',2X,'TRUCKS',3X,'ENGINES',3X,
3'REBLS',3X,'MRR REP',2X,'MRR REP')
DO 20 I=1,N0
WRITE(10,21)I,PR(I),AVL3LT(I),TBC(T(I)),EC(T(I)),OHCT(T(I)),
1RCT(T(I),EDTCT(I))
IF(T,NE.2.,AND.I,NE.40)GO TO 23
WRITE(10,13)TITLE
WRITE(10,14)TAG,POL(1),PCL2,POL3
WRITE(10,19)
20 CONTINUE
WRITE(10,15)PVTB,PVEB,PVCH,FMV,R,FRP
21 FORMAT(1X,15,2X,F10.0,F8.2,2F10.0,1X,F8.0,1X,2F8.0)
64 WRITE(4,62)
62 FORMAT(/'ANOTHER RUN ? : 1=YES 0=NO ',S)
READ(4,63)IRUN
53 FORMAT(I1)
IF(IRUN,NE.1.)GO TO 110
GO TO 50
25 IF(ICALL,NE.2.)WRITE(4,26)
IF(ICALL,NE.3.)WRITE(4,27)
27 FORMAT('RPR() IS NOT DIMENSIONED PROPERLY')
26 FORMAT('OVR() IS NOT DIMENSIONED PROPERLY')
50 STOP
END
**SUBROUTINE POLICY**

**FUNCTIONS:**
- TRUCK RETIREMENT AFTER 'TAG' OP. HRS.
- ENGINE RETIREMENT AT FIRST FAILURE AFTER RETIREMENT AGE
- TRUCK AND ENGINE PURCHASES AS REQUIRED
- OPERATION SIMULATION AND FLEET PARAMETERS UPDATING AT EVERY QUARTER-END.

**SUBROUTINES CALLED:**
- FAIL, NREP, CVHAUL, AVL3

**FUNCTION SUBPROGRAMS CALLED:**
- RAND

**ARGUMENTS:**
- NONE

**INPUT/OUTPUT:**
- NONE

---

**DIMENSION TAGE(100), D(100), ITPOS(100)**

**COMMON/BLK1/EAGE(100), ITPOS(EAGE0, ITFOSdue )**

**COMMON/BLK2/ITBUY(100), IEBUY(100), IFL1S(100), IFL1(100), IFL2S(100),**

**1IFL2(100), EDT(100), EDTCT(100), NG, ICALL**

**COMMON/BLK4/OVH(100), RPR(100), RMX(100), RAV(100), RMN(100)**

**COMMON/BLK5/IENPOS(100), AVL(100), IOT(100), EAGE(100), EH(100)**

**DO 1 I=1,100
1 DO 11 J=1,30
11 OVH(I, J)=0.
IF (I.GT.NNE) GO TO 11
H(I)=0.
EAGE(I)=EAGEW(I)
ITPOS(I)=ITPOS(I)
IENPOS(I)=IENPOS(I)

**DO 1 I=1,100**

**END**
OP(I)=0.
TAGE(I)=0.
IENPOS(I)=0
IOException(I)=0
CONTINUE

****

**COMPUTE REPAIR POLICY FOR REELIiT ENGINES, HAVING THE
SAME RELIABILITY THAN INPUT POLICY FOR NEW ENGINES**

****

IF(POL(2).LT.GAMMA(1)) POL(2)=GAMMA(1)*1.31
POL2(1)=POL(2)
POL3(1)=POL(3)
RX=XHFR(1)*POL(3)
RY=(POL(2)-GAMMA(1))/BETA(1)**ALPHA(1)
DO 2 J=2,5
POL2(J)=GAMMA(J)+BETA(J)*(RY**1/ALPHA(J))
POL3(J)=RX/XHFR(J)

2

****

**COMPUTE OVERHAULS AND SIMULATE ONE QUARTER THROUGH ST. 3**

****

ICALL=-1
I=3
CALL OVHAUL(I,0,0,0,0,ICALL)
IF(ICALL,GE,2)RETURN
DO 3 IQ=1,NQ

****

**INITIALIZE QUARTER**

****

IF(1(IQ)=3
IFL1S(IQ)=.2
IFL2S(IQ)=.2
ITBUY(IQ)=3
IEBUY(IQ)=.2
DO 33 J=1,(NNE+10)
EH(J)=.2.
D(J)=.2.
OP(J)=.2

33

****

**PUT OLD TRUCKS OUT OF SERVICE AND COMPUTE**

**BASIC AVAILABILITY THROUGH ST. 7**

****

J=1
X=2197.**SCHRT*.5*.7
IF((TAGE(J)+X).LT.TAGE)GO 17 &
DO 83 J=1,NNE
IF(IENPOS(1J),EQ,J)IENPOS(1J)=1002
CONTINUE

83

DO 81 K=J,INT
TAGE(K)=TAGE(K+1)
DO 82 IK=1,NNE

82
IF(IENPOS(IK).NE.(K+1))GO TO 82
IENPOS(IK)=K
GO TO 81

42 CONTINUE

41 CONTINUE
NNT=NNT-1
GO TO 84

3 X=X*TAGE(J)
CALL AVLB(X,AVK0,AVK1,AVJ)
AVL(J)=AVJ
IF(J.GE.NNT)GO TO 7
J=J+1
GO TO 84

C****

C GENERATE ENGINE AVAILABILITY, ENGINE POSITIONS

C AND FIRST ENGINE FAILURE FOR ALL ENGINES

C****

7 DO 201 I=1,NNE
X=EAGE(I)+2193.*SCHRT*.7*.5*ENR
CALL AVLB(X,AVENK0,AVENK1,AVENG(I))
J=IENPOS(I)
IF(J.EQ.1000)GO TO 202
ITPOS(J)=I
IF(HU(I).GT.0.)GO TO 202
K=I
CALL FAIL(K,3.)
GO TO 201

202 TM(I)=HU(I)
201 CONTINUE

C****

C FIND SPARE ENGINE "IS" TO REPLACE "IK"

C****

273 OPMN=2189.*SCHRT
TMN=OPMN
JMN=0
IS=2
DO 210 J=1,NNT
IF(OP(J).GT.OPMN)GO TO 210
OPMN=OP(J)
JMN=J
IK=ITPOS(J)

210 CONTINUE
IF(JMN.EQ.J)GO TO 300

DO 211 I=1,NNE
IF(IENPOS(I).NE.130J.OR,HU(I).GT.TMN)GO TO 211
TMN=HU(I)
IS=I

211 CONTINUE
IF(IS.EQ.7.OR.(OPMN+TM(IK)).LT.TMN)GO TO 220

C****

C EXCHANGE ENGINE, UPDATE TIMES AND GENERATE
**NEXT ENGINE FAILURE FOR EXCHANGE ENGINE**

```plaintext
IEPPOS(IS) = JMN
IEPPOS(IK) = 1MNN
IPPOS(JMN) = IS
IK = IS
IF(OPMN.GT.TMN) GO TO 225
OP(JMN) = TMN
D(JMN) = D(JMN) * TMN - OPMN
GO TO 225
222
OP(JMN) = OPMN * TH(IK)
IF(OP(JMN) .LE. (2189.*SCHRT)) GC TO 221
D(JMN) = D(JMN) * 2190.*SCHRT - OPMN
GO TO 203
221
D(JMN) = D(JMN) * TM(IK)
225
OPJ = OP(JMN)
CALL FAIL(IK, OPJ)
GO TO 203
```

**COMPUTE PRODUCTION AND CHECK AGAINST REQUIREMENTS**

```plaintext
300
NNER = NNE
DO 306 I = 1, NNE
IF(EAGE(I).GT..9E6) NNER = NNER - 1
306
CONTINUE
307
HH = 2.
DWE = 0.
DL = 2.
DT = 2.
DO 321 I = 1, NNE
HH = HH + EH(I) / ENR
DWE = DWE + EH(I) * (1.-AVENG(I)) / AVENG(I)
321
DL = DL + EH(I) * (1.-DLR)/(DLR*ENR)
DO 332 J = 1, NNT
322
DD2 = DT + D(J)
DWT = 2190.*SCHRT*NNT-HH-DWE-DL-CT
HHLOSS = DT/(1./AVT+1./DLR*ENR/AVE-ENR-1.)
IF(HH•JE, HHRO) GO TO 403
```

**PRODUCTION REQUIREMENTS ARE NOT MET WITH PRESENT FLEET**

```plaintext
350
IF(NNER.LE. NNT) GO TO 350
314
```

```plaintext
IF(IQ.EQ.1.) GO TO 314
IF((PRMN(IQ-1).GT.PRMN(IQ-1))) GO TO 314
IF((CICLE(IQ).GT.0301).GT.CICLE(IQ-1)) GO TO 314
HHNEED = HHRO - HH
IF(HHNEED.LE.HHLOSS) GO TO 352
```
BUY A NEW TRUCK AND ITS ENGINE THROUGH ST. 352

NNT=NNT+1
ITBUY(IQ)=ITBUY(IQ)+1
NNE=NNE+1
NNER=NNER+1
X=2190.*SCHRT*.7*.5*ENR
CALL AVLB(X,AVENK0,AVENK1,AVENG(NNE))
ICALL=1
CALL OVHAUL(NNE,0.,0.,0.,0.,ICALL)
IF(ICALL, GE.2)RETURN
IEBUY(IQ)=IEBUY(IQ)+1
IENPOS(NNF)=NNT
ITPOS(NNT)=NNE

X=2190.*SCHRT*.5*.7
CALL AVLB(X,AVK0,AVK1,AVNNT)
AVL(NNT)=AVNNT
JMN=NNT
IK=NNE
GO TO 225

BUY A NEW ENGINE THROUGH ST. 400

NNE=NNE+1
NNER=NNER+1
X=2190.*SCHRT*.7*.5*ENR
CALL AVLB(X,AVENK0,AVENK1,AVENG(NNE))
ICALL=1
CALL OVHAUL(NNE,0.,0.,0.,0.,ICALL)
IF(ICALL, GE.2)RETURN
IEBUY(IQ)=IEBUY(IQ)+1
TL=DT
IF(DT,GT,(2190.*SCHRT))TL=2192.*SCHRT
EH(NNE)=TL/((1./AVT+1./DLR-1.)/ENR+1./AVE-1.)
HU(NNE)=2190.*SCHRT
IENPOS(NNE)=1200
DO 352 I=1,NNE
IF(IENPOS(I),EQ.1000,OR,EAGE(I),LT,.9E6)GC TO 352
IENPOS(NNE)=IENPOS(I)
IENPOS(I)=1000
GO TO 353

352 CONTINUE

353 CONTINUE
351 CONTINUE
DO 351 I=1,NNT
IF(D(I),LE,0.)GO TO 351
D(I)=D(I)-TL
IF(D(I),GE,0.)GO TO 300
TL=-D(I)
D(I)=0.
351 CONTINUE
GO TO 327
COMPUTE AVAILABILITY FOR THE QUARTER

AVLBLT(IQ)=HH/(2190.*SCHRT*NNT-CL)
PRI(IQ)=HH*PAYLD/(CICLE(I))*1020.
EDT(IQ)=DNE

UPDATE FLEET PARAMETERS

DO 450 I=1,NNE
EAGE(I)=EAGE(I)+EH(I)
HU(I)=HU(I)-2190.*SCHRT
IF(HU(I),LE,1.)Hu(I)=0.
IF(I,GT,NNT)GO TO 450
IP=ITPOS(I)
CHFACT=(1./AVL(I)*1./DLR-1.)/ENR*1./AVENG(IP)-1,
TAGE(I)=TAGE(I)+(2190.*SCHRT-C(I))/CHFACT*ENR*DLR
CONTINUE

PUT DOWN OLD ENGINES THROUGH ST. 275

I=1
IF(EAGE(I).LT.,9E6.0R.IENPOS(I),NE,1000)GO TO 272
DO 273 K=1,NNE
EAGE(K)=EAGE(K+1)
I0HT(K)=I0HT(K+1)
HU(K)=HU(K+1)
IENPOS(K)=IENPOS(K+1)
DO 273 I00=1,30
273 OVH(K,100)=OVH(K+1,100)
NNE=NNE-1
GO TO 271
272 IF(I,GE,NNE)GO TO 274
I=I+1
GO TO 271
274 NT(IQ)=NNT
NEX(IQ)=NNE
3 CONTINUE

COMPUTE ECONOMICAL PARAMETERS AND RETURN TO MAIN PROGRAM

CALL NPV
RETURN
END
SUBROUTINE FAIL(I,OPR)

FUNCTIONS : CONTROL OF FAILURE TIMES AND DOWNTIMES
UPDATING FLEET PARAMETERS WITHIN A QUARTER
PUT ENGINES DOWN FOR RETIREMENT AT FIRST MAJOR
FAILURE AFTER RETIREMENT AGE OR AT 130% OF RETIRE
MENT AGE, WHICHEVER OCCURS FIRST.

SUBROUTINES CALLED : OVHAUL, MREP
INPUT/OUTPUT : NONE
ARGUMENTS : I - ENGINE NUMBER
OPR - TRUCK OP. HRS. IN QUARTER

COMMON/BLK2/IBUY(80), IE6LY(82), IFL1S(80), IFL1(80), IFL2S(80),
1IFL2(80), EDT(83), EDTO(83), NC, ICALL
COMMON/BLK5/IENPOS(100), AVL(127), I0HT(100), EAGE(100), EH(100),
1OVH(127), ALPHA(5), BETA(5), GAMMA(5), XMFR(5), AVK6,
2AVK1, NNE, POL(3), ENR, SCHRT, DLR, NNT, HU(I), OP(100), TM(100),
3IO, POL2(5), POL3(5), AVENG(100), AVEAK2, AVEAK1

CHFACT=(1./AVG(I))+1./OLR-1.,/ENR/I-1.,
IF(EAGE(I)<1.)=1E7
EAGE(I)=1.
TM(I)=HU(I)-OPR
RETURN

CALL OVHAUL(I,OPR,OH,H,ISCH,2)
IF(OH.GT,1.) GO TO 10
CALL MREP(I,OPR,RP,H,ISCH)
IF(RP.GT,1.) GO TO 10
TM(I)=.
EH(I)=EH(I)+(HU(I)-OPR)/CHFACT
OP(J)=2192.*SCHRT
RETURN

XXX=EAGE(I)+EH(I)+H/CHFACT
IF(XXX.LE.POL(1)) GO TO 22
EAGE(I)=1E7
TM(I)=HU(I)-OPR-H
EH(I)=EH(I)+H/CHFACT
OP(J)=OPR+H
RETURN

EH(I)=EH(I)+H/CHFACT
OP(J)=OPR+H
IF(OH.LE,1.) GO TO 25
HU(I)=OPR+H+OH
TM(I)=OH
IF(ISCH.EQ.1) IFL1S(IQ)=IFL1S(IQ)+1
IQ+T(I)=10HT(I)+1
IF(ISCH.EQ.1) IFL1(IQ)=IFL1(IQ)+1
RETURN

HU(I) = OPR + H + RP
T1(I) = RP
IF (ISCH, EQ, 0) IFL2S(IQ) = IFL2S(IQ) + 1
IF (ISCH, EQ, 1) IFL2(IQ) = IFL2(IQ) + 1
RETURN
END
SUBROUTINE MREP(I,OPR,RP,H,ISCH)

FUNCTIONS : GENERATION OF TIME TO MAJOR REPAIRS AND MAJOR REPAIR DOWNTIME.

SUBROUTINES CALLED : EXPON

ARGUMENTS : I - ENGINE NUMBER
OPR - HOURS OPER. BY TRUCK J IN QUARTER
RP - ENGINE CHANCE MAJOR FAILURE REPAIR DOWNTIME
H - TIME TO FAILURE
ISCH = 1 REPAIR WAS NOT PLANNED
      = 0 REPAIR WAS PLANNED

INPUT/OUTPUT : NONE

COMMON/BLK4/IOVH(100,30),RPR(123,30),RMX(5),RAV(5),RMN(5)
COMMON/BLK5/IEPOS(100),AVL(123),IQT(120),EAGE(100),EH(100),
10VH(100),ALPHA(5),BETA(5),GAMMA(5),XMF(5),AVK0,
2AVK1,NVE,POL(3),ENR,SCHR,DLR,NT,HL(120),OP(100),TM(100),
3IQ,POL2(5),POL3(5),AVENG(120),AVENK0,AVENK1
COMMON/BLK6/ISEED,ISEED0
J=IENPOS(I)
CHFACT=(1./AVL(J)+1./DLR-1.)/ENR*1./AVENG(I)-1.,
RP=2.
K=0
2
   K=K+1
   IF(K.GT.3.OR.ABS(RPR(I,K)).LT.1)GO TO 6
   H=(ABS(RPR(I,K))-EAGE(I)-EH(I))*CHFACT
   IF(H.GT.2.)GO TO 3
   GO TO 2
3
   IF(H.GT.(2+N)*SCHRT-OPR)GO TO 6
   IF(RPR(I,K).GT.0.)GO TO 5
   ISCH=1
   CALL EXPON(RMX(3),RAV(3),RMN(3),RP)
   GO TO 7
5
   ISCH=2
   CALL EXPON(RMX(4),RAV(4),RMN(4),RP)
7
   RP=RP*SCHR
6
   RETURN
END
SUBROUTINE OVAHL(I, OPR, OH, H, ISCH, ICALL)
FUNCTIONS : GENERATION OF WEAR-OUT TIME TO FAILURE AND DOWNTIME.
SUBROUTINES CALLED : EXPON, WEL
FUNCTIONS SUBPRG. CALLED : RAND
ARGUMENTS : I - ENGINE NUMBER
OPR - HOURS OPER. BY TRUCK J IN QUARTER
OH - REBUILD DOWNTIME
H - TIME TO REBUILD
ISCH - =1 REBUILD WAS NOT PLANNED
=0 REBUILD WAS PLANNED
ICALL - =-1 GENERATE ARRAY 'Ovh()' AND RPR()'
FOR ALL ENGINES OF INITIAL FLEET,
=0 RETURN NEXT WEAR-OUT FAILURE TO SUBROUTINE 'FAIL' AND GENERATE ARRAY RPR() AFTER REBUILD FOR ENGINE I,
=1 GENERATE ARRAYS Ovh() AND RPR() FOR THE NEW ENGINE I
=2 ARRAY Ovh() IS UNDERDIMENSIONED
=3 ARRAY RPR() IS UNDERDIMENSIONED
INPUT/OUTPUT : NONE

COMMOVBlK4/OVH<100,30>, RPR<100,30>, RHX<5>, RAV<5>, RHN<5>
COMMON/BLK5/ISEED, ISEED0
IF (ICALL.EQ.0) GO TO 6
A A = 2.
IF (ICALL.EQ.0) GO TO 6
AA = 2.
GO TO 7

COMPUTE REBUILD TIMES FOR THE NEW ENGINE

J=IENPOS(I)
CHFACT = (1./AVL(J)+1./DLR-1.)/ENR+1./A VEN G(I)-1.
I=IOHT(I)+1
X=EAGE(I)+EH(I)*(2190.*SCHNT-COR)/CHFACT
IF (ABS(Ovh(I, IO)), LE.X) GO TO 2
OH=2.
RETURN
2 ISCH=1
IF (Ovh(I, IO).GT.0.) ISCH=0
IF (ISCH.EQ.0) CALL EXPON(RMX(2), RAV(2), RHN(2), OH)
IF (ISCH.EQ.0) CALL EXPON(RMX(1), RAV(1), RHN(1), OH)
H = 2190. * SCHRT - OPR - (X - ABS(CVH(I, IO))) * CHFACT
IF (H, LT, 0.1) H = 0.1
OH = OH + SCHRT

C*****
COMPUTE MAJOR REPAIR TIMES TO NEXT REBUILD
C*****

7 IOR = IOR + 1
IF (IOR .GT. 5) IOR = 5
FAILIM = GAMMA(IOR) + BETA(IOR) * ((-ALG((, 2) ** (1. / ALPHV(IOR))))
IF (FAILIM, GT, (POL2(IOR) * 0.8)) FAILIM = POL2 (ICR) * 0.8
XRT = 0.
DO 9 K = 1, 3
IF (XRT, GT, FAILIM) GO TO 14
R = RAND(ISEED)
XR = (-ALOG(1. - R)) / XMFR (IOR)
IF (XR, LT, POL3(IOR)) GO TO 17
XRT = XRT + POL3(IOR)
GO TO 11
9 XRT = XRT + XR
10 IF (IO, EQ, 3) GO TO 15
RPR(I, K) = ABS(OVH(I, IO)) * XRT
GO TO 16
15 RPR(I, K) = XRT
16 IF (XR, LT, POL3(IOR)) RPR(I, K) = -RPR(I, K)
GO TO 9
14 RPR(I, K) = 0.
9 CONTINUE
IF (XRT, GT, FAILIM, AND, ICALL, EQ, 3) RETURN
IF (ICALL, NE, 5, AND, XRT, GT, FAILIM) GO TO 3
ICALL = 3
RETURN

C*****
COMPUTE REBUILD TIMES FOR INITIAL FLEET
C*****

1 I = I + 1
IF (I, GT, NVE) RETURN
IO = IOHT(I)
AA = OVH3(I)
GO TO 7
3 IO = IO + 1
IF (IO, LE, 33) GO TO 8
ICALL = 2
RETURN
5 IOC = 10
IF (IO, GT, 5) IOC = 5
CALL WBL(ALPHA(I0C), BETA(IOC), GAMMA(I0C), X)
IF (X, LT, POL2(I0C)) GO TO 5
X = POL2(I0C)
5 AA = AA + X
IF (AA, LT, EAGE(I)) AA = EAGE(I) + 2.
OVH(I, IO) = AA
IF(X.LT.POL2(IOC)) VH(I,IC) = -AA
IF(AA.LE.POL(1)) GO TO 3
IF(NCALL.LT.J) GO TO 1
RETURN
END
SUBROUTINE NPV

FUNCTIONS: EVALUATION OF A POLICY

SUBROUTINES CALLED: EXPOX

INPUT/OUTPUT

DIMENSION KF(4), CE(4)
COMMON/BLK2/IBUY(80), IEBUY(80), IFL1S(80), IFL1(80), IFL2S(80),
IFL2(80), ECT(80), ENCT(80), MCT, MCT
COMMON/BLK3/TBCT(80), EBCT(80), DBCT(80), RCT(80),
1PVEL, PV0, PVR, PVEB, RINF, RCC, TAX, TRCT, ENCT, XRA(5), XRB(5), XRC(5),
2PVR, PVP, NDEP, SVG

PVBT = 0,
PVEB = 0,
PVR = 0,
PVEP = 0,
RINF = ((1. + RINF)**25-1.)*4,
RCC = ((1. + RCC)**25-1.)*4,
DO 2 I = 1, NO
FCT1 = ((1. + RINF/4.)*1)
FCT2 = ((1. + RCC/4.)*(-1))*(1. - TAX)

** COMPUTE TRUCK AND ENGINE PURCHASE COST

TBCT(I) = IBUY(I)*TRCT*FCT1/1223,
PVS = TBCT(I)*SVG*((1. + RCC)**(-NDEP))
DEP = TBCT(I) - PVS*TAX/NDEP
IF (RCC.MAT, 26) GO TO 17
PVDEP = DEP*(((1. + RCC)**NDEP - 1.)/(RCC*((1. + RCC)**NDEP))
GO TO 1

** COMPUTE ENGINE REPAIR COST

KF(1) = IFL1(1)
KF(2) = IFL1S(I)
KF(3) = IFL2(1)
KF(4) = IFL2S(1)
CALL EXPON(XRA(5), XRB(5), XRC(5), CT)
DO 5 K = 1, 4
CE(X) =
IF(KF(K), EQ, 2) GO TO 5
DO 6 L = 1, KF(K)
CALL EXPON(XRA(K), XRB(K), XRC(K), X)
X = FCT1
6 \quad \text{CE}(K) = \text{CE}(K) \times X

5 \quad \text{CONTINUE}

\text{OHCT}(I) = (\text{CE}(1) + \text{CE}(2)) / 1000.
\text{RCT}(I) = (\text{CE}(3) + \text{CE}(4)) / 1000.
\text{EDTCT}(I) = \text{EDT}(I) \times \text{CT} / 1000.

C***
COMPUTE CASH FLOW AND PRESENT VALUE OF ENGINE COSTS
C***

PVTB = PVTB \times (TBCT(I) - PVSV - PVDEF) \times FCT2
PVEB = PVEB \times EBCT(I) \times FCT2
PV0H = PV0H + OHCT(I) \times FCT2
PVMR = PVMR + RCT(I) \times FCT2
PVRP = PVRP + EDTCT(I) \times FCT2

RETURN
END
SUBROUTINE EXPON(XMX, AV, XMN, C)
FUNCTIONS : Generates a truncated exponential random variable

ARGUMENTS : 
XMX - maximum value
AV - average value
XMN - minimum value
D - variable generated by the subroutine

FUNCTIONS CALLED : RAND

COMMON/BLK6/ISEED, ISEED
R=RAND(ISEED)
D=-AV*ALOG(R*EXP(-XMX/AV)+(1.-R)*EXP(-XMN/AV))
RETURN
END
SUBROUTINE WBL(A,B,G,TIME)

FUNCTIONS : GENERATE A WEIBULL RANDOM VARIABLE

ARGUMENTS : A - FAILURE RATE WEIBULL PARAMETER
             B - DISPERSION PARAMETER
             C - FAILURE-FREE PERIOD PARAMETER
             TIME - A WEIBULLY DISTRIBUTED RANDOM VARIABLE.

INPUT/OUTPUT : NONE

COMMON/BLK6/ISEED, ISEED0
R=1,-RAN(D(ISEED))
IF(R.EQ.0)R=1.E-10
TIME=G+B*((-ALOG(R))**(1./A))
RETURN
END

SUBROUTINE WBL CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

FUNCTIONS : GENERATE A WEIBULL RANDOM VARIABLE

ARGUMENTS : A - FAILURE RATE WEIBULL PARAMETER
             B - DISPERSION PARAMETER
             C - FAILURE-FREE PERIOD PARAMETER
             TIME - A WEIBULLY DISTRIBUTED RANDOM VARIABLE.

INPUT/OUTPUT : NONE

COMMON/BLK6/ISEED, ISEED0
R=1,-RAN(D(ISEED))
IF(R.EQ.0)R=1.E-10
TIME=G+B*((-ALOG(R))**(1./A))
RETURN
END
SUBROUTINE AVL8(AGE, F0, F1, AV)

FUNCTIONS: GENERATE A TIME DEPENDANT EXPONENTIAL ESTIMATE FOR MINOR FAILURE AND SERVICE AVAILABILITY RATE.

ARGUMENTS: AGE - ENGINE AGE OR TRUCK AGE
            F0 AND F1 - MODEL CONSTANTS
            AV - AVAILABILITY ESTIMATE

AV = EXP(-F0 - F1*AGE/1000.)
RETURN
END

FUNCTION RAND

FUNCTIONS: TO GENERATE A UNIFORM PSEUDORANDOM NUMBER BETWEEN 0 AND 1. THE CODE IS MACHINE DEPENDANT AND AT PRESENT IS ADAPTED TO A MACHINE OF 35 BITS/WORD. MACHINE AUTOMATIC TRUNCATION AT OVERFLOW IS USED FOR TIME SAVING.

ARGUMENTS: ISEED - THE LAST RANDOM INTEGER GENERATED BY THE CODE (BETWEEN 2 AND 2**35). IF FIRST CALL ISEED MUST BE INPUT.

ERROR MESSAGES: SOME COMPUTERS PRODUCE AN 'INTEGER OVERFLOW' ERROR MESSAGE BUT IT DOES NOT HAVE INFLUENCE ON THE QUALITY OF THE NUMBERS GENERATED.

FUNCTION RAND (ISEED)
ISEED = ISEED * 3125
RAN = ISEED
RAND = RAN / 34359738337.0
RETURN
END
APPENDIX B

A Description of the Data Processing from Historical Records.
Record-keeping Required by the Model

For the application of the mathematical model, a minimum amount of record keeping is necessary. Three types of records will be described here as the most important for the application of the model;

1. **Haulage Statistics.** Daily and monthly report for each truck including the following information:
   - Number of loads and tons hauled
   - Hauling, standby and operation delay times.
   - Downtime coded at least into three groups:
     a) Due to engine repair and service.
     b) Due to truck repair and service.
     c) Due to reasons not related to repair

   Downtime coding is perhaps the most important part of these records regarding to failure analysis.

2. **Engine Historical Records.** Each engine should have an individual file. The format is should be designed in such a way that at least the following information can be easily obtained:
   a) Date of purchase, delivery price, serial number and other information of general character.
   b) Date, engine age and number of the truck powered at the time of occurrence of every event reported.
   c) Total engine repair downtime, total cost, and description for every major engine repair, indicating
whether the repair was planned or performed after failure.

d) Estimated total engine downtime and cost resulting from minor engine repairs and service, by months.

3. Cost Report.- Costs should be recorded by cost centers and clearly associated with a reference number or work order number. The number of cost centers depends upon the importance of the system but in any case, engine, tires and fuel, lube and servicing should have separate centers.

Parameter estimation for the Major Wear-out failure Weibull Model.

Each interval of engine operation between two consecutive engine rebuilds is assumed to follow a different reliability Weibull function. However, in practice it is possible that only the first and perhaps the second rebuild occurrences are available. In this case, Weibull parameters for the unavailable operation intervals should either be obtained by extrapolation of the trends observed for available rebuild intervals or assumed to be constant after the last rebuild interval recorded. The last method (constancy) assumes that no further deterioration will result from succeeding rebuilds and this method is the one recommended. However, at least the parameters for the second rebuild
must be obtained from actual data records. The results will be conservative (engine replacement delayed) and will not be far from the best policy because of the fact that most of the reliability decrease takes place as a consequence of the first engine rebuild.

To estimate the Weibull parameters from a sample of N observations of "time to rebuild" obtained from the engine historical records, a least square method proposed by Mutmansky (1968) was used. The step-by-step procedure is as follows:

   a) Rank time-to-rebuild times \( t_i \) in ascending order.

   b) Estimate the value of the probability of failure function \( F(t_i) \) at time \( t_i \) by the mean ranks method, where:

   \[
   F(t_i) = \frac{i}{N + 1}
   \]

   when \( i \) is the rank of the observation \( t_i \) and \( N \) is the total number of failure times available.

   c) Obtain the Weibull linearized function variables X and Y, as shown in chapter IV, from the expressions
\[ Y_i = \ln \ln \frac{1}{1 - F(t_i)} \]

\[ X_i (\gamma) = \ln (t_i - \gamma) \]

Since the parameter \( \gamma \) is not known, the computerized trial and error process described below is necessary.

\textbf{d}) Apply linear regression analysis to the pairs \((Y_i, X_i (\gamma))\) for different values of \( \gamma \) and find the value of \( \gamma \) which makes the correlation coefficient maximum.

\textbf{e}) Once obtained the equation of the line

\[ Y = AX + B \]

and the value of \( \gamma \), the parameters \( \alpha \) and \( \beta \) are estimated as follows;

\[ \alpha = A \]

\[ \beta = e \times p (-B/A) \]

Table 17, shows an example of the application of the method for the estimation of Weibull parameters for the time to first rebuild.
a) Computation of $F(t_i)$ from failure data by 'mean ranks'.

<table>
<thead>
<tr>
<th>$i$</th>
<th>$t_i$</th>
<th>$F(t_i) = i/(N+1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5501</td>
<td>0.06</td>
</tr>
<tr>
<td>2</td>
<td>5650</td>
<td>0.13</td>
</tr>
<tr>
<td>3</td>
<td>6562</td>
<td>0.19</td>
</tr>
<tr>
<td>4</td>
<td>6903</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>7218</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>7220</td>
<td>0.38</td>
</tr>
<tr>
<td>7</td>
<td>8110</td>
<td>0.44</td>
</tr>
<tr>
<td>8</td>
<td>9002</td>
<td>0.50</td>
</tr>
<tr>
<td>9</td>
<td>9022</td>
<td>0.56</td>
</tr>
<tr>
<td>10</td>
<td>9310</td>
<td>0.63</td>
</tr>
<tr>
<td>11</td>
<td>9466</td>
<td>0.69</td>
</tr>
<tr>
<td>12</td>
<td>10262</td>
<td>0.75</td>
</tr>
<tr>
<td>13</td>
<td>10531</td>
<td>0.81</td>
</tr>
<tr>
<td>14</td>
<td>10589</td>
<td>0.88</td>
</tr>
<tr>
<td>15</td>
<td>11323</td>
<td>0.94</td>
</tr>
</tbody>
</table>

b) Trial and error least square method for Weibull parameter estimation (Mutmansky, 1968).

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.21</td>
<td>9176</td>
<td>0.97485</td>
</tr>
<tr>
<td>3500</td>
<td>2.81</td>
<td>5578</td>
<td>0.97977</td>
</tr>
<tr>
<td>4000</td>
<td>2.43</td>
<td>5051</td>
<td>0.98019</td>
</tr>
<tr>
<td>4100</td>
<td>2.35</td>
<td>4945</td>
<td>0.98020 * BEST CORRELATION</td>
</tr>
<tr>
<td>4200</td>
<td>2.27</td>
<td>4839</td>
<td>0.98015</td>
</tr>
<tr>
<td>4300</td>
<td>2.19</td>
<td>4733</td>
<td>0.98004</td>
</tr>
</tbody>
</table>

**TABLE 17 : Method for Weibull Parameter Estimation**
In Figure 11, the failure observations have been plotted on base-10 semilog paper.

The minimum number of failure observations required for a meaningful estimation of the Weibull parameters is 7 (King, 1965). In the case presented in Table 17 and Figure 11, 15 observation of time to first rebuild were used and the correlation coefficient obtained indicated a significant linearity for 99% level of confidence using the F-of-Fisher's test for adequacy of the linear model.

Several other methods for Weibull parameter estimation can be found in any text on reliability or mathematical statistics.

A thorough analysis on the Weibull distribution can be found in Johnson and Koth (1970). Of special interest for the estimation of $F(t_i)$ from failure observations is the method of median ranks proposed by Johnson (1951) which is more efficient than the used here for small failure samples.

Mean Failure Rate Parameter Estimation for Chance Major Failures

Mean failure rate $r(t)$, (defined in chapter II), was
WEIBULL PARAMETER ESTIMATION (NEW ENGINES)

(t = time to rebuilt)

\[ Y_1 = \log_{10}(\log_{10} \frac{1}{1 - F(t)}) \]

\[ Y_2 = 1 - F(t) = R(t) \]

\[ X = \log_{10}(t-4100) \]

Equation: \[ Y_1 = 2.3515X - 9.049 \]

Correlation coef. R = 0.9801926

FIGURE 11: Graphical Representation of the Weibull Model for Wear-out Failures on Semi-log paper.
estimated following a method described by Polovko (1968). The model allows for a different value of \( r \) for each operating period between consecutive rebuilds. The model assumes that after engine rebuilds the engine loses part of its previous reliability (deteriorates). An increase of \( r \) after each rebuild should be, in general, expected.

In the case study (chapter VI) the information on chance failure after the first rebuild was not sufficient to detect a significantly different failure rate for new and overhauled engines and hence the value of \( r \) was assumed to be constant throughout the life of the engine.

The step-by-step technique is as follows:

a) A time interval is selected in such a way that each time class contains enough failures to produce stable results (a minimum of two failures per class is recommended).

b) The failure rate \( r_i \) for the time class \( i \) is then obtained from the expression:

\[
\hat{r}_i = \frac{n_i}{N_{av} \Delta t}
\]

where:
- \( n_i \) = number of observations in class \( i \)
- \( N_{av} \) = number of engines which have not failed at time \( t_i \) where \( t_i \) is the midpoint for class \( i \).
At = time interval.

Figure 12 shows the histogram obtained by the above method. Failure rate is sensibly constant between 0 and 5,000 hrs. and increases sharply after 5,000 hrs.

The failure rate increase after 5,000 hrs. represents the beginning of the wear-out region where failures are no longer due to chance but to generalized wear-out of major engine elements. It can be said that the failures which occurred after approximately 4,000 hrs. of major failure-free operation of a given engine, should have been repaired by an engine rebuild rather than just a partial major repair. From the above reasoning, the potential benefits of failure analysis are evident since it is obvious that the partial repair decision was erroneous.

The mean failure rate $\lambda$ is obtained as the reciprocal of the mean time to failure:

$$\lambda = \frac{1}{T}$$

$$T = \frac{\sum_{i=1}^{N} t_i}{N}$$

where: $t_i$ = time to chance failure i

$N$ = total number of failure observations

$T$ = mean time to failure

$\lambda$ = mean failure rate

and the probability of failure after t hours of failure-
a) Failure-free time classification for a sample of 21 major chance failures, using a time interval of 1000 engine hours.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>n(i)</th>
<th>N_av</th>
<th>r(i) x 10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1000 hrs.</td>
<td>4</td>
<td>19.5</td>
<td>.21</td>
</tr>
<tr>
<td>1001-2000</td>
<td>7</td>
<td>13.5</td>
<td>.52</td>
</tr>
<tr>
<td>2001-3000</td>
<td>3</td>
<td>9.0</td>
<td>.33</td>
</tr>
<tr>
<td>3001-4000</td>
<td>2</td>
<td>6.0</td>
<td>.33</td>
</tr>
<tr>
<td>4001-5000</td>
<td>2</td>
<td>4.0</td>
<td>.50</td>
</tr>
<tr>
<td>5001-6000</td>
<td>3</td>
<td>1.5</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Mean time to failure = 2441 hrs.
Mean failure Rate = 0.41 x 10^{-3}

b) Histogram of failure rate

FIGURE 12 : Failure Rate for Major Chance Failure
free operation is given by:

\[ F(t) = 1 - \exp (-\lambda t) \]

Estimation of Parameters for the Minor Failure and Service Maintenance Model

Engine downtime due to minor failures and engine service and maintenance was estimated as follows:

Let:

- \( DW_{ij} \) = Total downtime due to minor failure and engine service maintenance for engine i during time period j (hours).
- \( OP_{ij} \) = Total engine hours run by engine i during time period j.
- \( t_{ij} \) = Average age (engine hour meter reading) of engine i during time period j (the average of the engine age at the beginning and at the end of the time period).

then, the average engine minor repair availability rate is obtained as:

\[ A_{ij} = \frac{OP_{ij}}{OP_{ij} + DW_{ij}} \]
The values of $A_{ij}$ and $t_{ij}$ were calculated for 6-month periods for 20 engines operating over a period of two years. A computer routine was employed. The pairs $A_{ij}, t_{ij}$ were used to estimate the parameters $s$ and $d$ of the equation:

$$A(t) = \exp(-s - d \ t) \quad t= \text{engine age}$$

Applying linear regression analysis to fit the logarithmic transform:

$$\ln A(t) = -s - d \ t$$

Since average availability is the mean value of a random variable, the time period $j$ should include a sufficient number of repair and maintenance events to allow total downtime to approach its expected value. For the case study, time periods of six months (24 hours operation schedule) were used and the correlation was significant at the 99% level.

An excessively long time interval would result in a lower sensitivity of the model, and a very short period would generate a totally random estimation of availability.

As a rule of thumb a time period equivalent to 2000 to 3,000 hrs. of engine operation is recommended.
Estimation of Parameters for the Major Repair Downtime Model

Engine major repair and rebuild times should be recorded for each individual major failure and records for scheduled and non-scheduled repairs should be kept separately.

The truncated exponential distribution is used to estimate downtime because it requires very simple record-keeping and computation for the estimation of parameters.

For both scheduled and non-scheduled repair downtime records, the average, maximum and minimum values are easily computed (or estimated from experience), and the probability of a repair causing a downtime \( t \) is given by:

\[
F(t) = \frac{\exp\left(-t_{\text{min}} / \bar{t}\right) - \exp\left(-t / \bar{t}\right)}{\exp\left(-t_{\text{min}} / \bar{t}\right) - \exp\left(-t_{\text{max}} / \bar{t}\right)} \quad (t_{\text{min}} < t < t_{\text{max}})
\]

where:

\( \bar{t} = \) average downtime
\[ t_{\text{min}} = \text{minimum downtime} \]
\[ t_{\text{max}} = \text{maximum downtime} \]

**Engine Repair Cost Estimation**

The repair cost model is also the truncated exponential function. Similarly, cost records for scheduled and non-scheduled repairs are modeled by different exponential functions.

For minor repair and service the cost variable is unit repair cost per hour of engine downtime due to minor repairs. Therefore, the model makes the assumption that the cost of a minor repair is proportional to the time required to do it. This assumption is perfectly acceptable and greatly simplifies the record-keeping and computational requirements.
APPENDIX C

Typical Failure Laws
Time to failure can be characterized by a variety of probability functions. The selection of the failure model should be based on considerations such as;

i) Physical Characteristics of the Failure.- A failure can be caused by a manufacturing defect during the 'burn-in' period. It can also occur by chance during normal operation or it can result from the wear-out of the equipment. The 'burn-in' period is characterized by a decreasing failure rate and the 'wear-out' failures have an increasing failure rate (see Chapter II).

ii) Variation of Failure Rate in Normal Operation.- During the normal operation period, some types of systems suffer an 'aging' process. The number of failures per unit time tend to increase as the time of operation increases. This is normally the case of those systems where the repair and maintenance activities are incomplete and hence, after each repair, the system is not restored back to its 'as good as new' state.

In other cases, the failure rate remains constant throughout the life of the system (the system does not age).

Also, in some cases, the failure rate tends to decrease with time and the system becomes more reliable. This is the case of some steel alloys having a 'work hardening' property, where the quality and resistance improves with operating time.
iii) Objectives of the Analysis.- In some cases, where the accuracy required is not high, systems that age can be modeled by a constant failure rate (exponential) model, thus greatly simplifying the analysis. In other applications, however, more accurate failure analysis is imperative due to safety considerations.

In this appendix, the probability functions most widely used in the analysis of failure will be described.

The following failure laws will be presented:

- Exponential
- Rayleigh
- Truncated Normal
- Log-Normal
- Gamma
- Weibull
- Other Special Failure Models

The Exponential Law

For many years, the exponential failure law was used almost exclusively. It is still one of the preferred models due to its simplicity and analytical advantages.

If a constant failure rate is assumed, then;

\[ r(t) = \lambda = \text{constant} \]
and:

\[ F(t) = 1 - R(t) = 1 - \exp\left(-\int_0^t \lambda \, dt\right) = 1 - \exp(-\lambda t) \]

\[ f(t) = \frac{dF(t)}{dt} = \lambda \exp(-\lambda t) \]

\[ T = \text{Mean time to failure} = \frac{1}{\lambda} \]

\[ \lambda > 0 \quad ; \quad t \geq 0 \]

The exponential probability functions are shown in Figure 13.

A particular case of exponential distribution is the truncated-exponential distribution. The truncated-exponential model assumes that the value of the exponential random variable has upper and lower bounds. When the upper bound is infinity (unbounded), the distribution is said to be 'truncated below'. If the upper bound is finite and the lower bound is zero, the distribution is referred to as 'truncated above'.

The truncated-exponential law is widely applied in reliability theory where the random variable is frequently bounded. As an example, the distribution of repair times for a given failure mode must have some bounds resulting from the physical characteristics of the activities required to perform the repair. Due to similar reasons, the distribution of repair costs for a given type of repair, would also be bounded within some limits.
FIGURE 13: Exponential and Rayleigh Failure Laws

a) Exponential Law

b) Rayleigh Law
The truncated-exponential density function is given by:

\[ f(t) = k \lambda \exp(-\lambda t) \quad t_1 < t < t_2 \]

Where \( \lambda \) is the mean failure rate parameter, \( t_1 \) is the lower bound on the value of the random variable \( t \) and \( t_2 \) is the upper bound on \( t \).

The parameter \( k \) (truncation parameter) is obtained from the following condition:

\[
\int_{t_1}^{t_2} f(t) \, dt = 1
\]

And by solving the above equation;

\[
k = \frac{1}{\exp(-\lambda t_1) - \exp(-\lambda t_2)}
\]

The cumulative function \( F(t) \) is given by:

\[
F(t) = \int_{t_1}^{t} f(t) \, dt = \frac{\exp(-\lambda t_1) - \exp(-\lambda t)}{\exp(-\lambda t_1) - \exp(-\lambda t_2)}
\]

The Rayleigh Law

Here, the failure rate is assumed to increase linearly with time. Then:

\[
r(t) = t/s^2
\]
and; \[ F(t) = 1 - R(t) = 1 - \exp\left(-\frac{t^2}{2s^2}\right) \]

\[ f(t) = \frac{t}{s} \exp\left(-\frac{t^2}{s^2}\right) \quad (t > 0) \]

\[ T = \text{Mean time to failure} = (\sqrt{2})s \]

\[ s = \text{Parameter of the Rayleigh law} \]

The Rayleigh probability functions are shown in Figure 13.

**The Truncated Normal Law**

The probability density function of the truncated-normal law is given by:

\[ f(t) = \frac{b}{\sigma \sqrt{2\pi}} \exp\left[-\frac{1}{2}(t - \mu)^2/\sigma^2\right] \quad t > 0 \]

The parameters \( \mu \) and \( \sigma \) are the mean and standard deviation respectively. The parameter \( b \) (truncation parameter) is obtained from the following condition:

\[ \int_0^t f(t) \, dt = 1 \]

The value of \( b \) obtained from the above equation is given by the following expression:

\[ b = \frac{1}{F\left(-\mu/\sigma, 0, 1\right)} \]
The value of $F(-\mu/\sigma, 0, 1)$ is the value of the standard cumulative normal distribution $F(t)$ for $t = -\mu/\sigma$. The function $F(t)$ is given by:

$$F(t) = \frac{b}{\sqrt{2\pi}} \int_{0}^{t} \exp\left[-\left(\frac{u-\mu}{\sigma}\right)^2\right] du$$

and the failure rate $r(t)$ (Polovko, 1968) is given by:

$$r(t) = \frac{2/\sqrt{\pi} \exp\left[-\left(\frac{t-\mu}{\sigma}\right)^2\right]}{\sigma \left[1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left(-\frac{x^2}{2}\right) dx\right]}$$

Where: $\phi(x) = \sqrt{\pi} \int_{-\infty}^{x} \exp(-t^2) dt$

The normal law has an increasing failure rate (IFR), thus, it can be applied to characterize the reliability of aging (IFR) systems. It is also applied to characterize failure in the wear-out period (see Chapter II).

Gnedenko et al (1969) proposes a general model that leads to the normal reliability law: Suppose that the reliability of a device can be expressed as a function of the parameters $r_0$ and $r$, such that:

$$r = f(t, r_0)$$

Where $r_0$ is a normal random variable related to the initial state of the device and $r$ is an increasing function of time. Furthermore, the device fails when, at time $t = T$, the value of $r$ reaches a critical value $r_1$. Then, the instant of failure is determined by the following expression:
Gnedenko shows that the time $T$ is a normal random variable.

In Figure 14, the failure characteristics of the normal model are shown.

The Log-Normal Law

$$f(t) = \frac{1}{t \ln(g) \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\ln(t) - \ln(\tilde{g})}{\ln(g)}\right)^2\right]$$

$$F(t) = \frac{1}{t \ln(g) \sqrt{2\pi}} \int_0^t \exp\left[-\frac{1}{2} \left(\frac{\ln(t) - \ln(\tilde{g})}{\ln(g)}\right)^2\right] dt$$

The failure rate: $r(t) = \frac{f(t)}{R(t)}$ has a complicated mathematical expression. Its value increases from $t=0$ and reaches a maximum value, and then decreases.

The log-normal probability Law (Barlow and Proschan, 1965), has been widely used to characterize the distribution of repair times.

In the above expressions, the parameters $g$ and $\tilde{g}$ are the antilogarithms of the mean and standard deviation of the log-transformed data, respectively and thus are easily computed from failure or repair data.
FIGURE 14: Normal and Lognormal Failure Laws

a) Normal Failure Law

b) Log-Normal Failure Law
The Gamma Law

\[ f(t) = \lambda_0 \frac{(\lambda_0 t)^{k-1}}{(k-1)!} \exp(-\lambda_0 t) \]

\[ F(t) = \exp(-\lambda_0 t) \sum_{i=0}^{k-1} \frac{(\lambda_0 t)^i}{i!} \]

\[ r(t) = \frac{\lambda_0 (\lambda_0 t)^{k-1}}{(k-1)! \sum_{i=0}^{k-1} \frac{(\lambda_0 t)^i}{i!}} \]

where: \( k \) = a positive integer
\( \lambda_0 > 0 \)
\( t \geq 0 \)

\[ T = \text{Mean Time to Failure} = \frac{k}{\lambda_0} \]

In general, the parameter \( k \) is not necessarily an integer, and in the general case the expressions for \( F(t) \) and \( r(t) \) would be integral equations.

When \( k=1 \), the gamma distribution becomes the exponential distribution. For \( k>1 \), the function has an increasing failure rate and for \( k<1 \) the failure rate is decreasing.

The gamma function can adopt a great variety of shapes, and hence it can be satisfactorily applied to
FIGURE 15 : Gamma and Weibull Failure Laws

a) Gamma Failure Law

Rs(t) = \frac{\beta^\alpha}{\Gamma(\alpha)} t^{\alpha-1} e^{-\beta t}

f(t) = \frac{\beta^\alpha}{\Gamma(\alpha)} t^{\alpha-1} e^{-\beta t}

F(t) = 1 - e^{-\beta t}

b) Weibull Failure Law

R(t) = e^{-\beta t}

f(t) = \frac{\beta\alpha}{\beta^\alpha} (t^{-\alpha})^{\alpha-1} e^{-\beta t}

F(t) = 1 - e^{-\beta t}
many failure patterns. Polovko (1968), states that the gamma function satisfactorily represents the distribution of times to failure of some redundant systems.

Barlow and Proschan (1965), show that when the time to failure is exponential, then the probability of failure of a device having failed \( n \) times follows the gamma distribution. The gamma model has also been used to characterize failure during the burn-in period (for \( k < 1 \)).

The Weibull law

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

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

\[
r(t) = \frac{\alpha}{\beta} \left( \frac{t - \gamma}{\beta} \right)^{\alpha - 1}
\]

\[
T = \text{Mean time to Failure} = \gamma + \beta \Gamma\left( \frac{1}{\alpha} + 1 \right)
\]

\( t > 0 \)

\( \alpha > 0 \); \( \beta > 0 \); \( \gamma \geq 0 \)

The Weibull function shape is shown in Figure 15. In Chapters IV and V, the applications of the Weibull model and the methods for the estimation of its parameters are shown.
Other Special Failure Models

The following models have also been used to characterize reliability in some special cases;

i) Modified Extreme Value Distribution

\[
f(t) = \frac{1}{\lambda} \exp \left[ - \frac{\exp(t) - 1}{\lambda} + t \right] \quad (\lambda > 0)
\]

\[
r(t) = \frac{1}{\lambda} \exp(t)
\]

Since the failure rate increases exponentially, the model can be applied to characterize 'wear-out' failures.

ii) Linearly Decreasing Hazard Models

\[
F(t) = 1 - \exp \left[ -(2\lambda t - \lambda^2 t^2) \right]
\]

\[
f(t) = 2\lambda (1-t) \exp \left[ -(2\lambda t - \lambda^2 t^2) \right]
\]

\[
r(t) = 2\lambda (1-t)
\]

This model can be applied to characterize the 'burn-in' period.

iii) Superposition of Exponential Models

\[
f(t) = C_1 \lambda_1 \exp(-\lambda_1 t) + C_2 \lambda_2 \exp(-\lambda_2 t)
\]

Where; \( \lambda_1 < \lambda_2 \) and \( t > 0 \)
\[ R(t) = 1 - F(t) = C_1 \exp(-\lambda_1 t) + C_2 \exp(-\lambda_2 t) \]

\[ r(t) = \frac{C_1 \lambda_1 \exp(-\lambda_1 t) + C_2 \lambda_2 \exp(-\lambda_2 t)}{C_1 \exp(-\lambda_1 t) + C_2 \exp(-\lambda_2 t)} \]

\[ T = \text{Mean time to failure} = \frac{c_1}{\lambda_1} + \frac{c_2}{\lambda_2} \]

In this model, the failure rate initially decreases but after some time \( t \), the model becomes exponential since the terms in \( \lambda_1 \) become much larger than the terms in \( \lambda_2 \). The above property makes this function ideal to characterize constant failure rate systems whenever the 'burn-in' period has to be considered.

iv) Power Series Models

\[ r(t) = k_0 + k_1 t + k_2 t^2 + \ldots + k_n t^n \]

\[ F(t) = 1 - \exp \left[ -\left( k_0 t + k_1 t^2/2 + k_2 t^3/3 + \ldots + k_n t^{n-1}/(n-1) \right) \right] \]

\[ f(t) = (k_0 + k_1 t + \ldots + k_n t^n) \exp \left[ -\left( k_0 t + k_1 t^2/2 + \ldots \right) \right] \]

v) Piecewise-Linear Models

In this case, the failure rate is defined as a different linear function for each of the time regions considered.