Decision support for determining steady state production rates as a function of repair policy.

Lydia Ann Chastain
DECISION SUPPORT FOR DETERMINING STEADY STATE PRODUCTION RATES AS A FUNCTION OF REPAIR POLICY

by

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May 10, 1981
Date

Professor in Charge

Chairman of Department
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ABSTRACT

General studies of decision making and studies of specific decisions have indicated the potential benefits of computer support for decision making. The name Decision Support System (DSS) emphasizes the role which computer-based support plays with respect to users. DSS can be defined as systems applicable to problems which are at least partially, but not completely, structurable. DSS provide high level operations for retrieving data, generating alternative solutions, and evaluating these alternatives.

The purpose of this research is to develop a decision support framework that can be used to aid the designer in predicting operating characteristics of a system. The procedure proposed is based on an analytical model to obtain the steady state production rate of the Primer Insert Submodule used in small caliber ammunition. A continuous Markov process was used to model the system. The methodology and techniques presented in this study involve 1) taking information currently available on existing systems, 2) projecting these parameters into the future time frame in which the system will become operable, and 3) using these projected parameters and the proposed methodology for decision support to determine the early prediction of system operating characteristics. Applications of these
techniques will provide a rational basis for investigating steady state capabilities and evaluating policies for allowed failures. The final results from the application of the methodology presented is a model for specifying possible courses of action and a program which will achieve an optimum balance between maintenance and logistics on one hand and equipment performance on the other for a given state of operational readiness. It is still up to the user, however, to select each specific alternative to be assessed.
CHAPTER I

INTRODUCTION

General studies of decision making and studies of specific decisions have indicated the potential benefits of computer support for decision making. The name Decision Support System (DSS) emphasizes the role which computer-based support plays with respect to users. DSS provides high level operations for retrieving data, generating alternative solutions, and evaluating these alternatives. They are designed to help decision makers cope with partially structured decision tasks. If a problem is partially structured, it is possible to bring some structure to the problem if the decision maker is willing to accept a certain data set or certain processing routines as relevant to the problem solution. DSS are better defined as systems applicable to problems which are at least partially, but not completely, structurable. A good DSS brings as much structure to the problem as possible. A decision maker is faced with a problem in which 1) relevant information for decision making is unavailable, 2) alternatives are unknown, or 3) appropriate values for making a choice are unknown. The purpose of DSS is to facilitate the judgment process as one attempts to contend with these unknowns.

The purpose of this research is to develop a decision
support framework that can be used to aid the designer in predicting operating characteristics of a system. The procedure proposed is based on an analytical model to obtain the steady state production rate of the Primer Insert Sub-module used in small caliber ammunition. A continuous Markov process was used to model the system. The methodology and techniques presented in this study involve 1) taking information currently available on existing systems, 2) projecting these parameters into the future time frame in which the system will become operable, and 3) using these projected parameters and the proposed methodology for decision support to determine the early prediction of system operating characteristics. If the designer had this computer-based support available, he could then estimate the reliability, availability, maintainability, and sparing procedures of the system in order to evaluate competing designs.

In this study, a general application is presented and the techniques for applying decision support capabilities to the Markov process are demonstrated to predict the expected steady state production rate as a function of repair policy. Applications of these techniques will provide a rational basis for investigating steady state capabilities and evaluating policies for allowed failures. The final results from the application of the methodology presented will be a model for specifying possible courses
of action and a program which will achieve an optimum balance between maintenance and logistics on one hand and equipment performance on the other for a given state of operational readiness. It is still up to the user, however, to select each specific alternative to be assessed.

This study is divided into five sections including the introduction. Chapter II describes the Markov process as it is related to the Primer Insert Submodule. The approach is discussed and structured in order to evaluate the production of the Submodule.

Chapter III depicts the physical configuration of the Primer Insert Submodule. The Markov process described in Chapter II is then modeled for the process flowchart of the Submodule. Several sets of data are described which are necessary input for the model's calculation. The results of the calculations are then tabulated.

Chapter IV concludes the study and suggests recommendations. The Appendices follow this chapter and include a deck setup, a program listing, and a sample output for the application language used.
CHAPTER II

MATHEMATICAL MODEL

This chapter develops an analytical model to obtain the steady state production rate of a turret type submodule for Primer Insert. A decision was made to approach the problem by enumerating the states in which the system will exist. The basic configuration of the system, a series of turrets with 24 stations per turret, led to the concept of treating the system as a collection of 24 equal independent parallel elements and a number of series elements.

![Diagram of basic configuration]

Figure 1. Basic Configuration.

The kth parallel element represents the composite of all equipment associated with station k on all turrets, the failure of which will cause failure of line k and hence cause a reduction of 1/24 in the production rate, but would not force the entire submodule to be shut down. The
series element mathematically represents all failures in the submodule which would cause mandatory shutdown of the entire submodule for repair.

By carefully cataloging all elements in the submodule into one of these failure classes and obtaining reasonable estimates on mean failure and repair times, one can, through statistical analysis, obtain composite MTBFs and MTTRs for each parallel and series element, and hence the failure and repair rates.

A continuous Markov process was used to model the system. The basic assumption of a Markov process is that the state of the system at future times depends only on the present state and not on past states. The states of the system are given as follows:

<table>
<thead>
<tr>
<th>State</th>
<th>System Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Zero failures present, system operating</td>
</tr>
<tr>
<td>1</td>
<td>One parallel line failed, system operating</td>
</tr>
<tr>
<td>2</td>
<td>Two parallel lines failed, system operating</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>n-1</td>
<td>n-1 parallel lines failed, system operating</td>
</tr>
<tr>
<td>n</td>
<td>n parallel lines failed, shutdown for repair</td>
</tr>
<tr>
<td>n+1</td>
<td>A series element has failed, shutdown for repair</td>
</tr>
<tr>
<td>n+2</td>
<td>Series plus one parallel line failed, shutdown for repair</td>
</tr>
<tr>
<td>n+3</td>
<td>Series plus two parallel lines failed, shutdown for repair</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>2n</td>
<td>Series plus (n-1) parallel lines failed, shutdown for repair</td>
</tr>
</tbody>
</table>

The value of n is varied from 1 to 10 to obtain the best
management policy for the rates given.

Further assumptions made for the model are:

(1) The probability density functions for all failures and repairs are exponential.

(2) The probability of multiple failures in \((t, t+dt)\) is negligible, i.e., transitions from state 0 to state 2 directly are impossible.

(3) No failures may occur in a repair state.

The following state diagram, Figure 2, was developed to aid in analyzing the structure of the model.

Figure 2. State Diagram.

The numbered circles represent the states previously described. The expressions on the connecting arrows represent
sent the conditional transition rates for communicating between states, that is:

\[ p = \text{the failure rate of one parallel line} \]
\[ p^* = \text{the failure rate for a series failure} \]
\[ r_n = \text{the repair rate for } n \text{ failed rotary tools} \]
\[ r^* = \text{the repair rate for a series failure} \]
\[ r^*k = \text{the repair rate for a series plus } k \text{ failed rotary tools}. \]

Define \( P_i(t) \) as the probability of being in state \( i \) as a function of time, \( i = 0, 1, \ldots, 2n \). It is now possible, using the state diagram, to write a set of equations expressed in matrix form as:

\[
\frac{d\bar{P}}{dt} = A\bar{P}
\]

Specifically:

\[
\frac{dP_0}{dt} = -(2^4p+p^*)P_0 + rP_1 + r^*P_1 + r^*P_{n+1} + r^*P_{n+2} + \ldots + r^*P_{n-1}P_{2n}
\]

\[
\frac{dP_i}{dt} = (25-i)pP_{i-1} - [(24-i)p + p^*]P_i
\]

\( , i = 1, 2, \ldots, n-1 \)

\[
\frac{dP_n}{dt} = (25-n)pP_{n-1} - rP_n
\]

\[
\frac{dP_k}{dt} = p^*P_{k-1} - r^*P_{k-1} - k
\]

\( , k = n+1, n+2, \ldots, 2n \)
Since the system must exist in one of the states specified, we have the additional equation

\[ P_0 + P_1 + \ldots + P_{2n} = 1 \]

It was decided that steady-state probabilities were sufficient for the purpose of this study. Hence, setting all time derivatives equal to zero in the above equations one obtains

\[ P_1 = \frac{24p}{23p + p^*} \cdot P_0 \]

\[ P_i = \frac{(25-i)p}{(24-i)p + p^*} \cdot P_{i-1} \quad , i = 2, 3, \ldots, n-1 \]

\[ P_n = \frac{(25-n)p}{r_n} \cdot P_{n-1} \]

\[ P_k = \frac{p^*}{r^*} \cdot P_{k-1} \quad , k = n+1, \ldots, 2n \]

It is observable that in the above equations all probabilities \( P_i, i=1, \ldots, 2n \), are defined in terms of a lower numbered probability. For example,

\[ P_2 = \frac{23p}{22p + p^*} \cdot P_1 \]

One may thus avoid using matrix inversion techniques in solving these equations.

The approach taken in the enclosed FORTRAN program
was to solve all $P_i, i=1,2,...,2n$, in terms of $P_0$.

By substituting into the equation $\sum_{k=0}^{2n} P_k = 1$, one may solve explicitly for $P_0$ and use this value to directly solve for all remaining $P_k$. Given the estimates of failure and repair parameters, the program varies $n$, the number of turret stations allowed to fail before shutdown for repair. The output printed is the steady state production rate, $\text{PROD}$, and the probability of being in a repair state, $\text{DOWN}$, as a function of $n$, where

\[
\text{PROD} = \sum_{k=0}^{n-1} P_k \cdot \frac{(24-k)}{24 \cdot \text{PMAX}},
\]

\[
\text{PMAX} = \text{Maximum production rate}
\]

and

\[
\text{DOWN} = P_n + P_{n+1} + \ldots + P_{2n}
\]
CHAPTER III

PRIMER INSERT SUBMODULE

Description of Submodule

The primer insert submodule's function is to insert primers into bullet cases. Six rotary turrets and other driving, inspecting, and feeding devices make up this submodule. The process flow is as follows:

1. Bullet cases are loaded onto a carrying chain by the Chain Loading Turret. A case is not loaded into a chain loading position if a corresponding downstream tool station is down.

2. Primers are placed into primer cups of the cases by the Primer Insert Turret.

3. Primers are permanently fastened into the cases by the Primer Crimp Turret.

4. The primer's position in the bullet cases is checked by the Primer Inspect Turret. If a defect is detected, the case will be ejected by the Reject and Unload Turret further downstream.

5. The primers are then sealed in the cases with a lacquer and the inside mouth of the case is coated with a varnish. These operations are done by the Sealant Application Turret. Two optical inspection stations check the process.

6. Defective cases are ejected by the Reject and Unload Turret. Cases not rejected are sent on to the Load and Assemble Submodule.

For the purpose of modeling, repair actions connected with the Primer Insert Submodule were broken into two distinct classifications, 1) those concerned with the
failures of the rotary turrets tools (parallel failures), and 2) those concerned with failures that cause the entire submodule to shut down (serial failures). The types of parallel failures considered by the model are chain loading turret tool failures, primer insert tool failures, crimp turret tool failures, primer inspect turret tool failures, sealant application turret tool failures, and reject and unload turret tool failures.

The types of serial failures considered are primer feed tray failure, which is the detonation of primers in the feed tray or the improper feeding of primers; jam failure, which is when a bullet case jams in one of the rotary turrets or elsewhere in the submodule; electrical failures, which are the power failures or the failure of an inspection station; turret series failure, which is the failure of the turret driving mechanism; and chain failures, in which the chain breaks, derails, or fails in some other manner.

A failure of a single tool on one of the six turrets (each containing 24 tools) decreases the production rate of the Primer Insert Submodule by fifty rounds per minute. Each subsequent failure of a rotary tool decreases the production rate by another fifty rounds per minute. Repair of a rotary tool may or may not be initiated when the tool fails, depending on the repair policy. The submodule must be shut down to effect a repair of a rotary tool. A
serial failure causes the submodule to immediately stop production and repair must be completed before production can resume.

**Process Flowchart**

Figure 3 shows the process flowchart for the Primer Insert Submodule. The series elements in the flowchart do not correspond exactly to the serial elements described in the submodule description. The primer feed and inspect correspond to the primer feed tray of the submodule description. However, the primer inspect and mouth varnish inspect are included in the electrical serial failures.

**Input Data**

Table 1 contains the best estimates available of the failure and repair data for the parallel and serial elements described in the submodule description. To avoid proprietary disclosure, the data used for the purposes of demonstration were fictitious.

**Output and Results**

The program described in Appendix I was used to investigate ten tool repair policies for the primer insert submodule. These repair policies ranged from repair after the first rotary tool failure to repair after the tenth rotary tool failure. Table 2 shows the expected steady
Figure 3. Primer-Insert Submodule Process Flowchart.
Table 1

PRIMER-INSERT FAILURE AND REPAIR ESTIMATES*

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>PARALLEL</th>
<th>SERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MTBF</td>
<td>MTTR</td>
</tr>
<tr>
<td>Chāin Loading Turret</td>
<td>4800</td>
<td>15</td>
</tr>
<tr>
<td>Insert Turret</td>
<td>4800</td>
<td>15</td>
</tr>
<tr>
<td>Crimp Turret</td>
<td>9600</td>
<td>15</td>
</tr>
<tr>
<td>Primer Inspect Turret</td>
<td>2400</td>
<td>15</td>
</tr>
<tr>
<td>Sealant and Lacquer Turret</td>
<td>9600</td>
<td>5</td>
</tr>
<tr>
<td>Unload and Reject Turret</td>
<td>14400</td>
<td>15</td>
</tr>
<tr>
<td>Primer Feed Tray</td>
<td>960</td>
<td>15</td>
</tr>
<tr>
<td>Jam</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Electrical</td>
<td>960</td>
<td>10</td>
</tr>
<tr>
<td>Turret Series Failure</td>
<td>24160</td>
<td>30</td>
</tr>
<tr>
<td>Chain Breakage</td>
<td>6000</td>
<td>30</td>
</tr>
</tbody>
</table>

*Estimates expressed in minutes per tool.

The process time estimates used were:

- Time to Stop = 30 Seconds
- Time to Jog = 2 Seconds
- Time to Start = 60 Seconds
<table>
<thead>
<tr>
<th>No. of Tools Failed Before Shutdown</th>
<th>Expected Steady State Production Rate</th>
<th>Probability of Being Down for Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>817.8</td>
<td>.3185</td>
</tr>
<tr>
<td>2</td>
<td>828.7</td>
<td>.2973</td>
</tr>
<tr>
<td>3</td>
<td>826.5</td>
<td>.2885</td>
</tr>
<tr>
<td>4</td>
<td>821.9</td>
<td>.2833</td>
</tr>
<tr>
<td>5</td>
<td>817.2</td>
<td>.2798</td>
</tr>
<tr>
<td>6</td>
<td>813.0</td>
<td>.2774</td>
</tr>
<tr>
<td>7</td>
<td>809.6</td>
<td>.2756</td>
</tr>
<tr>
<td>8</td>
<td>807.0</td>
<td>.2744</td>
</tr>
<tr>
<td>9</td>
<td>805.1</td>
<td>.2735</td>
</tr>
<tr>
<td>10</td>
<td>803.7</td>
<td>.2729</td>
</tr>
</tbody>
</table>

State production rate and the probability of being down for repair for each of the ten repair policies. The maximum expected steady state production rate occurred when the policy was repair after the second rotary tool failure.

At this point, the decision maker can select alternatives to be assessed based on other factors such as the value of lost production, number of maintenance crewmen available, sparing of equipment, etc. Various combinations of rotary MTBF and MTTR were made for the purpose of
demonstration representing the following combinations:

1. MTBF (best estimate), MTTR (best estimate)
2. 1/2 MTBF, MTTR
3. MTBF, 2MTTR
4. 1/2 MTBF, 2 MTTR
5. 2 MTBF, 2 MTTR
6. MTBF, 1/2 MTTR
7. 2 MTBF, 1/2 MTTR.

These combinations can be read into the program interactively. The results of this sensitivity analysis are shown in Table 3.

Table 3

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Rotary MTBF (Min)</th>
<th>Rotary MTTR (Min)</th>
<th>Optimum Policy Allowed Failures (Tools)</th>
<th>Average Prod. Rate per Shift (Rds/Min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900.000</td>
<td>14.063</td>
<td>2.</td>
<td>828.747</td>
</tr>
<tr>
<td>2</td>
<td>450.000</td>
<td>14.063</td>
<td>3.</td>
<td>651.027</td>
</tr>
<tr>
<td>3</td>
<td>900.000</td>
<td>28.125</td>
<td>2.</td>
<td>658.267</td>
</tr>
<tr>
<td>4</td>
<td>450.000</td>
<td>28.125</td>
<td>3.</td>
<td>462.741</td>
</tr>
<tr>
<td>5</td>
<td>1800.000</td>
<td>14.063</td>
<td>2.</td>
<td>959.840</td>
</tr>
<tr>
<td>6</td>
<td>900.000</td>
<td>7.031</td>
<td>2.</td>
<td>952.026</td>
</tr>
<tr>
<td>7</td>
<td>1800.000</td>
<td>7.031</td>
<td>2.</td>
<td>1037.651</td>
</tr>
</tbody>
</table>
CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

The maximum expected steady state production rate for the primer insert submodule was 828.7 rounds per minute. This optimum policy occurred when the rotary tool repair was initiated after the second rotary failure. The data indicated that the most frequent failures would occur in the primer inspect turret and primer feed or by electrical failure or jam. Detonation was a major cause of failure.

The serial failures contribute to downtime more than the rotary failures. The serial Mean Time Between Failure (MTBF) (81.4 minutes) is significantly less than the rotary Mean Time Between Failure (MTBF) (900 minutes).

The model is fairly insensitive to different tool repair policies. That is, there is no great change in expected steady state production rate in a small range about the optimum tool repair policy. However, the model is sensitive to variations in the parallel MTBF and MTTR estimates. As shown in Table 3, overestimating or underestimating the failure and repair times has a great effect on the expected steady state production rate. The tool policy, however, remains at repair after either two or three tool failures for all seven time combinations. Decisions relating to preventative and corrective maintenance, repair crew scheduling, redundancy, and the value
of lost production could greatly affect the failure and repair times. It is the purpose of this computer-based support to eliminate as many unknowns as possible and to add structure to the problem so that the decision maker can make a satisfactory decision based on other decisions.

It is recommended that the most recent data available be used in determining the tool policies. This data would replace the data in Table 1 and would produce different results.
BIBLIOGRAPHY

Alter, S.L., "Transforming DSS Jargon into Principles for DSS Success," paper presented to DSS-81, Atlanta Georgia, June 8-10, 1981.


APPENDIX I

A. Deck Setup

The computer program is written in FORTRAN 77. The values for MTBF and MTTR can be entered interactively to aid in decision support. These variables may be changed for program operation on a different computer.

The data cards follow the following format:

NP corresponds to number of parallel elements
NS corresponds to number of series elements.

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMN</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21-25</td>
<td>Number of parallel elements</td>
</tr>
<tr>
<td>2 to NP + 1</td>
<td>1-28</td>
<td>Name of turret</td>
</tr>
<tr>
<td></td>
<td>30-39</td>
<td>Mean time between failures $X10^3$ in minutes</td>
</tr>
<tr>
<td></td>
<td>40-49</td>
<td>Mean time to repair in minutes</td>
</tr>
<tr>
<td>NP + 2</td>
<td>21-25</td>
<td>Number of series elements</td>
</tr>
<tr>
<td>NP + 3 to NP + NS + 2</td>
<td>1-28</td>
<td>Name of series element</td>
</tr>
<tr>
<td></td>
<td>30-39</td>
<td>Mean time between failures $X10^3$ in minutes</td>
</tr>
<tr>
<td></td>
<td>40-49</td>
<td>Mean time to repair in minutes</td>
</tr>
<tr>
<td>NP + NS + 3</td>
<td>10-19</td>
<td>Combined starting and stopping time in minutes</td>
</tr>
<tr>
<td></td>
<td>20-29</td>
<td>Jog time in minutes</td>
</tr>
<tr>
<td></td>
<td>30-39</td>
<td>Maximum production rate per minute</td>
</tr>
<tr>
<td>Line</td>
<td>Description</td>
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</tr>
<tr>
<td>------</td>
<td>-------------</td>
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</tbody>
</table>

**dictionary of variables**

- **nturet**: number of turrets, right justified integer
- **turret**: name of turret
- **tmtbf**: mtbf for turret, 10**2**-3 min, floating pt.
- **tmttr**: mttr for turret, floating pt.
- **tss**: combined starting and stopping time for the submodule, minutes, floating pt.
- **jostm**: jost time, minutes, floating pt.
- **fmax**: max. production rate of submodule, 1/min., floating pt.
- **ttr**: mean time to repair derived by averaging the repair time excluding the stop, start, and jost times, minutes, floating pt.
- **rtmtbf**: reciprocal of tmtbf, 10**2**-3 min., floating pt.
- **slm**: tmtbf/mtbf, 10**2**-3 min., floating pt.
- **srmtbf**: summation of 1/mtbf for given data
- **sslm**: summation of tmtbf/mtbf, 10**2**-3 min.
- **ttf**: mean time between failures, 1000/srmtbf
- **ttr**: mean time to repair derived by averaging the repair times excluding stop, start, and jost times, minutes, floating pt.
- **ps**: 1/ttf
- **rs**: 1/ttr
- **n**: number of tools failed before shutdown
- **prod**: expected steady state production, rounds/min.
- **down**: probability of being down for repair
- **ii**: number of variations for sensitivity analysis
- **xhld**: array containing rotary mtbf, rotary mttr, optimum allowed failures(tools), and average
dictionary of variables

00100 00200 00300 00400 00500 00600 00700 00800 00900 01000 01100 01200 01300 01400 01500 01600 01700 01800 01900 02000 02100 02200 02300 02400 02500 02600 02700 02800 02900 03000 03100 03200 03300 03400 03500
c
nturet  number of turrets, right justified integer
turret  name of turret
tmcbf  mtbf for turret; 10**-3 min., floating pt.
tmttr  mttr for turret, floating pt.
tss  combined startings and stoppings time for the submodule, minutes, floating pt.
jostm  job time, minutes, floating pt.
pmax  max. production rate of submodule, 1/min., floating pt.
ttr  mean time to repair derived by averaging the repair time excluding the stop, start, and job times, minutes, floating pt.
rtmcbf  reciprocal of tmcbf; 10**-3 min., floating pt.
slm  mttr/mtcbf, 10**-3 min., floating pt.
srmmcbf  summation of 1/mtcbf for given data
smttr  summation of mttr/mtcbf, 10**-3 min.
ttf  mean time between failures; 1000/srmcbf
ttr  mean time to repair derived by averaging the repair times excluding stop, start, and job times, minutes, floating pt.
ps  1/ttf
rsl  1/ttr
n  number of tools failed before shutdown
prod  expected steady state production, rounds/min.
prob  probability of being down for repair
ii  number of variations for sensitivity analysis
rmttr  arrays containing rotary mtbf, rotary mttr,
xxfld  optimum allowed failures(tools), and average
*production per shift*

dimension f(20), r(10), rfp(10)
dimension xild(25,4)
dimension turret(14)
real Jostm
nanal=0

*assignment of input/output numbers*

open(unit=2,device='dsk',file='test.dat')
open(unit=6,device='tls')
in=2
to=6
iflas=0

read in data on turrets in parallel, then in series

(turret name, mtbf, mttr)

continue

do 251 iu=1,2
read(in,201) nturet
format(20,5)f
if(naturet) 1000,1000,1020
continue

continue

write headings for entered data
07100    write(io,699)
07200    write(io,290)
07300    290 format(i16,name*i38/,mtbf=16e1/mtbf=56.0/mtir/',
07400        t63*,mtir/mtbf '*',t37',10**3*t46',10**-3't55',
07500        t163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
07600    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
07700    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
07800    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
07900    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08000    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08100    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08200    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08300    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08400    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08500    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08600    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08700    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08800    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
08900    + 't163*,mtir/mtbf '*'t37',t164',10**3't46',10**-3't55',
09000    291 format(4:*14.2 t34.4f5.2)
09100    250 continue
09200    291 format(4:*14.2 t34.4f5.2)
09300    250 continue
09400    291 format(4:*14.2 t34.4f5.2)
09500    250 continue
09600    291 format(4:*14.2 t34.4f5.2)
09700    250 continue
09800    291 format(4:*14.2 t34.4f5.2)
09900    250 continue
10000    291 format(4:*14.2 t34.4f5.2)
10100    250 continue
10200    291 format(4:*14.2 t34.4f5.2)
10300    250 continue
10400    291 format(4:*14.2 t34.4f5.2)
10500    250 continue
10600    291 format(4:*14.2 t34.4f5.2)
10600  go to (210,211), ij
10700  10800  210  trl=ttf
10900  ttf=ttf
11000  211  write(io,294) ttf
11100  294  format(///r8.2,vtmtr= mean time to repair derived by \\
11200  \"averaging the repair\",//16x\"times excluding stop\",\"
11300  \"job and start times\",//8.0\"mtr = \"f9.3\" min.\"
11400  do to (251,220), ij
11500  220  ps=1.0/ttf
11600  251  continue
11700  251  continue
11800  11900  c***** read and write time to start and stop, jostime, and 
12000  c maximum production rate
12100  12200  read(in,203) tss,jostm,emax
12300  203  format(9x,3f10.4)
12400  write(io,699)
12500  write(io,692) tss
12600  'write(io,693) jostm
12700  write(io,696) emax
12800  12900  c***** read data interactively
13000  13000  write(6,100)
13100  13100  205  format(///r1x\"enter mtrbf and mtrr you wish to use\", 
13200  \"for analysis in the following form\",//2x,\"
13300  \"xxx.xxx,xxx.xxx\"/
13400  \"read(6*102) ttf,trl
13500  102  format(1x,F8.2,1x,F8.4)
13600  nan1=nan1
13700  13800  nan1=nan1
13900  if(iflag.eq.1) go to 104
14000  14000
c***** write headers for analysis

write(io,700)
write(io,701)
write(io,702)
write(io,703)

if last = 1

****** begin sensitivity analysis

do 310 ii = 1, npanel
xprod = 0.0
rs = rs1
fr = 1.0 / ttl

do 60 n = 1, 10
nn = n - 1

do 11 k = 1, n
fk = k
r(k) = 1.0 / (tss1(fk - 1) + jostm + fk * tr)
if (rs - r(k)) < 5.0, 4.
rsr(k) = r(k)

do to 11
rsr(k) = rs
continue

rsr(1) = 0.0
r(1) = 24.0 * fr / r(1) * po
f(nli) = rs / rs * po
if (n - 1) > 17.0, 6
r(1) = 24.0 * fr / (2.5 * fr) * po
17600     do 10 j=2*nn
17700         fj=j
17800  10     r(j)=(25.-fj)*pr/((24.-fj)*pr+fs)*r(j-1)
17900     fn=nn
18000
18100     do 15 k=2*n
18200         k=k+nn
18300  15     s(k)=s+rpr(k-1)*p(k-1)
18400     s(n)=s2+(25.-fn)*r/n(r(n)*s(n-1)
18500  17     n2=n*2
18600     sum=sum
18700
18900     do 20 k=1*n2
18900  20     sum=sum+r(k)
19000     ro=sum/sum
19100
19200     do 30 k=1*n2
19300  30     r(k)=r(k)/sum
19400     prod=ro*ro*ro*
19500     1=n-1
19600     if(n-1) 50,50,45
19700
19800  45     do 50 j=1,1
19900     prod=prod + r(j)* (float(24-j)/24.) * pmax
20000  50     continue
20100     down =0.0
20200
20300     do 51 j=n*n2
20400     down=down + r(j)
20500  51     continue
20600
20700
20800     if(prod<prod) 302,303,303
20900  302     xhlid(nanal+1)=tif
21000     xhlid(nanal+2)=tr
21100  xchild(nans1,3)=float(n)
21200  xchild(nans1,4)=prod
21300  *prod=prod
21400
21500  303  if(nans1-1) 301,301,60
21600  301  write(10,704) nxprod,down
21700  60  continue
21800  310  continue
21900
22000  c**** end analysis
22100
22300  c**** formats for write statements
22400
22500  699  format( 'submodule' )
22600  692  format( 'time to start and stopt50','f10.4','min.' )
22700
22800  693  format( 'time to start and stopt50','f10.4','min.' )
22900  696  format( 'maximum production rate',t50,'f10.2' )
23000
23100  700  format( 'no. of tools','5x','expected', '11x', 'probability of')
23200
23300  701  format( 'failed before','4x','staged state', '7x','being down')
23400
23500  702  format( 'shut down','8x','production rate','4x')
23600
23700  703  format( 'expected', '11x')
23800
23900  704  format( 'rounds/min','f10.2' )
24000
24100  write(6,299) xchild(nans1,4)
24200  299  format( 'production rate', 'f10.2',' rounds/min' )
24300
24400  331  write(6,332)
24500  332  format( 'do you wish to continue? ' )
+ 'Type y for yes or n for no'
read(6,333) answer
format(61)
if(answer.eq."y") go to 205
if(answer.eq."n") go to 335
write(6,207)
707 format(1x,'error message - you did not type the'
+ ' correct response')
do to 331

C***** write headings for sensitivity analysis

write(ior,320) nanai
format(1x,'sensitivity analysis',/t18,'note')
+ 'run no. 1 is best estimate while'/*t24,'2 thru'/*i2,
+ 'are answers obtained by varying'/*t24,'mthf and'/*
+ 'mttr'/*t12,'run'/*t17,'rotary mthf'/*t30,'rotary'
+ 'mttr'/*t44,'optimum policy'/*t60,'average prod.'/*
+ t12,'no.'/*t20,'(min)'/*t33,'(min)'/*43,'allowed'
+ 'failures'/*t60,'rate per shift'/*t49,'(tools)'/*t62,
+ '(rds/min)'/*

C***** write values for analysis

do 325 ii=1,nanai
write(ior,330) ii*(xhd(ii,j)),j=1,4)
write(ior,330) format(t11*i3*t18*i10.3*t31*i10.3*t49*f4.0*t62*f10.3)
write(6,400)
format(1x,/)
### submodule

<table>
<thead>
<tr>
<th>Name</th>
<th>MTBF (10**3)</th>
<th>1/MTBF (10**-3)</th>
<th>MTTR (mins.)</th>
<th>MTTR/MTBF (10**-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain Loading Turret</td>
<td>4.80</td>
<td>0.21</td>
<td>15.00</td>
<td>3.12</td>
</tr>
<tr>
<td>Insert Turret</td>
<td>4.80</td>
<td>0.21</td>
<td>15.00</td>
<td>3.12</td>
</tr>
<tr>
<td>Crimp Turret</td>
<td>9.60</td>
<td>0.10</td>
<td>15.00</td>
<td>1.56</td>
</tr>
<tr>
<td>Primer Inspect Turret</td>
<td>2.40</td>
<td>0.42</td>
<td>15.00</td>
<td>6.25</td>
</tr>
<tr>
<td>Sealant and Lacquer Turret</td>
<td>9.60</td>
<td>0.10</td>
<td>5.00</td>
<td>0.52</td>
</tr>
<tr>
<td>Unload and Reject Turret</td>
<td>14.40</td>
<td>0.07</td>
<td>15.00</td>
<td>1.04</td>
</tr>
</tbody>
</table>

**Summation**

<table>
<thead>
<tr>
<th>MTBF = Mean Time Between Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF = 900,000 Mins.</td>
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</table>

**MTTR = Mean Time to Repair Derived by Averaging the Repair Times Excluding Start, Stop, and Start Times**

<p>| MTTR = 14.063 Mins.               |</p>
<table>
<thead>
<tr>
<th>submodule name</th>
<th>mtbf (10**3 mins.)</th>
<th>1/mtbf (10**-3)</th>
<th>mttr (mins.)</th>
<th>mttr/mtbf (10**3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>chain loading turret</td>
<td>4.80</td>
<td>0.21</td>
<td>15.00</td>
<td>3.12</td>
</tr>
<tr>
<td>insert turret</td>
<td>4.80</td>
<td>0.21</td>
<td>15.00</td>
<td>3.12</td>
</tr>
<tr>
<td>crimp turret</td>
<td>9.60</td>
<td>0.10</td>
<td>15.00</td>
<td>1.56</td>
</tr>
<tr>
<td>primer inspect turret</td>
<td>2.40</td>
<td>0.42</td>
<td>15.00</td>
<td>6.25</td>
</tr>
<tr>
<td>sealant and lacquer turret</td>
<td>9.60</td>
<td>0.10</td>
<td>5.00</td>
<td>0.52</td>
</tr>
<tr>
<td>unload and reject turret</td>
<td>14.40</td>
<td>0.07</td>
<td>15.00</td>
<td>1.04</td>
</tr>
<tr>
<td>summation</td>
<td></td>
<td></td>
<td></td>
<td>1.11</td>
</tr>
</tbody>
</table>

**mtbf** = mean time between failures

**mtbf** = 900,000 mins.

**mttr** = mean time to repair derived by averaging the repair times excluding stop, job, and start times

**mttr** = 14.063 mins.
### Submodule

<table>
<thead>
<tr>
<th>Name</th>
<th>MTBF (10**3)</th>
<th>1/MTBF (10**-3)</th>
<th>MTTR (mins.)</th>
<th>MTTR/MTBF (10**3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primer feed tray</td>
<td>0.96</td>
<td>1.04</td>
<td>15.00</td>
<td>15.63</td>
</tr>
<tr>
<td>Jam</td>
<td>0.10</td>
<td>10.00</td>
<td>2.00</td>
<td>20.00</td>
</tr>
<tr>
<td>Electrical</td>
<td>0.96</td>
<td>1.04</td>
<td>10.00</td>
<td>10.42</td>
</tr>
<tr>
<td>Turret series failure</td>
<td>24.16</td>
<td>0.04</td>
<td>30.00</td>
<td>1.24</td>
</tr>
<tr>
<td>Chain breakage</td>
<td>6.00</td>
<td>0.17</td>
<td>30.00</td>
<td>5.00</td>
</tr>
<tr>
<td><strong>Summation</strong></td>
<td><strong>12.29</strong></td>
<td></td>
<td><strong>52.28</strong></td>
<td></td>
</tr>
</tbody>
</table>

MTBF = mean time between failures

MTBF = 81.358 mins.

MTTR = mean time to repair derived by averaging the repair times excluding stop, jog, and start times

MTTR = 4.254 mins.

### Time to Start and Stop

- Time to start: 1.5000 min.
- Time to stop: 0.0333 min.

### Maximum Production Rate

- Maximum production rate: 1200.00 rounds
enter mtbf and mttr you wish to use for analysis in the following form

900.00 14.063

<table>
<thead>
<tr>
<th>no. of tools</th>
<th>expected production rate</th>
<th>failed before</th>
<th>steady state shut down</th>
<th>probability of being down for repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>817.8</td>
<td></td>
<td></td>
<td>0.3185</td>
</tr>
<tr>
<td>2</td>
<td>820.7</td>
<td></td>
<td></td>
<td>0.2973</td>
</tr>
<tr>
<td>3</td>
<td>826.5</td>
<td></td>
<td></td>
<td>0.2885</td>
</tr>
<tr>
<td>4</td>
<td>821.9</td>
<td></td>
<td></td>
<td>0.2833</td>
</tr>
<tr>
<td>5</td>
<td>817.2</td>
<td></td>
<td></td>
<td>0.2798</td>
</tr>
<tr>
<td>6</td>
<td>813.0</td>
<td></td>
<td></td>
<td>0.2774</td>
</tr>
<tr>
<td>7</td>
<td>809.6</td>
<td></td>
<td></td>
<td>0.2756</td>
</tr>
<tr>
<td>8</td>
<td>807.0</td>
<td></td>
<td></td>
<td>0.2744</td>
</tr>
<tr>
<td>9</td>
<td>805.1</td>
<td></td>
<td></td>
<td>0.2735</td>
</tr>
<tr>
<td>10</td>
<td>803.7</td>
<td></td>
<td></td>
<td>0.2729</td>
</tr>
</tbody>
</table>

production rate is 828.74 rounds/min.

do you wish to continue?
type y for yes or n for no:
y

enter mtbf and mttr you wish to use for analysis in the following form

450.00 14.063

production rate is 651.02 rounds/min.
do you wish to continue?
type y for yes or n for no:
y
enter mtbf and mttr you wish to use for analysis in the following form

900.00 28.125
production rate is 658.27 rounds/min.
do you wish to continue?
type y for yes or n for no:
y
enter mtbf and mttr you wish to use for analysis in the following form

450.00 28.125
production rate is 462.74 rounds/min.
do you wish to continue?
type y for yes or n for no:
y
enter mtbf and mttr you wish to use for analysis in the following form

1800.00 14.063
production rate is 959.84 rounds/min.
do you wish to continue?
type y for yes or n for no:
y
enter mtbf and mttr you wish to use for analysis in the following form
xxxx.xx xxxx.xxxx
900.00 7.031
production rate is 952.03 rounds/min.
do you wish to continue?
type y for yes or n for no:
y
enter mtbf and mttr you wish to use for analysis in the following form
xxxx.xx xxxx.xxxx
1800.00 7.031
production rate is 1037.65 rounds/min.
do you wish to continue?
type y for yes or n for no:
n
sensitivity analysis

Note: Run no. 1 is best estimate while runs 2 thru 7 are answers obtained by varying MTBF and MTTR.

<table>
<thead>
<tr>
<th>run no.</th>
<th>rotary MTBF (min)</th>
<th>rotary MTTR (min)</th>
<th>optimum policy</th>
<th>allowed failures rate per shift (tools)</th>
<th>average prod. (rds/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900.000</td>
<td>14.063</td>
<td>2</td>
<td></td>
<td>828.739</td>
</tr>
<tr>
<td>2</td>
<td>450.000</td>
<td>14.063</td>
<td>3</td>
<td></td>
<td>651.018</td>
</tr>
<tr>
<td>3</td>
<td>900.000</td>
<td>28.125</td>
<td>2</td>
<td></td>
<td>658.267</td>
</tr>
<tr>
<td>4</td>
<td>450.000</td>
<td>28.125</td>
<td>3</td>
<td></td>
<td>462.741</td>
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<tr>
<td>5</td>
<td>1800.000</td>
<td>14.063</td>
<td>2</td>
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<td>959.835</td>
</tr>
<tr>
<td>6</td>
<td>900.000</td>
<td>7.031</td>
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VITA

Lydia Anne Chastain is the daughter of Dr. and Mrs. Herchel Eugene Lynch of New Boston, Texas. She graduated from New Boston High School as valedictorian in 1976. She attended the University of Arkansas and received a Bachelor of Science in Industrial Engineering in 1980. During her undergraduate years, she was a member of Kappa Kappa Gamma Sorority, the Engineering Council for Students, and the American Institute of Industrial Engineering. She also served as editor of the Arkansas Engineer for two years.

Since graduation, Anne has worked for Owens Corning Fiberglas, AT&T Technologies, and Lehigh University.

Anne currently lives in Breinigsville, Pennsylvania with her husband, Michael and their infant son, Matthew Evans.